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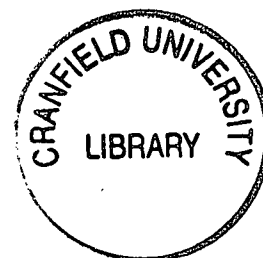


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Orbital Plasma Welding of Small Bore Tubes

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Orbital Plasma Welding of Small Bore Tubes

Supervisor: Dr I M Richardson

To my parents
Σταύρο και Έλσα
and my brother
Μάνο

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ABSTRACT

This work was primarily motivated by the industrial need for control of problems associated with the Gas Tungsten Arc Welding (GTAW) of small bore titanium and austenitic stainless steel tubes. These include: pore creation and entrapment in the weld zone, and variability of the fusion zone geometry. The primary aim of this study was the development of a low current orbital plasma welding capability using a structured approach which could lead to defect minimisation. The methodology should also have the potential to be used in a number of different conditions, extending the use of plasma welding in both melt-in and keyhole modes for the orbital welding of small bore tubes.

The project originally involved the modification of a totally enclosed orbital GTAW welding head for low current welding operations. It was established that for the current range required for small bore and small to medium thickness tubes, the use of a solid copper torch was sufficient to provide the required heat absorption. A stable arc was produced even for very low current values (down to 7A) while arc voltages were within the operating range of a standard GTA welding power source.

Procedural (i.e. off line) control was adopted for identification and optimisation of welding parameters. Since no procedure was available for the proposed welds it was necessary to generate the parameters required for the production of consistent weld profiles. Simultaneously, an expert system has been developed for the determination of optimum process parameters based on empirical models, developed using statistical techniques. Parameter combinations were selected based on physical as well as statistical relevance, providing a measure of confidence when predicting the required weld bead output characteristics. The approach also indicates the influence of the major input parameters on weld bead geometry and defect formation, such as undercut.

Two quality acceptance criteria were employed during this investigation, weld bead dimensional accuracy, and the type and seriousness of defects present (penetration / burn-through, porosity and undercut). Off line programming was utilised to control heat build up and to ensure welds were obtained with the desired geometry and minimal defect levels. The end result was the development of a prototype system for low current orbital plasma welding (in both melt-in and keyhole mode) of small bore tubes in a totally enclosed head. Tolerant procedures for low current orbital melt-in and particularly keyhole welding have been generated and a systematic methodology for the prediction and optimisation of welding procedures based on predetermined criteria has been developed.

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ABBREVIATIONS

A.S.S.:	Austenitic Stainless Steel
COV:	Coefficient of Variation
DT:	Period Between Arc Initiation and Initiation of Torch Rotation
ESB:	Electrode Set Back Distance
GMAW:	Gas Metal Arc Welding
GTAW:	Gas Tungsten Arc Welding
G(UND):	Average Undercut Indication Factor
HI_i:	Average Welding Current Employed During the Torch Rotation
HIS:	Total Heat Input During the First Segment expressed as a product of the Delay Time (DT) and the Average Welding Current Before the Initiation of Torch Rotation (I _{st})
IBW:	Inner Bead Width
I_b:	Background Welding Current
I_p:	Peak Welding Current
I_{st}:	Average Welding Current Before the Initiation of Torch Rotation
ND:	Nominal Deviation
NW:	Not Welded
OBW:	Outer Bead Width
O.D:	Orifice Diameter
OR:	Obtained Response
PAW:	Plasma Arc Welding
PGFR:	Plasma Gas Flow Rate
PR:	Predicted Response
RW:	Width Range Between the Maximum and Minimum Bead Width
SDT:	Torch Stand Off Distance
SGC:	Shielding Gas Composition
t_b:	Background Current Time
TIG:	Tungsten Inert Gas
t_p:	Peak Current Time
WS:	Welding Speed

1. Introduction

1. INTRODUCTION

1.1 Introduction and justification

Pipework fabrication is becoming a more demanding technology with the introduction of increasingly rigid standards to ensure quality and safety of fabrication in several fields, such as chemical processing, semiconductor manufacture and aerospace applications. These standards are often fulfilled with the use of manual techniques at the expense of productivity and reliability. The extensive mechanisation and automation of the equipment used for orbital welding helps to assure the quality and productivity requirements in the increasingly competitive world market. At the present time the most appropriate automatic welding machines are those in which the welding torch or electrode rotates around the workpiece in the welding head to make a circular weld joint, hence the designation of "orbital welding".

Although a wide range of high quality equipment and accessories are available for pipework fabrication today these are generally restricted to the following welding processes:

- a) gas tungsten arc welding (GTAW) with or without filler wire,
- b) gas metal arc welding (GMAW),
- c) flux cored arc welding (FCAW).

The implementation of advanced techniques such as plasma, laser and electron beam welding for orbital pipeline welding has not yet been exploited.

In particular, plasma arc welding was introduced over 35 years ago. The process is a modification of gas tungsten arc welding in which the arc from a tungsten electrode is constricted by being passed through a small diameter orifice before impinging on the workpiece, producing a weld. Although, the unique characteristics of the constricted arc give very important advantages to the process (see sections 2.1.2, 2.2.3.1, 2.2.3.2), the use of the process seems to have been restricted to only a few applications. This may be attributed to the relatively high cost of the equipment, the difficulties arising from the increased complexity of the torch and the manipulation of a large number of the control variables. The latter leads to difficulties with the optimisation of process parameters.

At the present time, the implementation of the plasma process to orbital welding has only been reported with open welding heads. The application of plasma techniques to totally enclosed weld heads, which offer the best results for clean, even weld beads, consistent quality production, greater flexibility and portability has not yet been reported. Such an application is quite attractive since it extends the application of the plasma process to areas where the advantages offered by the technique, such as more columnar weld, reduced heat affected zone, reduced electrode contamination, full penetration (particularly in the keyhole mode), reduced susceptibility to porosity formation, high depth to width ratio and high arc pressures, can prove crucial for the quality and safety of the joints.

The improvement of the welding technique is of particular interest in certain cases such as:

- a) titanium and titanium alloy welding, where oxidation or creation of large gas pores is completely unacceptable,
- b) stainless steel welding where variable weldability has been experienced [232],

Results from an earlier feasibility study (conducted by the author) concerning the benefits that the implementation of the plasma process can offer, revealed that a reliable solution to these problems can be obtained [46]. Furthermore, an initial evaluation of the requirements of a totally enclosed orbital plasma welding head had been made in terms of the equipment requirements and the characteristics of the system. However, the need for control of a large number of significant variables associated with orbital plasma welding, particularly in the keyhole mode, has limited the industrial exploitation of the process. Therefore, the implementation of a statistical approach for modelling of the process, suitable for the handling of a large number of parameters (including weld bead characteristics and welding parameters) would be particularly useful, since it could reduce the number of trials required to achieve an acceptable weld.

1.2 Objectives of the Research Work

The purpose of this study is to design and develop an orbital plasma welding system, investigate its characteristics and relate the processing conditions to the geometry of the welds produced by using statistical modelling techniques. This study

also aims to provide the necessary framework for extending plasma welding applications to low current orbital keyhole welding.

The research is primarily focused in the following four major aims:

1. to evaluate the performance and effectiveness of the orbital plasma welding process for low current plasma applications, particularly in the keyhole mode, based on the results obtained from the utilisation of a prototype orbital plasma welding system in a number of applications.
2. to evaluate the effectiveness of the mathematical modelling process in order to obtain empirical statistical models relating the major welding parameters (input variables) and weld bead characteristics (output variables) for orbital plasma welding of small bore tubing.
3. to evaluate the empirical models constructed for several applications along with the optimisation strategy developed with their support, as an aid for predicting optimum weld bead characteristics within the range of parametric settings investigated. Simultaneously, to develop a structured approach that could lead to defect minimisation (particularly bead width variation due to heat build-up and undercut formation problems) and which could subsequently be used for a number of different conditions and processes.
4. to highlight the physical mechanisms governing the weld bead formation in orbital plasma welding and examine the influence of the major plasma process parameters on the resultant output characteristics.

1.3 Work Programme and Methods

A systematic approach has been employed for the process of prediction and optimisation in a range of pipe compositions, sizes and wall thicknesses. Emphasis has been placed throughout the research work on the development and implementation of systematic control strategy for automated welding systems. The latter can only be achieved through a better understanding of the complex interaction between the large number of welding parameters as well as the large number of solidification and physical parameters (heat build-up and variation of the effect of gravitational forces respectively) involved in the welding process.

Following the feasibility studies related to the materials concerned (titanium alloys and stainless steels initially) along with a market research to investigate the currently available systems, the design and fabrication of an orbital plasma welding

system for low and intermediate current plasma welding was undertaken. Since considerable effort has already been invested in the design and fabrication of GTAW heads the main target in this study has been the modification of already existing GTAW heads, in order to utilise the major benefits offered by these systems, such as precise pre-programming and control of the welding atmosphere. The primary aim has been to achieve sufficient constriction of the arc and provide adequate heat absorption from the nozzle in order to avoid any damage, without making the torch bulky and without the need for extensive re-machining of the welding head. Following the integration of the head with the controller, power source and data acquisition system, two major areas related to the characteristics of the modified head were investigated. These were:

- a) the temperature rise of the torch very close to the nozzle, along with the influence of the major welding parameters on the heating and cooling of the torch,
- b) the relationship between the arc voltage and the major welding parameters.

The second phase of research, as already noted, was the systematic approach for welding parameter prediction. The main objective has been the development of models for a range of materials and wall thicknesses which can be used to predict and optimise the welding procedures using statistical analysis techniques. Equations have been developed for a number of positions along the weld bead profile providing an accurate representation of the geometric characteristics throughout the weld bead which particularly allowed a better evaluation of the heat build-up and undercut problems in orbital plasma welding of small bore tubes. Regression analysis has been utilised since it is extremely effective for solving complex multi-factor problems, such as those encountered in orbital plasma welding. Nevertheless, due to the large number of process parameters involved, the examination of all parametric combinations was not possible within the confines of this study. Therefore, using the experience gained through the feasibility studies, the influence of the most important parameters on the resultant weld as well as the general process behaviour in a totally enclosed plasma welding head has been investigated.

The models for two different materials and techniques (Ti-3Al-2.5V welded using the melt-in-mode and 316L austenitic stainless steel welded using both the melt-in mode and the keyhole mode) have been developed and successfully used for parameter selection before welding in order to achieve optimised conditions for the multivariable orbital welding procedures. The optimisation procedure adopted is based on a simple and flexible Excel 5.0 spreadsheet which also provides an assessment of the effect of individual parameters.

2. Literature Survey

2. LITERATURE SURVEY

2.1 Introduction

The literature review covers a wide range of subjects related to the orbital plasma welding of small bore tubes, and can be divided into four major parts. The first part attempts a general review of the principles and inherent characteristics of plasma welding and gives several examples of its applications within the welding field. It also demonstrates recent advances in process technology along with the characteristics of both older and the latest commercially available equipment (sections 2.1 to 2.3).

The second part discusses the individual effects of the major plasma welding parameters on weld quality in plasma welding. It also identifies the major causes and suggests a number of control actions for the most common defects encountered in plasma welding (section 2.4).

The third part deals specifically with the application of the plasma process in tube welding. It describes the current status in orbital welding of tubes and the equipment presently available. Furthermore, it illustrates the main problems and solutions in tube welding with particular emphasis on problems associated with orbital plasma welding (section 2.5).

The final part is concerned with modelling of the welding processes and illustrates the most common techniques employed for modelling and optimisation of the welding procedures. A summary of the most important statistical techniques utilised for the development of an information-calculation system for optimising orbital welding procedures is also presented (sections 2.6 and 2.7).

2.1.1 The Constricted Arc - A Brief History

In order to gain a better understanding of the plasma process it is useful to present some general features associated with the constricted arc processes.

Although various definitions have been proposed the term "electric arc" which is the basis for arc welding is currently defined as [1]:

"a discharge of electricity between electrodes in a gas or in vapour from the electrodes, which has a voltage drop at the cathode of the order of the excitation potential of the electrode vapour (viz. only of the order of 10 volts) and in which the current flowing can have any value almost without limit, above a minimum, which is about 100 milliamperes but varies with the electrode material up to about 1A".

More specifically, the term *plasma* which is commonly applied to electric discharges can be defined as (2):

"a highly ionised gas which contains (approximately) equal number of ions and electrons in sufficient density so that the Debye shielding length is much smaller than the dimensions of the gas"

The origin of a constricted arc though, goes back to the 1920s, although the use of arcs as a heat source was first described in a US patent in 1908 [3] but is not clear whether this refers to constricted or non-constricted arcs. According to Gage[4], Gerdien is considered the originator of the constricted arc where constriction was achieved by means of a water vortex. However, it was not until the middle 1950s that R. Gage of Union Carbide (Linde) in US discovered that constriction of an open arc could lead to significant alterations of the characteristics of the GTAW process increasing significantly the temperature of the arc [5].

Since the 1950s, the term "plasma" in welding has evolved an alternative meaning, used to describe the high energy state caused by the constriction of an electric arc. All modern welding processes related to the "plasma arc" have as a basis this constricted arc.

2.1.2 General Characteristics of the Constricted Arc

Welding, cutting and surfacing are the most important applications for the constricted arc. A number of ways can lead to the constriction of the arc. Magnetic, thermal and physical constriction are the most common ways to achieve this. According to Richardson [6]: *"For free burning arcs, the expansion pressure due to hot gas in the core is balanced by an inward acting Lorentz force due to the interaction between the arc current and its associated magnetic field. Further constriction can be achieved by the application of an external magnetic field."*

Thermal constriction can occur when cold gas jets impinge on the outer region of the arc. Energy (heat) loss from the outer core restricts the available area through which the current can flow due to the reduced number of ionised particles. For a given welding current the core temperature must therefore rise to accommodate the increase in current density necessary to compensate for conduction losses in the outer core region. Energy density therefore increases.

Plasma welding is usually performed using a physical constriction. The influence is similar to that observed with magnetic and thermal modes; however, the degree of constriction can generally be greater, resulting in high energy density and high temperature arcs."

The physical constriction of the arc forms the principal feature of the Plasma Arc Welding process and reveals the close relation between GTAW and PAW. Figure 1 [7] illustrates the key features of a constricted plasma arc along with a comparison with a non-constricted arc used for GTAW.

In order to realise the benefits that the constriction of a GTAW arc offers, it is necessary to understand the inherent characteristics of the constricted arc mode of operation. The following list summarises some of the most important characteristics of plasma arc [8,9]:

- The arc column is stiff and directional,
- The arc column is nearly parallel sided and retains a smaller diameter than a free burning arc even at relatively long arc lengths,
- The arc which issues from the duct has a reduced cross section and thus the heat input area is reduced,
- The torch protects the welding electrode, hence reducing the risk of contamination which results in improved electrode performance and increased electrode life,
- The arc temperature is increased and the arc voltage is raised,
- By controlling the operating parameters the heat transfer to the workpiece and the arc pressure can be controlled,
- relatively long torch-to-workpiece distances can be tolerated.

2.2 Plasma Arc Welding

2.2.1 Principles of Operation and Terminology

All plasma arc torches use the same operating principle: production of heat by a constricted arc between an electrode and a workpiece (transferred arc), or between a non-consumable tungsten electrode and a constricted orifice (non-transferred arc). The most significant effect of such constriction is that the temperature and the momentum of the plasma can be markedly increased by using a fine bore nozzle and a high plasma gas flow rate. The main features and terms used to describe plasma arc torch geometry are presented in figure 2 [10].

The constriction of the arc is achieved in most of the cases by a water cooled constricting nozzle, designed to squeeze the arc and thereby increase the potential gradient. The orifice has two principal dimensions; the diameter of the orifice, and the throat length.

The constriction nozzle is usually made from water cooled, oxygen free copper in order to dissipate efficiently the excess heat from the nozzle walls close to the arc, although the use of several refractory materials have also been reported. It is normally coaxial and parallel to the electrode although nozzles with converging or diverging taper have been used in several cases.

Two separate streams of gas supplied to the torch complete the welding plasma torch features. The orifice or plasma gas surrounds the electrode within the orifice body and is constrained to pass through the orifice providing the arc with the required material for continuous operation and forming a jet of intensely hot plasma. In most of the cases the plasma gas is supplied axially from the top of the torch contributing in that way to the cooling of the electrode, although tangential provision of the gas, close to the arc origin for improved constriction of the arc within the nozzle is also widely used [11].

The second gas stream is provisional and is called the "shielding gas". It is provided through an additional outer gas cup issuing between the orifice body and the

outer cup. The purpose of this gas is to shield the molten pool. This separation of the gas supplies offers the flexibility of separate control of their composition and flow rate.

The "electrode setback" is defined as the distance that the electrode is recessed within the torch. The term "torch stand-off" is used to describe the distance from the outer face of the torch nozzle to the workpiece. The designation "plenum" or "plenum chamber" refers to geometric characteristics of the torch. It describes the space between the inside wall of the constricting nozzle and the electrode excluding the constricting part of the nozzle. The geometry of that area has a strong influence on the flow behaviour of the plasma gas.

The dimension of the axial length of the constricting channel of the nozzle is defined as the "throat length". Finally, the diameter of the hole through which the arc is squeezed is defined as the "orifice diameter".

Extra care should be taken with the use of the terms nozzle and orifice. In most of the cases the terms are used to describe the solid part of the torch where the hole through which the arc is obliged to pass is situated and not just the hole. Throughout this thesis the above terms will be used for description of this solid, often interchangeable part of the torch.

Figure 3 presents the basic circuitry of a plasma arc welding installation [12]. Arc current is provided by an A.C or D.C power supply with a "drooping" volt-ampere output curve. In most cases a GTAW welding power source provides the correct characteristics. Depending on the application, touch striking or high frequency techniques can be applied for initiation of a "pilot arc" between the electrode and the nozzle. A high frequency generator is used when a high frequency spark is employed for arc initiation. Ionised gas from the pilot arc plasma is blown through the nozzle forming a low resistance path to the workpiece. Subsequently, the main arc is established with the application of a voltage between the electrode and the workpiece.

Although much higher temperatures are obtained by constricting the arc this is not the main advantage of the process. The main advantages of plasma welding, as a result of the inherent characteristics of the constriction of the arc mentioned in the previous section, are the directional stability and focusing effect of the plasma jet.

2.2.2 Arc Modes

Two distinct operating modes are possible for both welding and cutting: transferred arc and non-transferred arc.

2.2.2.1 The Transferred Arc Mode

In this mode of operation the arc is maintained between the electrode and through the orifice to the workpiece, i.e. the circuit is closed by the workpiece (figure 4a). Since the workpiece is usually the anode, heat is obtained on the workpiece from electronic effects at the anode spot in addition to the heat transmitted from the plasma jet [1, 2, 7]. The high energy densities achieved make this mode generally more attractive for welding and cutting applications [10].

2.2.2.2 The Non-Transferred Arc Mode

In the non-transferred arc mode (figure 4b) the current flow is from the electrode inside the torch to the nozzle containing the orifice and back to the power supply. A hot non-current carrying plasma gas is exhausted from the torch nozzle due to the forced gas flow. With this technique very little energy is transferred to the workpiece. Normally, this mode is used for surfacing, welding of thin sections or when the material is a poor electrical conductor. The application of non-transferred arcs for cutting have also been reported [13,14]. Generally, their main use is to form a "pilot" arc which enables the main transferred arc to be established rapidly [15].

The constricting orifice is usually connected to the positive side of the power supply, and for this reason the orifice is referred to as the anode. For this technique two basic forms of anode root behaviour have been reported:

a) the one described as "internal" [3, 4, 11] where the non-transferred arc has little extension beyond the nozzle (figure 5a).

b) the one described as "external"[3, 4] or "blown arc" [12] where the non-transferred arc exits freely through the constricting annular anode orifice (figure 5b).

Which form the technique should follow depends on the operating conditions, mainly the gas flow rate, the throat length and the orifice diameter. The "external"

mode is the usual mode of operation for most non-transferred arcs supported by high gas velocities in the torch.

2.2.3 Modes of Operation

The plasma welding process may be carried out in one of two modes:

- melt-in-mode
- keyhole mode

2.2.3.1 Melt-in Mode

The melt-in-mode is the most often used with PAW processes. It is conducted in a similar manner to GTAW, the only difference being the use of a constricted arc as a heat source. The plasma impinges on the work and melts or penetrates the surface to some depth.

According to [16] this type of weld mode is accomplished with a softer, less constricted arc, using lower plasma gas flow rates, reduced electrode setback, and current levels in the range of approximately 1-200 amps.

The advantages that the operation in melt-in mode offers over GTAW include the following:

- Higher depth to width ratio is achieved for a given penetration, resulting in minimised distortion. In general, the heat input area is restricted.
- The higher energy concentration results in higher welding speeds and lower required current, resulting again in reduced distortion.
- The operation is reasonably tolerant to torch stand-off variations. This makes the addition of filler metal easier where required.
- Control variation can be achieved by controlling one of the variables.
- The arc is more directional and stable.

The disadvantages of this type of operation over GTAW include the following:

- Little tolerance in joint misalignment is allowed due to the narrow constricted arc. This makes joint preparation critical and sometimes extensive fixturing is required.
- More expensive equipment is required.
- Control of a large number of parameters is required.

2.2.3.2 Keyhole Mode

One of the most important characteristics of the plasma arc welding process is the ability to produce deep seam welds by forming a "keyhole" in the workpiece, a phenomenon which can only be found with high energy density processes such as electron beam and laser. An appropriate combination of plasma gas flow, current and travel speed combined with a small nozzle diameter and increased electrode set back will produce a highly constricted directional plasma jet. The jet displaces the molten metal completely and penetrates the workpiece. As the plasma torch is moved along the weld joint, surface tension forces cause the molten material to flow around the side of the hole from the front to the rear, maintaining the keyhole and producing fully penetrated welds (figure 6). Parameters should be chosen carefully so that the molten metal is not expelled. In order to maintain stable operating conditions at a given travel speed, a balance between the keyhole-generating forces (gas velocity, vapour pressure and recoil pressure) and the forces tending to close the keyhole (surface tension and gravitational forces) is required [17].

Due to the unique mechanism of weld pool formation the behaviour of the molten pool has attracted significant attention in order to understand keyhole operation and thus improve control of the process [18-24]. The construction of operational envelopes [25-29] and the applications of the keyhole technique have also received significant attention [30-36]. Attempts have also been made to predict the fusion behaviour of a fully penetrated plasma arc by applying techniques similar to those adopted for investigation of the behaviour of the laser keyhole [37-40].

Some of the major advantages and limitations of plasma keyhole welding over GTAW are listed below:

- Reduced current values are required.
- Many welds can be completed in a single pass.

- Reduction in weld preparation and machining costs due to the joint type (square butt) which is generally used.
- Narrower weld beads are obtained.
- There is visual proof of 100% weld penetration.
- The escape path formed by the plasma gas flushing through the open keyhole, allow impurities to flow to the surface and gases which could form porosity to be expelled from the molten metal. In general the technique is more tolerant of surface and internal defects.
- Reduced distortion due to the symmetrical fusion zone is achieved.
- Requirements for filler material due to the higher penetration are minimised.

Some of the limitations of plasma keyhole welding are:

- The application of the technique to positions other than the 1G is quite complex and difficult.
- The technique is generally restricted to automated operations. Manual operations require increased operator skill and are not recommended because of difficulties in maintaining consistent travel speeds and torch position. In general, instabilities can easily result in the loss of the keyhole increasing the risk of porosity and giving only partially penetrated welds or even worse, cutting.
- The keyhole is very sensitive to changes of the input variables (e.g. welding current, welding speed, plasma gas flow rate).
- A large number of parameters influence the process performance, their interaction is complex and the operational envelopes are relatively narrow.
- One of the major limitations of the process is the formation of undercut although it can be eliminated or minimised by careful selection of the operating parameters.

A wide number of applications are associated with plasma keyhole welding and will be discussed in section (2.3.3).

2.2.4 Polarity

For most plasma arc welding applications direct current, electrode negative power is used (DCEN). Current pulsation is frequently employed, and it has been shown

that current pulsation offers significant advantages [27, 28, 41]. Direct current, electrode positive (DCEP) is used only for aluminium welding to a limited extent due to excessive electrode heating. Even with sine wave alternating current, used for aluminium and magnesium alloys, the current range that can be applied is restricted to less than 100 amps. The primary reason is again the excessive electrode deterioration during the electrode positive current cycle. Variable polarity plasma arc welding (VPPA) is used as an alternative, for welding these materials, where the cathodic etching property is retained during the positive current half-cycle of the unbalanced square wave.

The unique properties of the constricted plasma arc have led to a broad classification of the welding process to the following three subdivisions [5, 6, 8, 15, 33, 44] which is convenient for a better understanding of the features and applications of the process:

- Micro-plasma or low current or needle arc welding - 0.1 to 15A.
- Medium or intermediate current welding - 15 to 200A.
- High current or keyhole welding - >100A.

The above classification can be treated as a general guideline because of the significant overlap between the categories, mainly between the intermediate and high current ranges. Furthermore, the application of the keyhole mode - which is primarily a high current operating technique - has been extended to medium and low currents, thus making rather arbitrary any attempt to classify the process into broad subdivisions.

2.2.4.1 Low Current or Micro-plasma Welding

Micro-plasma welding has been so termed because a very stable and controllable arc can be formed and maintained even at welding current levels as low as 0.1-1 amps at which the use of GTAW presents severe problems due to lack of stability and directionality (although the use of modern transistor controlled power sources extends GTAW limits to less than 1A). The starting of the transferred arc is more reliable at these current levels through the use of a pilot arc which for very low currents operates continuously to provide sufficient quantities of ionised gas for stable transferred arc behaviour. Micro-plasma is less sensitive to arc length variations even for very low current work, which is very important considering that even very small fluctuations in

arc current produce a fairly large change in voltage in GTAW (figure 7) [34]. Furthermore, the influence of small arc length variations on the total heating area is considerably greater in GTAW than it is in PAW due to the shape of the arc (figure 8).

The micro-plasma welding equipment basically is the same as that of conventional plasma arc welding systems incorporating small adaptations for specific applications if necessary, such as the use of the continuously operating pilot arc. Another modification is the use of a higher than normal open circuit voltage power supply in order to handle the very high voltage values of the transferred arc that can be reached at fractional ampere currents with helium or with argon and hydrogen gas mixtures. Furthermore, the design of the pilot arc system and the nozzle geometry to provide a stable, columnar non-transferred plasma for applications requiring low energy density and heat transfer rates has also been reported [43]. Although, micro-plasma welding is used for low current applications, cooling of the torch is necessary due to the effects of arc constriction and the heat load imposed by the pilot arc. Two types of power sources are used for micro-plasma welding: a) power sources with normal drooping volt-ampere characteristics and b) power sources with a vertically characteristic [44].

The process can be used in both melt-in and keyhole mode. Plasma gas flow rates higher than usual (approximately 0.1 l/min.) are required for keyhole operation [45, 46]. Furthermore, modulation of the current has successfully been applied to micro-plasma welding, extending the advantages that the process offers even further [47, 48, 49].

Additional advantages that micro-plasma offers are:

- a narrow weld and small HAZ, resulting from a high energy concentration and a needle shaped arc offer a significant reduction of distortion, especially in thin materials. It has been estimated that in some applications deformation can be reduced by 25-30% [50, 51],
- lighting emitted from the pilot arc has advantages over GTAW in manual operations and helps to ensure accurate location of the joint line [15, 52],
- higher welding speeds can be achieved. Three times faster speeds have been reported by using micro-plasma welding instead GTAW [53],
- reasonable deviations in the arc length have little effect on heat concentration and bead width making possible the welding of components with uneven surfaces [5].

Apart from the general limitations associated with plasma welding such as complexity of the equipment and the large number of control variables, there are no significant limitations associated with micro-plasma welding in particular. The only restriction is considered to be the reduced tolerance for joint misalignment due to the narrow constricted arc.

A large number of applications associated with micro-plasma welding will be reported in section 2.3.1.

2.2.4.2 Intermediate Current Plasma Welding

Above the micro-plasma range and up to about 200A the plasma process is similar in characteristics to GTAW, due to the fact that a plasma arc produces similar melt runs to a free burning GTAW arc. However, for the same mean current, higher speed or improved melting efficiency may be achieved. In addition, the plasma arc is slightly "stiffer", more tolerant to variations in stand-off and the tungsten electrode is protected from accidental touch down and contamination. For the same mean current improved melting efficiency may be achieved. On the other hand, the relatively complex control of PAW and the high cost of the equipment may help to explain why the PAW process has not been widely implemented in industry.

The major advantage that plasma welding offers (in this current range) over GTAW is that appropriate combinations of the process variables make it possible to affect the size and shape of the weld bead by modifying the heat transfer efficiency and arc pressure to the workpiece [6, 33]. Furthermore, the keyhole mode of operation may be used which offers further advantages. Keyhole operation is achieved by increasing the plasma gas flow rate until a hole is "punched" through the plate and the molten weld pool is forced up behind the plasma column. However, this increases the risk of shielding gas and air entrapment through excessive turbulence in the gas shield and agitation of the weld pool.

The advantages mentioned above have ensured the growth of the technique over a wide range of application areas for both melt-in and keyhole modes (see section 2.3.2).

2.2.4.3 High Current or Keyhole Welding

The use of the keyhole mode of operation, described in section 2.2.3.2 is possible at high currents due to the fact that the plasma jet is very intense and possesses a high plasma force, especially at currents above 200A. This can be achieved without the use of high plasma gas flow rates which entails several risks as mentioned above.

Applications associated with keyhole welding are reported in section 2.3.3.

2.2.5 Arc Starting

In existing plasma welding systems direct current alone is not enough to initiate the main transferred arc between the electrode and the workpiece. Furthermore, the recession of the electrode in the constricting nozzle makes unfeasible the ignition of the arc by touching the electrode against the workpiece.

Arc initiation is usually provided by a low current, non-transferred pilot arc which is first struck between the electrode and the constricting nozzle. The pilot arc helps to break down the gap and ionise the orifice gas and thus creates a path for transferring the main arc to the workpiece.

2.2.5.1 Ignition of the Pilot Arc

Ignition of the pilot arc generally takes place by the use of a high frequency discharge [e.g. 5, 16, 46, 54]. The above can be achieved by means of high frequency AC power or a high-voltage DC pulse superimposed on the welding circuit. Pilot arc current can be drawn either from a separate low current high voltage power source (figure 9a) allowing welding power sources not fitted with HF units to be used, or from the main arc power source (figure 9b). In the latter a balance limiting resistor, first introduced by Linde Co. in 1955 [55], was placed in the circuit to assist in arc ignition and limit the pilot current preventing in that way the torch from overheating. With the use of a balance resistor the maximum pilot arc current value achieved is limited to the maximum working voltage of the power source divided by the value of the resistance.

Touch striking for initiation of the pilot arc has also been reported [56] and is usually employed in micro-plasma welding [45]. This is a two step procedure. Initially the electrode is pressed on to the nozzle in contact with the constricting duct. On release, the contact is broken and a spark forms since a spring brings back the electrode to the pre-set setback distance. The major problem associated with this technique is when the stub down current becomes excessive. This can lead to damage or contamination of the electrode [57]. One solution to this problem can be given by accurate control of the stub down current or by arranging that the point of contact with the orifice as the electrode slides coaxially is on the side of the electrode, avoiding the possibility of damage to the vulnerable tip [58].

Unlike the non-transferred plasma arc, the pilot arc is not necessarily constricted [3, 59]. Excessive heating and damage of the torch can be avoided by using currents less than 20A. After the ignition of the main arc the use of the pilot arc is not essential any more especially for high currents.

2.2.5.2 Initiation of the Main Arc

The plasma jet produced by the non-transferred pilot arc supports the initiation of the main arc providing the conducting path between the electrode and the workpiece which will pass sufficient current to allow the main arc to strike. Where a balance resistor is used in the pilot arc circuit the moment of main arc initiation depends on the proximity of the torch to the workpiece. The required voltage for starting a main arc is reduced as the torch approaches the workpiece while at the same time, the current demand and the combined potential drop across the pilot arc and series current limiting resistor increase. There is a critical point where the presence of ionised particles exhausted from the constricting nozzle makes energetically more favourable the conduction path to the workpiece and a *proximity strike* of the main arc takes place with simultaneous extinction of the pilot arc.

Where an independent pilot arc power source is used, ignition of the main arc is absolutely independent of the pilot arc. The above means that, providing the stand-off distance is not too large (usually must be less than 12mm [60]), energising the power source will initiate the main arc. Benefits associated with the use of such a configuration include the following [9]:

- the moment of main arc striking is fully controllable,
- alignment of the torch to the workpiece can be achieved with the assistance of the pilot arc and,
- HF tracking marks are eliminated since the pilot arc can be ignited remote from the workpiece,
- the pilot arc may be switched off at any time during the main arc operation or it can run continuously.

Control consoles operating in association with the main power source have been developed where all the ignition operations and sequence (plasma and shielding gas flow rate, pre and post weld purging, torch coolant supply and pilot and main arc ignition) are controlled [6, 33].

2.2.6 Arc Stability

As already mentioned one of the major advantages that plasma welding offers is the stiff, directional arc by contrast to GTAW. Movement of the arc around the electrode tip or wandering of the arc across the surface of the workpiece are eliminated even for currents below 1A [61]. The major problem that affects arc stability in plasma welding is a phenomenon called double arcing.

2.2.6.1 Double Arcing

Under normal operating conditions, an annular layer of a relatively cool, non-conductive gas with a very steep thermal gradient surrounds the arc column within the torch [11]. This layer provides thermal and electrical insulation protecting the inside surface of the nozzle. Considering that plasma temperatures are over 24,000° C while the melting point of copper, which is used almost always for production of the nozzles, is 1080° C, the above helps to explain why copper can be successfully used for effective constriction of the plasma arc.

If the plasma gas flow rate is insufficient, the current too high for a given nozzle geometry, the torch is touched to the workpiece or the nozzle cooling is inadequate an arc may form between the electrode and the workpiece since the metallic torch nozzle becomes part of the current path to the ground (figure 10). This

phenomenon is called "double arcing" and may cause significant damage to the nozzle by the heat generated at the cathode and anode spots formed where the two produced arcs attach to the nozzle.

Several actions can be taken to reduce the tendency for double arcing. Higher plasma gas flow rates are beneficial up to a certain maximum permissible value which does not causes excessive disturbance of the weld pool. For keyhole welding this action is closely associated and restricted by the operational envelopes.

The use of short ducts and the appropriate combinations of duct diameter/operating current further reduces the tendency for double arcing [10]. According to Malakhovski, the likelihood of double arcing decreases as the electrode set back decreases, as the nozzle diameter increases, the area of additional openings increases and as the current and nozzle duct length decreases [62].

Another action that has been reported to enhance arc stability (i.e. no tendency for double arcing) is the use of vortex plasma gas flow in welding torches [54, 63, 64, 65]. The use of vortex motion in the plasma gas flow has been reported several times in the past [e.g. 66, 67]. According to Browning [68] the improved arc stability with this type of gas flow is attributed to the relatively low pressures developed at the axial core of the vortex which causes a reduction in the arc voltage and makes the axial position in the duct preferable for the arc.

According to Petrov et al [69] and Bagryanskii and Gubenko [70] the tendency for double arcing increases with greater stand-off distances. On the other hand, according to Kusharev et al [71] for relatively short stand-off distances a triple arcing might be produced due to reflection from the surface of the weld pool and impingement on the nozzle of plasma. This can be avoided with greater stand-off distances. It can be concluded from the above that further investigation is necessary in order to fully examine the influence of stand-off distance on arc stability.

2.2.7 Arc Focusing

Several methods have been reported for shaping and even further focusing the arc after it emerges from the constricting duct.

The first attempt at arc focusing in welding applications appears to have been the multiport nozzle with which enhances constriction. An elliptical arc profile elongated along the axis of the weld is produced. According to Fillipski [54] this nozzle has an additional hole at either side of the constricting duct (figure 11a) and enables a portion of the plasma gas supply to be directed and impinge at the arc column. In this way the relatively cooler gas issuing from the auxiliary holes lowers the temperature of the outer region of the arc and the arc becomes asymmetrical and elongated in the direction of traverse.

According to Irving [72] and Filipski [54] this enables welding to be carried out at speeds increased by 50-100% over those obtained with nozzles having only the central duct (single port nozzles). Furthermore a narrower HAZ was produced. Smart however, found completely contradictory results [73]. He observed that although the arc issuing from the single port nozzle was less constricted the current and plasma gas flow rate required to match the welding speed of the multiport nozzle were lower. Moreover, the multiport nozzle produced welds with significant undercut even for very low welding speeds.

Other techniques for arc focusing were subsequently introduced. These include the use of several auxiliary holes situated around the central plasma orifice, the use of a conically shaped single port nozzle along with a similarly shaped shielding gas cup (figure 11b) [74] or even the use of magnetic methods. The latter had attracted significant attention by many researchers (e.g. 75-79) and the field is still under investigation.

Cooper et al suggested that the major effect of the focusing gas streams was to cool the outer region of the arc[11]. McLean thought that the ionisation potential in these regions will increase causing the de-ionisation of plasma and thus the arc must pass through a smaller cross section area [9].

When focusing gases have different composition than the plasma gas the relative ionisation potential of the gases is important. If the focusing gas has a higher ionisation potential (e.g. argon gas with a helium focusing flow) a greater focusing effect is obtained and more even weld underbead contour is obtained, whilst helium plasma gas and argon focusing gas may result in an increase in arc diameter. McLean [9] suggested again an explanation for the mechanism. He noted that (for the arc contraction case) as

the focusing gas mixes with the outer region of the plasma gas, the ionisation potential of these regions will increase and they will tend to de-ionise causing the arc to pass through a smaller cross-sectional area.

The magnetic shaping of the plasma arc is well explained since as it is well known that the arc is a fluid conductor of electricity and has an associated magnetic field and thus an external magnetic field can cause the arc to contract and concentrate the arc column power.

2.2.8 Power Source Requirements

According to Richardson [37], an increase in the arc voltage occurs as a result of arc constriction due to increased energy losses from the outer region of the arc. This increase is between 1.5 and 3 times the voltage of a corresponding free burning GTAW arc [6]. The characteristic shape of the plasma voltage-current curve has a similar form to the GTAW characteristic curve (figure 12) [80]. Several authors examined the influence of various parameters on the arc voltage. The following factors can cause an increase in the arc voltage: decrease of the orifice diameter and/or increase of the plasma gas flow rate [81, 82], increase of the throat length of the constriction nozzle [11], increase of the current [17], Addition of helium or hydrogen to the gas (plasma or shielding gas) [17, 83], increase of the stand-off distance [54].

Although some additional requirements might be necessary in order to meet the special characteristics of the plasma arc and some other demands of plasma operations (i.e. micro-plasma operation and ignition of the arc), conventional power sources with a drooping volt-amp characteristic (constant current or near constant current) are required for DCEN plasma welding. These are typically the standard power sources used for GTAW which might be used in conjunction with a plasma control console [28, 33, 56, 79]. For most of the applications an open circuit voltage of 65-80V is required [7, 9, 54, 84]. When hydrogen or helium additions have been made to the plasma and/or shielding gas in order to increase the heating potential of the arc [3, 33, 68, 83, 85], an increased OCV might be necessary. In that case two or even more power sources can be used in series [9, 54, 72, 86, 87]. Alternatively, power sources adapted for plasma welding with a high OCV of about 110-120V might be used [9]. An alternative approach where erratic ignition is experienced is the use of pure argon for arc striking and then switch over to the desired mixture (argon/hydrogen or argon helium).

According to Messenger and Cuny though [88], the use of power sources with a negative gradient characteristic is beneficial for operations in the keyhole mode, because narrowing of the keyhole results in an arc length decrease producing an increase in intensity (figure 13). A more penetrating arc is thus produced which causes an enlarging of the keyhole, sustaining a full penetration keyhole weld. This self regulating effect is not considered as important as the process stability which makes constant current power sources more favourable.

The use of pulsed current is essential for some plasma arc welding applications. Pulsed current power sources are similar to conventional GTAW drooping volt-amp characteristic units with the capability of pulsing between a high level current and a low level current. Transistorised, inverter, and SCR type power sources offer the required dynamic performance for pulsed-current applications. Modern power sources provide variable pulse frequencies and pulse width ratios thus enhancing the potential of the process, especially for keyhole welding. For applications requiring limited distortion, limited heat build-up or for keyhole welding of thin sections pulsation of the current is a necessity [28, 43, 49, 84]. Furthermore, the use of electronic power regulation enables the desired waveform to be obtained. The minimisation of the rise time (sides of the pulse virtually vertical), especially for higher frequencies is also necessary [41].

As in GTAW, plasma arc welding of aluminium and its alloys requires the use of alternating current (AC). Dudko et al [89] reported the arc voltage requirements for high current a.c. welding and described the required power source while Gvozdetkii et al [90] investigated the optimum volt-ampere characteristics of power sources for microplasma welding. For AC plasma welding an OCV of about 110 Volts is required for most of the applications. Partial and inherent rectification problems encountered with conventional sinusoidal current waveforms cannot be met with the use of continuous high frequency discharges [33] but with a matched pulsed DC pilot arc which reaches its maximum value as the main arc current passes through zero [91].

Variable polarity plasma arc (VPPA) welding has been used for aluminium, especially for keyhole mode applications. The development of power sources using silicon controlled rectifiers and transistors enables separate control of the duration and magnitude of the DCEN and DCEP current excursions. Consequently, better control of the heat input to the weld and the workpiece, improved torch and electrode life, and optimum cathodic cleaning are obtained [10, 33, 35, 92].

In micro-plasma welding where currents may be as low as 0.1 amps, the operating voltage is very high as can be observed from the static V-I characteristic of the arc (figure 7). Thus some modifications-described in section 2.2.4.1-are required to the commonly used equipment, especially when very low currents are used in combination with gas mixtures (argon/hydrogen or helium for shielding gas). Above about 30 amps a common GTAW power may be used [93].

2.2.9 Control of Power Source and Gas Flow Rates

For successful plasma welding it is fundamental to synchronise and control the primary welding parameters, especially for keyhole welding where close control is required to maintain the keyhole-weld pool stability. Apart from the control facilities provided by a common GTAW rectifier (i.e. current control downslope facilities, pre- and post- purge flow controls for the shielding gas), an extra gas flow meter along with pre- and post- flow timers is required for plasma gas along with provision for ignition of the pilot arc. Usually, these functions are all in a "mixing box", the plasma control console. In general, the plasma console can be characterised as a "junction box" for gases, coolant, pilot arc power supply and associated cables and hoses along with control for plasma and shielding gases. Other features that might be provided are upslope and downslope of the plasma gas and electronic governors for welding speed and wire feed regulation. Even the arc current supplied through a separate power source is routed through the console. The console though may be built into the main power supply and not take the form of an "add on" box.

With the development of microprocessors a complex sequence control of the main welding parameters can be achieved (plasma gas flow rate, current, travel speed) (e.g. 94). The major benefit, especially for keyhole welding is the provision for up slope and down slope for the gas and current which can be used for successful starting and closure of the keyhole [e.g. 5, 34], although for some materials the use of more sophisticated and complex techniques is required for defect free initiation and termination of the keyhole [95, 96]. This is absolutely necessary in circumferential welding where the start and the end position are both part of the weld and the use of run-on and run-off tabs is not possible [74, 97, 98].

2.2.10 Basic Design Requirements for Plasma Arc Welding Torches

A very essential element of the plasma welding process is the plasma torch and in particular, its constricting orifice. Separate passages required for the plasma and shielding gases and for cooling of the orifice body make the torches more complex than those for GTAW.

Torches are available in various designs and sizes. The basic configuration of a manual plasma welding torch is presented in figure 14. It consists of separate passages for the plasma and shielding gases, a liquid cooled (usually water) copper orifice body, an outer shield cup (usually ceramic) and cable supplies for the current and pilot arc. The electrode holder assembly is usually made from copper and is electrically insulated from the constricting nozzle, otherwise the arc will strike from the copper nozzle to the workpiece. Some plasma torches are also designed to centre the electrode automatically within the central section of the nozzle although several techniques have been developed for electrode centralisation [e.g. 99, 100], otherwise an asymmetric arc will be produced [101] which will result in excessive wear of the orifice, electrode contamination, and possibly undercut [10].

Cooling of the torch and particularly cooling of the nozzle where the higher temperatures are experienced is absolutely necessary to dissipate the excess heat generated in the nozzle by the welding arc and the pilot arc (absorbed by radiation, convection and conduction). According to Bykhovskii and Belyaev [102] 30% of the total arc power is absorbed by the nozzle although lower heat losses to the nozzle were proposed by Stikhin and Patskevich [103]. Failure to successfully extract the generated heat will result in overheating of the torch, double arcing and finally, serious damage to the torch. Results concerning the required position of the cooling channels relative to the nozzle and especially their proximity to the orifice have not been published. Natural cooling of the nozzle has only been reported up to now for low current plasma cutting equipment [104, 105].

For water cooled torches, the water requirements depend on the specific torch design and on the specific current rating of the torch. The manufacturer of the torch always recommends the necessary cooling water supply. The use of recirculating systems with a cooler and de-ioniser along with clean, mineral free water is usually recommended.

A wide variety of nozzles are available as noted in section 2.2.7 (single orifice nozzles, multiport orifice nozzles with holes arranged in various geometric patterns). They are usually interchangeable in order to allow the use of the appropriate nozzle for the application. Furthermore, orifices are considered consumable items since all of them suffer from gradual erosion and must be replaced after a number of welds.

The unique characteristics of each plasma torch along with the unique characteristics of the older power sources (which give different degrees of constriction and unique volt-amp characteristics respectively) may explain why recommended parameter settings found in various manuals can produce satisfactory welds only when applied to identical welding equipment and instrumentation [6, 28]. However, it must be mentioned that nowadays modern electronic power sources have similar characteristics and hence this factor is largely eliminated.

2.3 Plasma Welding Applications

During the last 10 years a growing number of industries have started to apply the wide range of plasma processes developed since the mid 1960s. A number of applications have been reported in the literature. They can be divided in terms of the three process variants: micro-plasma welding, intermediate current and high current which is usually associated with keyhole welding, although keyhole welds can be obtained in all three variants.

2.3.1 Typical Microplasma Applications

The primary use of microplasma arc welding apparatus has been the high quality precision welding of thin walled components (from 0.01mm to around 1.2mm thickness depending upon the power of the equipment), such as thin sheets, foils, meshes and wires of stainless steel, titanium, copper, tantalum, Inconel and other materials. In general, the applications for micro-plasma welding are, with a few exceptions, small components requiring low heat input and high joint integrity [8]. High quality results will only be achieved by strict adherence to the rules which apply equally to all arc welding procedures. The most important rules that must be followed are outlined below [45, 52]:

- The process is very intolerant to surface contamination and clinical cleanliness must be maintained.

- Joint mismatch must be less than 10% of the sheet thickness. For that reason the design of fixtures that will align properly the components is absolutely necessary.
- The use of the appropriate joint design is essential. Depending on the application and the materials used certain joint designs offer greater tolerances to joint fit up. Lahiri [45] and Gorman [60] investigated the benefits offered by various joint designs. The difficulty in feeding fine filler wire usually results in joint designs where one of the components provides the filler material, although Brown [106] developed a fine wire feeder and a wire tip guidance system for microplasma welding which gave very satisfactory results.
- Heat build-up must not be allowed for the thickness range used in microplasma welding since warping of joint edges may result in gaps that the melt cannot bridge, and burn-through can occur.

All these precautions must be taken because for thin materials the factor which strongly influences the shape of the weld pool is surface tension, regardless of the weld position. Poor cleaning, poor fixturing and poor shielding may influence surface tension and can lead to loss of control of the weld pool.

Micro-plasma welding has been used in a large number of industrial applications. Some of the applications in which the process has been applied successfully include the welding of bellows, the fabrication of office furniture, household items, electronic and aerospace components, thermocouples, insulating elements in the advanced gas-cooled reactor (AGR) vessel, wires, foils, thin tubes, filters and thin wall rocket cases. A large number of articles include applications and operating conditions for micro-plasma welding [8, 33, 43, 45, 52, 60, 61, 107-114].

2.3.2 Typical Medium Current Applications

In general, metals that can be GTA welded can be welded with the use of intermediate current plasma welding. Hence the two processes have similar applications for that current range (15-200A) [5]. The practical advantages offered by plasma have led to the development of equipment for this current range. Plasma welding applications in the melt-in-mode exploit the benefits that the process offers (described in section 2.2.4.2) which must be balanced against mainly the complexity and cost of the equipment, and the increased bulkiness of the torch. Furthermore, plasma welding offers

the special advantages that the keyhole mode of operation provides and in this mode plasma welding is not in direct competition with GTAW. However, it must be noted that the number of applications associated with medium current plasma welding is limited, due to the relatively small number of advantages that medium current plasma welding offers over GTAW (which employs a much cheaper system and a more easily maintained torch).

The welding of stainless steel pipes in fabricating brewery plant, which is particularly noteworthy as welding was carried out both in the factory and on site is a typical application where plasma has been selected in preference to GTAW, offering better control of the weld bead penetration profile, maximum allowable pipe misalignment of $\pm 0.13\text{mm}$, and the capacity to vary weld penetration by means of the plasma gas flow in preference to changing the welding current [33]. Plasma is also replacing GTAW in welding of electric motor stators where failures owing to inconsistent arc striking giving high reject rates have been reported [32]. Other industrial applications include the following: longitudinal pipe seams, circumferential positional welding of pipes, electric motors, bodies and silencers for the car industry, surface finishing, vessel welding and welding reactive metal sponge. A wide range of operating conditions and typical applications may be found in the literature [8, 10, 33, 34, 49, 54, 97, 98, 107, 115-119].

2.3.3 Typical Applications in the Keyhole Mode

The most important benefits of the plasma welding process can be achieved where keyholing can be obtained. Requirements, advantages and limitations for the application of the technique have been reported in section 2.2.3.2.

Keyhole welding is usually performed on square edge butt joints to a finite range of material thicknesses which as already mentioned can be expanded by proper control of the factors involved. Above a maximum thickness though, the use of U or V joint geometries with zero gap is necessary [98, 115]. In these cases, a keyhole weld root is initially performed followed by subsequent filler passes with the use of the medium current melt-in-mode technique. According to Mitchell [26], the following inter-related factors are believed to determine the minimum and maximum thicknesses for keyhole welding:

- Size and design of orifice.
- Type and amount of orifice gas.
- Electrical power input.
- Thermal characteristics of the workpiece.
- Geometry of the joint, including fit-up.

Filler metal can be added to the leading edge of the weld pool in the same manner as with GTAW [115]. The filler material will flow around the keyhole and will form a reinforced weld bead. Ashauer and Goodman suggested that for smoother weld pool flow in keyhole welding it is preferable to introduce the filler material into the arc [74]. With both techniques, special care should be taken to avoid contact between the nozzle and the filler wire which will immediately extinguish the transferred arc and a non-transferred arc will run instead, unless the filler wire is insulated from the welding earth. Figure 15 presents a typical joint preparation for welding 9.5mm thick high strength steel, where it can be observed that PAW requires about one-third as much filler metal as does GTAW [115].

Both manual [116] and automated keyhole welding applications have been reported in the literature although it must be noted that due to the inherent characteristics of the technique the vast majority of the applications are performed with the use of automated systems. A typical application is the use of plasma on tube mills for the welding of continuously formed stainless steel pressure tubing which resulted in increased welding speed and reduced rejection or repair rate compared to GTAW [34]. An equally successful application has been in the fabrication of the intermediate compressor casing for the jet engine where plasma keyhole welding offers better appearance and higher integrity compared to GTAW welds [33]. The advantages offered by the technique have ensured its growth, and other typical applications include: structural titanium joints, orbital joints of duplex stainless steel pipes, circumferential tube joints, fabrication of high integrity components for the aerospace industry, structural steel, high-strength microalloyed steel and strong formable microalloyed steel [9, 27, 30, 31, 33, 34, 36, 46, 49, 57, 74, 97, 115, 120-123]. The keyhole technique can be used to weld all metals weldable by the melt-in-mode technique. The major drawbacks to the application of the technique is the extensive mechanisation required and the accurate control of all major parameters in order to weld within the usually small operational envelopes, otherwise a number of problems may be encountered. These include humping,

collapse of the weld pool, gas entrapment and particularly undercut (an appearance very frequently encountered in keyhole welding) which will be described in section 2.4.

2.4 Effect of Welding Parameters on Weld Quality in Plasma Welding

The quality of welding thin tubes and generally thin sheets is measured in terms of penetration depth and weld bead geometry. A systematic monitoring and control of the primary parameters directly reflecting weld quality ensures the quality of the produced welds.

The large number of welding parameters involved, particularly in the keyhole mode, and the complicate parametric relationships further complicated by variations due to torch geometry, makes control of the process quite complicated but also enables the process to operate over a wide range of conditions. Richardson and Tabaie [124] presented a comparison of control parameters necessary for the specification of various arc welding processes (Table 1) where the requirement of plasma process for more information than the other welding processes is displayed.

According to Norrish [17] and Pinfold [125], the control variables may be divided into those normally used to match the conditions to the application, the primary controls (current, travel speed and plasma gas flow), and those which are normally chosen and fixed prior to the adjustment of the process, the secondary controls (orifice diameter, orifice shape/type, electrode angle and set-back, electrode type, welding gases, torch stand-off).

As mentioned in section 2.2.10, one of the major disadvantages of the process is the possibility that parameters developed using a specific torch will not be transferable to a torch of different design. Smart and Pinfold investigated several parameter settings recommended in various manuals and concluded that this type of information has little value unless applied to the same welding equipment and instrumentation [28]. Bashenko and Sosnin suggested that the optimisation of cooling and the construction of heat consuming elements in plasma arc welding equipment will ensure an increase in their universal acceptance and reliability since the stability of the plasma arc welding process is a result of thermal and hydrodynamic conditions in the zone of weld formation, and the stability is ensured when the optimal conditions for a constant thermal coefficient is maintained [126].

Discontinuities encountered in plasma welding can be classified according to their nature, their shape and their position. The most precise is the one that classifies defects according to their nature and is subdivided into the following three major categories:

- procedure and process,
- design,
- metallurgical behaviour.

The most common discontinuities associated with each of the three major groups are presented in Table 2.

Before investigating the individual and interactive effects of the main welding parameters on weld quality of plasma arc welding it is very useful to know the proportion of arc energy transferred to the workpiece, a quantity known as arc efficiency [1]. In plasma welding the thermal power of the arc may be divided into three parts for melt-in-mode welds and four parts for keyhole welding [127]: that transferred to the electrode (1.8-4.2%), the nozzle duct (6.6-37%) and the workpiece (47.3-73.5%), and it is also carried away by the plasma jet beyond the lower edge of the workpiece (1.3-4.5%) in the keyhole mode. Order of magnitude estimations for the amount of heat transferred to the workpiece for both the melt-in and keyhole plasma modes made by Metcalfe and Quigley [128] indicated that typical power transfer efficiencies for the melt-in and keyhole mode are 56% and 67% respectively. These estimations are in agreement with measurements made for low gas flows by Demin et al and Nestor [129, 130]. According to Tomsic and Jackson [131] the process efficiency in keyhole mode is lower (45% at 70A) and decreases linearly as the current (heat input) increases (28% at 105A), due to the fact that current increase causes enlargement of the keyhole width and thus the percent of heat loss out of the bottom of the keyhole increases, leaving less heating for the base material due to larger loss of heat in the arc column and cathode regions of the arc. The corresponding melting efficiencies are 25% and 16% respectively (see figure 16).

Melting efficiency (Z%) is defined as the percentage or fraction of the total power that is required to just melt the weld metal volume produced per second and depends on arc current, arc voltage and melting rate as follows:

$$Z\% = \frac{M * H}{I * V} \times 100 \quad (1)$$

where H is the energy per unit volume required to melt and raise the weld metal to the required weld pool temperature and M is the melting rate given by

$$M = v * A \quad (2)$$

where A is the weld fusion area and v is the welding speed.

Demin et al [129] suggested that the observed decrease in process efficiency (keyhole mode) with current increase can partially be accounted for by an increase in the degree of constriction of the arc column for the constant nozzle diameter and by the extent of heat losses into the nozzle. It was also observed that process efficiency depends only slightly on welding speed (very small increase with welding speed increase) and that it increases with increase of the plasma gas flow rate. The latter was attributed to an increase in the thickness of cold boundary layer of the gas, which improves the heat insulation of the nozzle, and by an increase in the concentration of thermal power as a result of a reduction in the extent of heat losses from the arc column to the nozzle.

The observations made by Demin et al for the influence of welding speed and plasma gas flow rate to process efficiency are in contradiction with findings from Tomsic and Jackson. The latter noted that both process and melting efficiency decrease as the travel speed decreases, the same reasons as given above for current applying here too. Furthermore, they observed that as the orifice gas flow increases, the melting and process efficiency decreases, something attributed to the increase of the width of the bottom of the keyhole which allows a larger percentage of the heat to exit from the bottom of the weld as the orifice gas flow increases.

In each case, reduced melting and process efficiency for high current values indicates that high arc energy losses occur at maximum energy density.

Many attempts have been made to predict the effects of the process parameters (or else input or control variables) in arc welding on the resultant weld bead characteristics. These can be broadly divided into two main categories. The theoretical

approach based on heat flow theory and the pragmatic [empirical] approach based on actual welding situations, for welding is a complicated phenomenon which is very difficult to describe theoretically. Shinoda and Doherty [132], McGlone and Doherty [133, 134] and Modenesi [135] reviewed the work related to weld bead geometry prediction and all of them followed the above classification which will also be used in the present work.

2.4.1 Theoretical Approach

Efforts for theoretical prediction of the weld bead geometry are mainly based on the work of Rosenthal [136, 137] who solved the heat flow equation for a heat source moving on the surface of an infinite plate and provided the basis for theoretical solutions to weld bead geometry. A number of models have been developed for the case of a free burning arc [138, 139, 140, 141] even for difficult conditions such as tube welding [142, 143] and difficult to weld materials such as aluminium and titanium [144] although it must be noted that a large number of significant problems were encountered. The most important problems are the large number of oversimplified assumptions that must be made even for simple conditions and the large number of interactions between the process variables which makes the description of the real welding situation quite complicated. The latter is further intensified by fluid motions in the weld pool which may be driven by a number of factors such as, the particularly sensitive to material composition and impurity content, surface tension gradients [145, 146, 147], electromagnetic forces and arc plasma forces [148] or a combination of these factors. The above restrict the solutions developed to specific geometries and conditions. Furthermore, solutions covering the wide range of arc forces and heat distributions covered by the plasma arc process have not yet been addressed, something that the absence of literature specifically concerning plasma melt-in weld bead characteristics also indicates. Models developed for keyhole geometries are not associated directly with plasma welding but with laser welding [149].

2.4.2 Practical Approach

A very small number of articles have been published concerning the individual and interactive effects of plasma welding parameters on weld bead geometry. A large number of experiments are required because of the large number of the variables in plasma welding as mentioned in section 2.4, but also due to the large number of other factors that influence the process such as weld joint design, joint fit-up, parent metal

composition, filler material composition, impurity content, cast-to-cast variation in the chemical composition of the material being welded etc. [88, 132, 150]. The influence of the primary and secondary plasma welding variables on the weld bead characteristics and quality are summarised below, although the limited number of the reported observations make it risky to determine the nature of the trends and only generalisations can be made. Furthermore, the way that these parameters affect the process characteristics is also reported.

2.4.2.1 Effect of Welding Current on Welding Bead Characteristics

Nearly always the effect of welding current on bead characteristics is connected to welding speed and plasma gas type and flow rate. Smart and Pinfold noted that plasma welding (melt-in mode) follows the well established pattern of the GTAW process, that is, an increase in speed required an increase in current for a given degree of penetration [28]. For a range of plasma gas flow rates Smart showed a linear relationship between welding speed and current and also revealed that a linear relationship also exists between welding current and plasma gas flow rate for varying travel speeds [73].

As expected, with increasing current an increase in weld penetration and depth-to-width ratio is obtained since arc temperature and pressure which directly affect these characteristics are affected by welding current. Arc force is proportional to the square of mean current in plasma welding [17, 151] and arc temperature increases with current when other parameters are held constant [1, 152]. Furthermore, an increase in welding current widens the weld joint, the reinforcement and the root in keyhole welding of structural steels but has no direct effect alone on weld quality if welding occurs within the acceptable range of current variation since it is nearly always connected to the welding speed and the plasma gas type and flow rate [36]. According to Tomsic and Jackson the top width of the keyhole increases as the current is increased while at the same time, the bottom width of the keyhole weld increases at a faster rate in 3mm thick 304 stainless steels [19]. Finally, inadequate current level causes lack of penetration while excessive current leads to excessive penetration or even collapse of the weld pool since the high arc forces developed overcome surface tension forces holding the weld metal in place [153].

Pulsation of the current proved to be beneficial for both melt-in and keyhole modes of operation [28, 29, 41, 84]. When optimum welding conditions are used it

enhances the weld bead penetration and the process melting efficiency. Penetration increases with both pulse frequency and peak/background current ratio [84]. Omar and Lundin [41] suggested that the lower the pulse frequency the wider the fused zone while for higher pulse frequencies the fusion zone becomes narrower, and melting efficiency decreased. Current pulsation also increases the tolerance to process variations and variation in welding parameters and thus aids control of weld bead penetration.

It must be noted that excessive currents can lead to electrode damage or to "double arcing" conditions and nozzle damage, which both affect the quality of the resultant weld.

2.4.2.2 Effect of Welding Speed on Welding Bead Characteristics

In practice, the optimum welding speed is determined by a combination of other welding parameters and factors, such as mean current, plasma gas flow rate, orifice type and groove tolerances.

If the welding speed is too high in relation to the other welding parameters, undercutting with humping of the top bead surface occurs usually accompanied by incomplete penetration. At low speeds, the size of the weld pool or the size of the keyhole may become excessive which leads to excessive penetration and subsequent collapse of the weld pool. For keyhole welding the top width of the keyhole decreases as the travel speed is increased while the bottom width decreases at a faster rate than the top width in 304 stainless steels [19]. According to Martikainen, for suitable current values it is possible to produce acceptable welds with a wide range of variation in welding speed [36]. Pinfold and Jubb illustrated that in order to maintain a penetrating keyhole when speed increases an increase in current is required [125]. Norrish, using several unconnected sources, plotted the relationship between thickness penetrated and welding speed at various plasma power levels (plasma power taken as the product of mean current and arc voltage) and revealed a remarkably consistent trend (figure 17).

2.4.2.3 Effect of Plasma Gas Flow Rate on Welding Bead Characteristics

One of the most critical factors to the success of welding is the selection of plasma gas and its flow rate. This is to be expected since plasma gas forms the medium for current flow and thus transportation of thermal and kinetic energy to the anode for

metal melting. According to Meimoth and Lucas [154], this parameter depends on nozzle design, welding current and gas type.

The appearance of weld bead, as well as a large number of weld defects are also related to the influence that the flow rate exercises on the arc force [84]. Arc pressures increases with increase in the flow rate up to a specific value. Above that value the excess arc pressure remains virtually constant [151]. Low gas flow rates produce insufficient arc force and thus loss of the keyhole along with a rough surface appearance [155]. Moreover, such conditions can result in "double arcing" as described in section 2.2.6.1 which causes arc instability and affects the quality of the weld produced. Excessive flow rates will cause the molten metal to be blasted away and thus cutting. Smart and Pinfold [28] observed that increasing the plasma gas flow rate at a given current level can led to an increase in welding speed or, conversely, a reduction in current for the same travel speed for a given penetration. Furthermore, they noticed that there is, in addition to the necessary decrease in welding current, a decrease in the fused area indicating a lower heat input. The above observation reveals that the relationship between the welding current and the plasma gas flow rate is not merely one of balancing the heating effect of the electron current and of the plasma gas. In practice this means that if a given penetration is attained with the use of higher flow rates this will result in a smaller fusion zone and thus less distortion and metallurgical problems.

Tomsic and Jackson [19] concluded for keyhole welding of 304 stainless steels (3mm thick) that the top width of the keyhole weld remains constant as the plasma gas flow rate is increased while the bottom width increases. Furthermore, the energy per unit area across the plasma-molten liquid boundary decreases as the orifice flow rate is increased. According to Smart and Pinfold, for a given welding speed, there is a range of plasma gas flow rate-current combinations that produce full penetration, satisfactory welds. Between these combinations and current-gas flow combinations that produce collapse of the weld pool, there is a range of high current-gas flow combinations which produced welds differing mainly in respect of the surface finish but which could in other respects be considered satisfactory. Rough surfaces were produced for high gas flow rates and attempts to increase the heat input to produce a smoother finish resulted in weld pool collapse [28]. Furthermore the use of high gas flow rates entail the risk of porosity. Watanangura suggested [82] that to some extent, the plasma gas flow dictated the current setting below which welding can not be carried out without reasonable consistency and acceptable weld quality.

2.4.2.4 Effect of Welding Gases on Weld Bead Characteristics

The effect of plasma and shielding gases is critical to the success of welding considering that the weld pool behaviour, particularly in keyhole welding, is dependent on the interaction of the welding gases used. Bead width, melted zone shape and welding speed are affected by the choice and combinations of these gases [36]. Both gases are required as the plasma gas alone is too turbulent to give adequate shielding, because of the small constricting nozzle [156]. The selection of the plasma and shielding gases is made according to the materials being welded. Table 3 shows the most common combinations for the plasma arc welding of different materials.

A. Plasma Gas

As can be seen from Table 3, the most widely applicable plasma gas is argon, which is suitable for most materials and for most situations. This is because argon is inert, has low ionisation potential which ensures reliable arc starting, and requires low voltage to sustain the plasma column which ensures good arc stability [5]. Argon's low thermal conductivity leads to a small cross section arc column, with a narrow, concentrated hot core with a cooler outer column, and as a result, a narrow weld bead is obtained throughout [5, 101]. It causes a convex and rough reinforcement in keyhole welding of structural steels [36]. Furthermore, it provides the lowest rate of erosion of both the nozzle and the electrode [156].

Apart from argon, helium and hydrogen are also added for specific applications. Helium additions increase arc voltage and enthalpy producing greater arc power and thus high melting rates, which in turn promote higher welding speeds [5, 156, 157]. However, the use of helium can reduce the current carrying capacity of the nozzle and can lead to reduced penetration because of the lower mass of helium as opposed to argon. This makes the formation of a keyhole difficult in certain materials. Hence helium is rarely added to the plasma gas when operating in the keyhole mode. Langford investigated plasma arc welding of titanium in the horizontal position and concluded that if helium addition exceeds 60% the penetrating capacity of the arc is reduced because the arc tends to increase in diameter thus reducing the heat input per unit area [158]. By contrast, 70% helium additions to argon eliminate gas entrapment and "tunnels" appearance [98].

Several researchers have suggested the addition of small amounts of hydrogen to argon [5, 61, 150, 159]. The use of hydrogen additions is not acceptable in welding reactive metals such as titanium and zirconium alloys and low alloy steels because it results in embrittlement but it can be proved beneficial for other metals, especially stainless steels where it is widely used. Additions up to 15% offer improved heat transfer and therefore increased welding speed for the plasma keyhole welding technique [5, 57, 74, 101, 115, 125]. Weld pool fluidity and penetration both benefit from the increased arc voltage and intensity obtained with argon-hydrogen mixtures due to the high ionisation potential of hydrogen, which also gives a flatter and smoother weld bead [101]. Reduced porosity and a clean weld bead appearance are also achieved since hydrogen provides a reducing atmosphere [5, 125]. Hoffmeister et al reported that the addition of hydrogen as an active plasma gas enables more reliable keyhole welding with increased welding speed for a 7mm wall thickness duplex stainless steel pipe [123]. Drews and Bohme noted that the use of argon-hydrogen instead of argon as a plasma gas reduced the possibility of undercut formation in the plasma arc welding of structural steels. They observed that undercut is produced at lower welding speeds with argon plasma gas than with an argon-hydrogen mixture [160]. On the negative side the use of hydrogen additions is thought to cause porosity when welding copper and its alloys [125]. Ignition of the arc becomes more difficult, especially with hydrogen contents in excess of 5% [54]. Larue and Thomsen observed that poor bead appearance and irregular penetration were obtained with the use of argon-hydrogen mixtures for carbon steel plate thicknesses greater than 4mm [161] while Nielson noted that unstable keyhole and weld pool collapse were obtained with the use of argon-7% hydrogen for keyhole welding of unalloyed steels [162].

B. Shielding Gas

In addition to protecting the molten metal shielding gas has also a second function. It penetrates into the plasma stream, and depending on its physical properties, affects arc characteristic and consequently weld properties [36]. Although the effect of shielding gas on weld quality is not as important as that of the plasma gas, careful consideration should be given to the choice of plasma gas. The most common shielding gases are argon, argon-hydrogen, argon-helium and argon-carbon dioxide.

The effect of shielding gas is dependent on the composition of the plasma gas used. The basic characteristics of the most common combinations are summarised below.

1. Argon Plasma gas, Argon Shielding gas.

Argon has been one of the most widely used shielding gases. It is broadly used for welding carbon and high strength steels, and reactive metals such as titanium, tantalum and zirconium alloys. It provides excellent shielding efficiency even with low flow rates (5 to 10 l/in). The plasma gas becomes less concentrated and intense as ionisation takes place on contact between the arc column and the colder shielding gas. Even though, the high temperature gradient in the gas leads to a small cross section arc column inside an envelope of cold gas and that results in a narrow bead throughout [101].

2. Argon Plasma gas, Argon Hydrogen Shielding gas.

This combination is very often used for keyhole welds in stainless steels, nickel based alloys, and copper-nickel alloys. Hydrogen additions are particularly suitable for austenitic stainless steels and nickel rich alloys, where the reducing action of the gas assists in the removal of oxides which would otherwise impede the process [163]. According to Craig [5] at approximately 3870°C the hydrogen molecules dissociate when in contact with the arc. On contact with the workpiece, the hydrogen molecules recombine releasing the energy absorbed by the molecular dissociation thus improving the heat transfer rate. This results in widening of the bead and permits an increase in welding speed [101]. The diatomic molecular action creates a barrier around the plasma column, maintaining column stiffness. It reduces the surface tension of the weld pool, increasing weld pool fluidity. By combining with the oxygen present in the arc and releasing it into the atmosphere, hydrogen supports weld cleaning.

According to Lucas, hydrogen addition up to 15% to the shielding gas produces a hotter arc and constricts the arc which can increase the depth of the weld pool penetration and promote higher welding speeds [33]. Miller and Fillipski reported that high welding speeds were achieved using argon-5% hydrogen as a shielding gas for welding of stainless steels and some nickel based alloys [115].

In contrast, Nielson noted that weld pool instability was caused by the addition of 3-5% hydrogen in the shielding gas when welding unalloyed steels. Enhanced

instability was observed by increasing hydrogen levels to 7% and local porosity occurred [162].

3. Argon Hydrogen Plasma gas, Argon Hydrogen Shielding gas.

With this combination the effects of hydrogen reported above are intensified due to the large proportion of hydrogen in the arc. Very high plasma temperatures are attained although the high hydrogen content increases the risk of porosity or cracking in the weld bead. Furthermore, the very high arc temperature achieved reduces welding current for a given orifice diameter [10]. Ashauer and Goodman reported that the use of identical shielding and plasma gas composition of this combination for keyhole plasma welding of stainless steels resulted in an erratically behaved puddle, and the keyhole tended to fluctuate from a circular shape to an oval shape and back again which caused the underbead contour to solidify in a bumpy fashion [74]. This phenomenon is attributed to the solidification cycle of the weld metal and is usually treated with the use of helium as a shielding gas.

4. Argon Hydrogen Plasma gas, Argon Shielding gas.

High plasma temperatures are again attained in the arc because of hydrogen. An expansion of the arc is observed, due to the extensive ionisation of the argon, which results in a demand for lower welding speeds for a given penetration [101] and a wider weld bead.

5. Argon Plasma gas, Helium (or Helium-Argon) Shielding gas.

Craig reported that the use of helium as a shielding gas increases the welding heat power because of the higher voltages utilised due to the increased ionisation potential [5]. A hotter but less constricted arc is generated, which can result in a wider weld bead compared with argon or argon-hydrogen shielding. Ludwig noted that its high thermal conductivity results in an excellent heat transfer and consequently an excessively wide and deep melting zone [28, 164]. The heavy and large molten pool can lead to operational difficulties [101].

Argon-helium mixtures containing 50 to 75% helium have been employed in making keyhole welds in titanium. Higher welding speeds than with pure argon were achieved and a concave root surface which is sometimes obtained with pure argon was

avoided [7]. In general, mixtures containing more than 40% helium are required in order to detect any significant change in the heat (according to [7] 50%). Craig suggested that at least 75% helium is usually required to obtain the helium thermal benefits [5]. However, the use of pure helium reduces the arc starting efficiency and increases significantly the heat load on the torch nozzle thus reducing its service life and current capacity.

6. Argon Plasma gas, Argon-CO₂ Shielding gas.

The use of argon-CO₂ as a shielding gas offers significant benefits in fusion welding of carbon steels, and argon with 20 to 30% CO₂ improves weld fluidity [5]. According to Yamamoto et al [165] who investigated plasma welding of mild steel with an argon plasma, CO₂ additions in the shielding gas influence both the arc and weld metal properties. The silicon and manganese content of the weld metal are reduced because of the oxidant behaviour of CO₂. Similar oxidant behaviour has been reported by Ilyushenko during plasma welding of thick section copper and chrome-bronze components with a marked loss of chromium and vanadium [122]. Furthermore, an increase in arc voltage is generally observed for CO₂ additions over approximately 5%, an increase also observed for electrode negative operations below this critical concentration.

Filipski noted that the use of CO₂ as shielding gas with argon as the plasma gas results in increased welding speeds for plasma welding of certain mild steel welding applications [54]. Yamamoto et al reported that increased penetration and bead width along with greater fusion areas are observed with increased CO₂ for bead on plate welds with filler wire additions, due to an increase in total process power [165]. Martikainen and Moisio stated that in keyhole welding of structural steels with argon-carbon dioxide the fluidity of the weld pool increases, the weld toe becomes smooth and continuous, and the sensitivity to undercut decreases, although the weld surface becomes relatively rough and therefore, argon-carbon dioxide is not suitable for welding the final run [36].

C. Backing Gas

As in GTAW, shielding gas is generally required to protect the weld underbead from atmospheric contamination. This is particularly essential when welding reactive

metals such as titanium, zirconium or tantalum where the use of an inert gas (argon in most of the cases) is essential [e.g. 26, 166, 167]. The major difference is in the shape of the backing support, which has to be much deeper (typically 19mm wide and 12mm deep) in order to provide a vent space for the plasma jet in keyhole welding and thus avoid disturbances of the keyhole efflux, which causes turbulence, leading to disturbance of the weld pool and ultimately to porosity [16, 156, 168]. Moreover, in plasma keyhole welding the weld pool is supported by the surface tension of the molten metal which is affected by the composition of the plasma gas [7].

According to Martikainen and Moisio [36], sagging of the low viscosity molten weld metal of structural low carbon steels is prevented by the use of an appropriate backing. They noted that the need for backing gas must be considered from case to case and that use or omission of backing gas does not affect the mechanical properties of the weld joint, unless a considerable geometrical irregularity is produced. They also recommended argon as the most suitable backing gas in order to avoid excessive penetration. Ashauer and Goodman recommended that the use of nitrogen gives better results in comparison with argon for keyhole welding of copper-nickel tubes, because it increases the surface tension of the weld puddle thus increasing the tolerance of minor changes in welding parameters [74]. Nitrogen's superiority stems from its ability to absorb heat quantities many times greater than argon or helium, providing an extremely efficient and rapid way of dissipating the heat of the protruding plasma arc without a detrimental effect on the weld appearance and quality.

2.4.2.5 Effect of Orifice Geometry/Type on Weld Bead Characteristics

The characteristics of the orifice and especially the orifice diameter is, along with the plasma gas flow rate and the electrode set-back, one of the major parameters that influence the arc constriction. Bashenko and Sosnin noted that the role of the plasma-forming constricting orifice is of decisive importance for weld quality since the geometry of the plasma formed at the orifice significantly affects the distribution of heat flow, current density and pressure in an active spot, all of which affect the weld dimensions and arc penetration into the weld pool [169].

Constriction of the arc can be achieved either using mechanical means (single, multiport nozzles and arc focusing techniques) as described in section 2.2.7, or pneumatic means using pneumatic nozzles (converging-diverging). Shaw [170] illustrated the

concept of pneumatic constriction qualitatively and proved that a conically convergent PAW torch orifice produces a plasma which offers certain advantages in comparison with a conventional cylindrical and a conically divergent orifice. The produced arc had a reduced diameter and cross-sectional area, higher temperature in the stand-off region, produced more energy per unit length of weld, achieved greater penetration and produced a narrower weld with smaller ratio of the widths at top and bottom than a conventional straight cylindrical orifice. The above proves the influence of nozzle profile on anodic heat distribution and resultant weld bead profile.

Malakhovskii stated that the nozzle design has a considerable influence on the dimensions of the arc, its degree of constriction, and the coefficient of concentration along its length [62]. He noted that increasing the diameter of the nozzle results in an increase in arc diameter, while the length of the nozzle channel has hardly any influence on arc dimensions. Malakhovskii and Stikhin reported though [127], that an increase in the length of the nozzle reduces the depth of penetration as a result of greater losses of thermal power in the nozzle duct, whereas the weld width remains almost unchanged. It was also illustrated that a reduction of the nozzle duct also increases the depth and reduces the weld width and that an increase in the area of the additional apertures reduces the weld depth and increases the weld width.

2.4.2.6 Effect of Electrode Geometry on Weld Bead Characteristics

As in GTAW the electrode size is dependent on the operating current level. For low current levels a small electrode diameter is required while larger electrodes are required for higher current levels or high duty cycles to withstand the heat [171]. Plasma torches designed to cover a current range of approximately 100-400Amp utilise electrodes varying from 1.6mm to 4.8mm in diameter [125]. In PAW, the common non-consumable tungsten electrodes used in GTAW are also utilised. The most commonly used are electrodes containing 1.7 to 2.2% thorium.

The electrode vertex angle is usually ground to an included angle of between 20 and 60°, and the tip is either sharp or flattened slightly. Pinfold and Jubb observed that changes to electrode vertex angle had very little effect on penetration, bead dimensions and weld surface appearance when using high plasma gas flow rates. At low plasma gas flow rates, an increase in electrode vertex angle from 30° to 90° will result in a decrease

in penetration and poor surface appearance [125]. The same behaviour was also observed by Smart [73] and Watanangura [82].

There is not an optimum form that the electrode tip should take. According to Pinfold and Jubb [125] a sharp point assists arc starting while a truncated electrode is easier to position and centralise within the nozzle. Stepanov and Nechaev reported that for a constant current, the arc pressure is greater in welding with the sharp electrode than in welding with an electrode with a spherical tip (figure 18). This is explained by the fact that the current density in the former case is considerably greater than in the latter [151]. Richardson observed that the electrode vertex angle does not appear to have any systematic influence on weld bead or HAZ areas under various pressures (figure 19a). The greatest scatter occurred in measured fusion area and corresponding melting efficiencies with all other parameters remaining virtually constant (figure 19b) [37]. Watanangura [82] observed that a 60 degree included angle preparation gave defect free welds of acceptable appearance. The same preparation was also recommended by Pinfold and Jubb [125] while Thermal Dynamics suggest a 20 degree included angle with the point removed [172].

Watanangura illustrated that an increase in electrode diameter raised the minimum arc voltage value of the V-I characteristic but the rate of rise of the voltage with increasing current remained almost the same. He also suggested that slightly higher welding speeds can be utilised when welding with a 2.4mm electrode compared with a 3mm electrode [82].

Richardson described mathematically the influence that the electrode characteristics (diameter and tip preparation) have on the plasma gas flow rate within the plenum chamber and also how this affects the constriction of the arc when the electrode is positioned within the parallel sided portion of an orifice. Increase of the electrode diameter and vertex angle will result in a increased constriction thus affecting the structure of the arc [37].

Special care must be taken in positioning the electrode tip concentrically with the nozzle orifice. Failure to succeed will result in an asymmetric arc which will lead to nozzle deterioration and the consistency of the welds will suffer. A gauge is usually specified to set the electrode axial position [10, 101].

Finally, the condition of the tip angle (along with the condition of the nozzle) should be regularly checked since it determines the shape of the arc and penetration profile of the weld pool. The oxidation behaviour and the rim formation mechanism of tungsten electrodes have been investigated by Matsuda et al [173]. It was concluded that the oxidation behaviour of tungsten electrodes is a function of arc current and shielding gas and changes significantly with arcing time, and that the presence of oxygen in the shielding gas promotes rim formation, accompanied by a necking area just behind the rim. Bukarov et al [174] investigated several methods for increasing the durability of tungsten electrodes in arc welding and suggested that by reducing the temperature gradient in the working part of the electrode, protecting its surface from droplets of the anode material, increasing the grain size of the structure of tungsten in the initial condition and increasing the dispersion of the low work function material, the durability of the electrode can be increased.

2.4.2.7 Effect of Electrode Set-Back on Weld Bead Characteristics

The electrode distance from the nozzle plays a significant role in the constriction of the plasma arc. An increase in the set-back distance will result in an increase of the effective arc length. This should in turn increase the arc voltage [82, 175]. Metzler also noted a reduction in arc efficiency of approximately 8% when electrode set-back was increased from 1 to 3mm [175]. Cooper et al observed that an increase of the set-back results in a decrease of the arc diameter at the exit plane of the nozzle. The increased arc confinement results in an increase of the plasma gas flow rate [11]. Although Lavigne suggested that a tolerance of 0.1 to 0.2mm on electrode setback is necessary [101], it is very important to maintain a constant set-back distance to ensure consistency. The maximum electrode set-back position and the maximum plasma gas flow rate have been used to establish the maximum current rating of each nozzle. Lower plasma gas flow rates can be used to soften the plasma arc with the maximum current rating of the nozzle only if electrode set-back distance is reduced, otherwise this will lead to fast nozzle deterioration [168].

2.4.2.8 Effect of Stand-Off Distance on Weld Bead Characteristics

According to Lundin and Ruprecht the variation which stand-off distance produces in penetration is similar to that produced by an arc length change in GTAW [84]. Increased stand-off distance decreases penetration and depth-to-width ratio while a

decrease in stand-off distance below a certain level can cause "blowing through". The pronounced influence on penetration of stand-off distance at three different plasma gas flow rates in the plasma welding of Inconel 600 is presented in figure 20. Tomsic and Jackson reported that in keyhole welding of 3mm thick 304 stainless steel the top width of the keyhole weld increases as the arc length is increased while at the same moment the bottom width decreases [19]. The latter means that the heat loss out of the bottom decreases, and the effect of the orifice gas flow diminishes. They also noted that the process and melting efficiency show little change, as shown in figure 21.

As expected arc voltage is also affected by stand-off variations, increasing as the stand-off distance increases [84, 125]. Furthermore, arc pressure increases with reduction in the stand-off distance [151] and undercut decreases as stand-off distance increases thus producing a "softer" arc [170].

2.4.3 Causes of Defects and Control Actions

Based on the theory illustrated above a brief summary of the causes and control actions for defects critical to plasma welding thin materials is presented below [10]:

2.4.3.1 Incorrect Bead Size and Appearance

Even if in some circumstances this is perfunctory, all welds are, in effect, subject to some form of dimensional control [176].

Bead appearance defects can accentuate risks of corrosion and failure by fatigue although usually do not affect the integrity of the weld. Furthermore oversized welds increase the production cost while undersized welds might fail to meet the required load carrying capability. Especially in tubes, poor weld bead appearance may result in turbulent flow or corrosion problems. The most common defects are: irregular surface, angular distortion and generally bead asymmetry, variations in weld height or reinforcement, surface contamination which results from insufficient gas coverage and excessive reinforcement, convexity or concavity.

Possible causes and remedies for incorrect bead size and appearance are presented in Table 4.

2.4.3.2 Overpenetration - Burn-through

One of the most critical defects which causes the rejection of components in thin sheet welding is burning-through [177]. The American Petroleum Institute (API) defines burn-through as "that portion of the root bead where excessive penetration has caused the weld puddle to be blown into the pipe" and for tubes with diameter less than 60.3mm defines that "no more than one unrepaired burn-through is acceptable and it shall not exceed 6.35mm or the thickness of the pipe wall, whichever is the smaller, in any dimension" [178].

This condition is normally preceded by overpenetration where the weld metal penetrates the full thickness of the joint without burning through.

The most common causes for burn-through and overpenetration are presented in Table 5.

2.4.3.3 Lack of Fusion - Inadequate Penetration

Lack of fusion and inadequate penetration are separate and distinct conditions which occur in different forms. Inadequate penetration is defined as the incomplete filling of the weld root or more explicit, when the actual root penetration fails to meet the minimum specified design requirements (figure 22) [10, 179]. Lack of fusion is the failure to fuse adjacent base metal and weld metal (figure 23) and thus to create a bond between them, or when there is a lack of bond between successive beads [10, 178].

Table 6 illustrates the most common causes and remedies for inadequate penetration and lack of fusion.

2.4.3.4 Porosity or Gas Pockets

Porosity is considered to be the most common subsurface discontinuity encountered and the most difficult to avoid when welding under shielding gas. It may appear in different shapes (i.e. spherical, elongated), different sizes and in different distributions (uniformly scattered, in small groups, concentrated at the root). Porosity is generally not considered dangerous but is very often banned, especially for critical

applications, because it may mask other more important defects particularly when it appears in excess. Common causes and remedies of porosity are described in Table 7.

It must be noted that the use of the keyhole mode offers certain advantages when welding materials susceptible to porosity such as titanium and titanium alloys, something which is directly attributed to the scouring action of the arc as the keyhole cuts through the material [29, 46]. As already mentioned in section 2.2.4.2 the application of keyhole type conditions with non-penetrating arcs increases the risk of gas entrapment. Shaw [180], described the frequent formation of "pipe" defects which are continuous voids extending for many millimetres parallel to the line of welding when the orifice gas flow rate is adjusted for full penetration keyhole- mode welding but the current is insufficient to achieve full penetration. The danger of gas entrapment when the two side method is applied to the plasma welding in thicker sections using the melt-in-mode has also been described by Langford [98] which illustrated the formation of "tunnels" which are holes extending to the entire length of the weld. Cooper et al [11], mentioned that this phenomenon could serve in a particular design situation as a tube for fluid flow which might be required for cooling purposes. Tunnelling effect is not only associated with inappropriate gas flow rate selection but it might be also the result of a combination of torch misalignment and improper welding variables, particularly travel speed [10].

2.4.3.5 Undercut

One of the most common geometric defects in plasma welding and certainly the major limitation of plasma keyhole welding is undercut. It is a groove melted into the base metal adjacent to the toe or root of a weld and left unfilled (figure 24), thus creating a mechanical notch at the weld interface. This discontinuity can become dangerous when is deep or when the fabrication is subjected to fatigue loading and it reduces significantly the high technological potential of the plasma welding process [181]. The high practical value of undercut led a lot of researchers to investigate various aspects of the subject and try to associate the dependence of formation of this defect on the welding process variables. This is very difficult considering the great complexity of the process of weld formation, the insufficient data on the physical effects in plasma-arc welding, and the large number of independent process variables [e.g. 19, 26, 36, 98, 181, 170, 182, 183, 169].

The most common causes and remedies for undercut formation are presented in Table 8.

It must be noted that the above corrective actions do not apply in every situation. The complicated nature of undercut formation, which is related to the hydrodynamic nature of the weld pool formation and the complex interaction of the large number of parameters which influence the phenomenon, as mentioned above, makes the choice of the appropriate corrective action difficult. A general rule that applies in most cases is that increase of the set-back distance and the plasma gas flow rate and the reduction of the nozzle diameter and the stand-off distance can lead to an increase of the undercutting area due to increase of the concentration of the thermal flux and arc pressure. The latter increases both the probability of melting-out and the probability of the crystallisation of the edges of the pool before it is filled, because of the small pool volume and the large kinetic energy of the steam of liquid metal. However, it is possible to reduce the undercut with suitable parameter combinations, even at high welding speeds and high concentrations of the thermal energy of the arc plasma [181].

The careful selection of suitable parameters is not the only solution to undercut problems. The use of pulsed currents especially with controlled current decay have been proven to be beneficial for alleviating undercut [17, 25, 29, 33] as well as the application of magnetic arc oscillation along the axis of the weld [17]. Where undercut is more severe, a wash or cosmetic pass might be necessary where a second non-penetrating weld pass is made to smooth the weld bead contour with plasma or GTAW and the possible addition of filler wire depending on the situation.

2.4.3.6 Humping

Humping is a phenomenon that has most commonly been reported for plasma welding and high speed GTAW welding, although very little has been published about it. According to Savage et al [184] humping may be defined as an irregular surface contour consisting of a series of bead like protuberances (figure 25) separated by intervals of relatively uniform bead-surface contour, and is usually associated with severe undercutting [170, 185]. According to Branstreet, humping is connected, like

undercutting, with surface tension and the way the molten metal flows behind the arc to form the weld bead.

2.4.3.7 Defects During the Initiation and Closing of the Keyhole

As already mentioned in section 2.2.9 the control of transient conditions of the keyhole PAW process, which are the initiation and closure of the keyhole, is quite difficult and complicated. Current and gas up slope and down slope are necessary especially in circumferential welding where the start and the end position are both part of the weld. It must be noted though, that especially for metals thicker than 2.5mm, ejected material may form even with the current and gas slope procedures [74], which makes subsequent overlap during the closure of the keyhole difficult. Apart from surface irregularities, the latter can contribute to the formation of large voids and porosity partly due to the volume of liquid metal which must be displaced under stable conditions to establish the cavity of the weld pool. Furthermore, stopping welding before the weld is completed will result in a hole left in the weldment. To avoid these problems, apart from using starting and ending tabs where possible, the only other solution is the precise programming of the welding current, orifice gas flow and welding speed if necessary. Several authors have suggested various control cycles for different materials and wall thicknesses [e.g. 5, 7, 34, 95, 96]. In general, they vary according to alloy and wall thickness. Preheating of the starting area for a few seconds will speed up keyhole penetration and minimise the eruption of the metal. The thicker the material, the longer it takes for the plasma arc to completely penetrate the wall section which results in a proportional increase of the erupted metal. This makes subsequent overlapping more difficult and sometimes impossible [74]. A typical control cycle is presented in figure 26.

2.5 Application of Plasma Process in Tube Welding

According to Kruger and Marya the quality and security requirements regarding tube and pipe welding are becoming more and more stringent in several fields such as chemistry, pressure vessels or pipework for the electronic, aeronautical and space industries [186]. Nowadays, a wide range of high quality mechanised welding systems and accessories are available to the pipework fabricator in order to meet their productivity and quality requirements. According to Cary two basic types of procedures are used [179]. One is "roll or circumferential pipe welding", when the joint is rotated under the

welding head, and the second is "orbital welding" when the pipe is in a fixed position and the machine rotates around the pipe to make the weld. A further subdivision is for thin- or heavy-wall pipe, or for small-or large diameter pipe or tubing, or according to the welding process utilised. Submerged arc welding is used for roll welding only, while gas metal arc (GMAW), flux cored arc (FCAW) and gas tungsten arc (GTAW), are used for making pipe welds in any position [179].

The plasma arc process has proved to be one of the most promising methods for high-speed, high-quality joining of pipes for a range of materials and wall thicknesses such as stainless steel, carbon steel, nickel-copper, copper-nickel, and titanium [e.g. 33, 46, 74, 121, 123, 179, 187], but until recently, the high cost of the equipment, the requirement for high precision and the complexity to control the process, especially when the keyhole mode is applied, made the industry reluctant to exploit this process for production purposes. The development of microprocessor controlled equipment combined with a better understanding of the process overcomes the major shortcomings and makes the potential of the process unique not only for significant improvements in productivity but also for critical welds in comparison with commercially available pipe welding systems. Most of these applications though, are restricted to circumferential welding since the complexity of the plasma torch makes the development of an orbital plasma welding head difficult. After reviewing the literature, it appears that the plasma process has not been used in production to weld materials orbitally and only evaluation trials have been carried out [94, 123, 188].

Norrish indicated that the two major advantages that PAW has for pipe welding over GTAW are [32]:

- the use of plasma gas flow rate in order to increase or decrease the required penetration without changing the weld bead size, a facility which is not available with GTAW where in order to increase penetration, it is necessary to increase the current which, in turn, will increase the weld pool size making it difficult to control when positional welding
- plasma welding offers an almost cylindrical arc which remains virtually constant in small stand-off variations resulting in consistent penetration and bead shape unlike GTAW where the conical shape of the arc will result in inconsistent penetration and bead shape if the distance from tungsten to pipe does not remain constant.

The significance of the latter is better appreciated in conjunction with another important aspect stressed by Lea [119]. He noted that maximum quality in welding can

only be achieved after full appreciation of the process and equipment and - most important of all - the preparation, taking into account the pipe manufacturers tolerances. He showed that, even working with strict standards, significant misalignment can occur without even considering any ovality that may exist. Thus, unless the fit up problem can be resolved, any time and money spent on welding problems would be unjustified as the welding will be inferior and unacceptable.

2.5.1 Orbital Welding - The Current Status

Orbital welding techniques are usually applied if the turning of tubes is not possible, or when it is impractical to fit long tubes or tubular fabrications into workshop lathes. Kruger and Marya noted that despite the large number of welding processes, GTAW has become the one which is the most used for precision welding of different types of materials with thin or medium wall thickness [186]. This was attributed to a very important feature that GTAW has for orbital welding; it allows separate control of the energy transfer and the filler material transfer making easier the solution of complex technological and material related problems, contrary to GMAW or FCAW, where the filler material brings the arc energy to the base materials. GTA orbital welding heads may be open or totally enclosed. Sewell suggested that the best results for clean, even weld beads are produced with totally enclosed weld heads where the tubes are clamped together with collets matching the tube OD. The tungsten welding electrode is supported on a rotary carrier and this rotates around stationary tubes and a family of heads is required to weld the different sizes of tubes [189]. With this type of heads, revolution and twisting of cables and hoses which is observed in the early orbital welding system designs where slip-rings or chain-drive assemblies were employed to carry the welding torch around the tube, are avoided. The latter is used for welding large-diameter pipes, using GMAW in most cases, and a typical example is illustrated in figure 27. The totally enclosed welding heads (typical heads are illustrated in figure 28), are usually available as complete systems consisting of the power source, programmer and welding head. Sewell noted that as the welding head design becomes more compact, the rate of energy dissipation from the head is reduced, which in turn lowers the permissible duty cycle although water cooled heads are nowadays available [189].

A wide range of orbital welding equipment is presently available as can be seen in Table 9 [190]. Arc Machines, Dimetrics, Hobart, ESAB and Messer Griesheim dominate the world market and are the most important producers of orbital welding heads.

Several attempts have been made until now to fabricate totally enclosed plasma welding heads. The complexity of the plasma torch makes something like this difficult and all previous trials have proven unsuccessful, the major problem being the difficulty in extracting the generated heat from the plasma torch [191]. Automated welding has however been applied to the plasma arc welding, keyhole and melt-in-mode processes for circumferential welding. Cary described such a system where the torch is stationary with automatic X, Y and Z adjustments while the pipe joint rotates under the arc [179]. Torch adjustment, pipe rotation, gas coverage and plasma arc, are all initiated through a microprocessor. The computer program provides control of the welding parameters, the filler material addition, and the initiation and closure of the keyhole which involves simultaneous changing of a number of variables.

2.5.2 Orbital Welding of Tubes - Main Problems and Solutions

A. Main problems

The most important problem in tube welding concerns the progressive heating of the weld area due to accumulation of heat energy transferred by the arc during its movement around the tube. This results in a progressive increase of the weld pool volume and a rise in the extent of metallurgical changes in heat affected zones if the arc energy input is not reduced as the weld progresses. The phenomenon is more distinct at small diameters where it is difficult to ensure a stable width and, in particular, a stable underbead width along the entire length of the joint. Furthermore, with continuous current the degree of heat build up in the joint increases with an increase in wall thickness for a given diameter. According to Kazakov et al [192] this is because the temperature field does not reach the quasi-steady state in the zone of formation of the weld throughout the entire welding process. It was confirmed experimentally that the special features of the temperature field in circular and annular joints are associated not only with the weld diameter but also with the thermophysical properties of the material of components and the welding speed, which, in turn, depends on the thermal power of the source and edge thickness. This relationship is confirmed satisfactorily by experiment as presented in figure 29. The use of complex criteria was also recommended in order to determine whether it is necessary to regulate heat input when welding circular or annular joints.

The heat flow during circumferential pipe welding has been successfully analysed for small diameter, high thermal conductivity tubes using semi-analytical finite element methods and it was again concluded that due to the heat build-up and preheating effect, the fusion zone increases in size as welding proceeds under constant process parameters [142]. Furthermore, mathematical models have been successfully developed and used for obtaining optimal welding conditions which give a uniform weld bead over the entire circumference for the GTA welding of thin tubes with small diameter and high thermal conductivity [143].

These considerations are important both in conventional and orbital welding of tubes since the volume of the weld pool affects the balance of the weld pool, that is to say the balance of the gravity and surface tension forces must be guaranteed. This is particular critical in orbital welding because the welding has to be done in all positions passing continuously from one to the other as illustrated in figure 30 [186]. It becomes even more critical when welding in the keyhole mode due to the fact that the behaviour and consequently the stability of the weld pool is completely changed and because of the complex dynamics of the weld pool.

Lancaster [1] suggested that when a keyhole is formed, the forces concerned at the bottom of the now open keyhole are different and that in practice the relative motion between the beam and the workpiece is often held at zero until full keyholing is obtained. In general, forces tending to form and maintain the keyhole are the beam pressure, vapour pressure and recoil pressure while forces tending to close the keyhole are the gravitational pressure and surface tension and are presented in figure 31. It is evident that in orbital keyhole welding, the gravitational pressure which is directly proportional to the density and height of the liquid metal above the keyhole, is also a force which tends to open the keyhole, depending on the relative position of both torch and tube to the level surface. Furthermore, it is expected that all the forces acting within the keyhole will vary in magnitude according to the welding position, with gravitational force being a predominant factor in disrupting keyhole stability. To obtain a better understanding of the problem, a short description on the effect of each force on the keyhole stability is presented below [1, 39, 193].

Arc Beam Pressure

The plasma jet exerts a pressure on the workpiece which is directly proportional to the square of the plasma gas flow rate and increases when the current rises due to the increased flow rates of the plasma in the nozzle.

Recoil Pressure

This is exerted on the workpiece due to the finite velocities of the evaporating particles leaving the surface, acting on the same direction as the beam pressure tending to open a closed keyhole and maintain an open one. It is directly proportional to the square of the power density and inversely proportional to the square of the energy required to vaporise 1kg of the workpiece. In an open keyhole there is only some recoil pressure from the front sloping surfaces.

Vapour Pressure

This results from vaporisation of metal at the bottom and leading edge of the keyhole and this tends to push back the walls of the keyhole. As the base of the closed keyhole is normally where the temperature is at maximum, this is the region of highest vapour pressure. The vapour pressure is dropping gradually up the hole and it becomes zero a short distance above the top of the keyhole.

Gravitational pressure

The gravitational pressure at any point in the liquid surrounding the keyhole is directly proportional to the density and height of metal above it, thus, it increases linearly with depth in a parallel sided hole, assuming constant density. It is significant in the case of deep keyholes.

Surface Tension

The surface tension can be considered as the force which tends to minimise the surface area of the liquid. For non fully penetrating welds with deep narrow keyholes, high depth to width ratios, surface tension tends to act upwards against the beam and recoil pressures. In a full penetrating weld the effect of the surface tension in a material thicker than the width of the weld is to try and close the keyhole by reducing the surface area of the molten pool while with materials thinner than the keyhole is to pull the molten metal back to the parent material, overcoming the forces tending to close the keyhole and so produce a cut (figure 32).

The penetration and stability characteristics of the keyhole are significantly influenced by the surface tension force. It is inversely proportional to the radii of the keyhole welding thus it is beneficial to minimise the keyhole size for positional weld pool control.

Moving Weld Pool

It must be noted that the pressure balance described above does not take into account the fact that the heat source is moving across the workpiece during welding, resulting in decreased pool temperature and size, which in turn decreases the vapour pressure and hence affects the ultimate penetration. In addition, the keyhole geometry becomes asymmetrical and also, instabilities which may cause closure of the keyhole before maximum penetration has been achieved are introduced. These instabilities may result in defect formation, such as undercut of the top bead and excessive penetration.

B. Solutions

Kruger and Marya proposed two solutions for the problems described above [186]. The first one, shown schematically in figure 33, is widely used and is the technique of current pulsation. A short energy peak assures full opening of the keyhole and is immediately followed by a reduction of energy which allows the weld pool to cool down. In that way the size of the weld pool is controlled. The efficiency of this method depends on upslope time for each current impulse which must remain very short in order to allow a rapid heat input into the workpiece, on the effective times for high and low currents and also on the frequency of pulsation. All these parameters have to be adapted to the wall thickness and the material chemistry of the tubes and makes control of the process more complicated since a greater number of welding parameters must be considered. Lucas noted that selection of welding parameters can be simplified with the knowledge that the pulse time is determined more by the physical requirements of forming the keyhole at a given traverse rate, than by the plate thickness or material composition and concluded that the pulsed current level and plasma gas flow rate are the major welding parameters which must be set to give an over-penetrating plasma for a particular material composition and plate thickness combination [33]. Lucas also reported that although the pulsed technique is quite satisfactory for vertical-down welding, problems of undercutting can be experienced in the vertical-up and horizontal-vertical positions [29]. Duthie noted that pulsed current increases the tolerance of the plasma process to variations in welding parameters and improves control of the weld

pool, allowing sound welds to be made in the 1G, 3G and 4G positions in plasma keyhole welding of large diameter, 25mm wall thickness carbon steel pipes [194].

The second solution for a consistent weld pool size can be achieved, dependent on the type of the power source, by programming the welding current and/or welding speed and hence influencing directly the thermal cycle. Depending upon the number of program steps needed and the number of parameters to be programmed the equipment required varies. Sewell noted that at least four quadrants of control are desirable for most applications, and fully computerised power sources are now available which offer almost unlimited control [189].

As already mentioned in section 2.4.3.7 plasma gas flow rate programming is essential for keyhole opening and closure. In orbital welding, programming of the plasma gas flow rate might be required to sustain the keyhole as the welding torch rotates around the tube due to the complexity of the balance of the forces [191]. Furthermore, the attitude of the welding head in situ, should always be taken into account when the programming requirements for procedure development are considered.

Pulsation of the current is normally the preferred solution, although simple programming of the welding current can often prove to be adequate [186]. For more complex applications, the variation of other parameters is necessary. Moreover, the strict synchronisation to the real movement of the welding torch for the control of the welding sequence is essential, especially for those parameters which are synchronised directly to the relative position of the torch with regard to the workpiece. Figure 34, shows a complex but very often inevitable welding sequence for GTAW orbital welding of tubes.

2.5.3 Tube Purging

Another important parameter in tube welding is the internal purge gas pressure. It affects the internal weld bead appearance and flat or penetrating, smooth or uneven weld beads can be obtained. According to Sewell, overpressure of the backing gas can cause concavity in the weld root area and can even cause blow holes through the weld [189]. A wide range of purging devices and methods are available [195].

2.6 Process Modelling

According to Box and Hunter [196] "the object of much experimentation is to build or discover a suitable model. This is done by an iterative procedure in which a particular model is tentatively entertained, strained in various ways over the region of application and its defects found. The nature of the defects interacting with the experimenter's technical knowledge can suggest changes and remedies leading to a new model, in turn, is tentatively entertained, and submitted to a similar straining process".

A model is not an exact replica of a system but a simplified representation of it, containing only those elements or features that the modeller considers important and is able to implement. Therefore, for a given system several different models can be developed by using different features or different interpretations for the same features, or by considering different approaches for model building. The available resources along with a clear understanding of the objectives of the model greatly influence the developing strategy, final form and applicability of the model [135]. Based on their objectives, Cross and Moscardini suggested five main categories for models [197]:

- understanding of the system,
- design,
- training,
- control,
- optimisation with respect to prescribed constraints.

Several classification systems have been used for model grouping. Gordon [198] separated them into mathematical and physical. Mathematical models can also be classified as analytical or numerical based on the technique used to solve them [198]. Mathematical models can be further separated into theoretical, empirical or semi-empirical, providing quantitative and/or qualitative relationships between the main process parameters and the outputs [199].

Theoretical models are usually computationally intensive due to the complexity of the resulting equations and are developed from first principles based on the process scientific and physical facts. They can be valid over a wide operating region [199].

Empirical models are derived from the relationship between process input and output variables using statistical analysis techniques, with regression analysis being the most commonly adopted technique. They are extremely effective for solving complex multi-factor problems like welding, because the analysis techniques applied are universal, and because the methods of building them up on the basis of experimental data are comparatively simple. These models have the great advantage that it is easy to make evaluations of their parameters more precise as further data is accumulated, without the need for extensive and accurate knowledge of all process variables. Their weakness is that they are of local nature and are not valid outside the range of the experiment although in a number of cases their field of action may be quite extensive [199, 200]. Finally, semi-empirical models combine the advantages of theoretical and empirical models to achieve modelling accuracy and are developed with regard to established fact or knowledge of the process.

Many other classifications for models are possible but it must be emphasised that placement of a model into any class is rather artificial and should be used only as a reference.

A considerable amount of work has been taken to model the relationship between weld bead shape and welding parameters using statistical analysis techniques [e.g. 176, 135, 201-204]. It is very important though, to note that improper application of statistics to experimental investigation may lead to degradation and invalidation of otherwise promising work [135].

2.6.1 Design of Experiments

According to Salter and Doherty [201], having decided to relate a defined set of welding parameters to a defined set of geometric dimensions by empirical means, the investigator has to adopt a statistical approach to the design of the experiments that will generate his data. Galopin and Boridy noted that this should be planned in a way that will lead to valid and objective conclusions since data analysis can never overcome a poorly designed experiment [205].

Recognition and statement of the problem in a clear and logical way along with formulation of a modelling methodology by setting out a series of well-defined logical steps are all very important, since they enable the *identification* and *choice* of the most

significant variables that affect the *defined* process responses within the *specified* operational limits [206].

There are a few general principles which should be kept in mind when designing experiments [207]. First, the parameter or parameters which is chosen to be the response of the process output, such as bead geometry and defects, and thus minimise, maximise or keep within a specification are normally referred as effect, quality features, but more often as response. They are also called the dependent variables [208]. The variables which can affect the welding procedure and which are directly controllable, such as machine settings and raw materials are called factors, estimators, treatments, regressors, controlling parameters, inputs, or independent variables. The ranges over which an independent variable can be varied are called levels. It is extremely difficult to understand and isolate all the factors and interrelationships which could affect a welding procedure. Obviously, a good modeller has the ability to build models including only a subsystem of the variables and interrelationships of the original system. Hence, the first stage in any statistical design program is the selection of the factors and the choice of the number of levels. In selecting them, it is important to keep in mind the experimental objectives.

Another important element is that a certain variability in the responses is possible, which can mask partially or completely the influence of some of the input variables. This is attributed to experimental variation which is outside the control of the investigator mainly due to unknown or not completely controlled variables, and fluctuations either inherent to the system or occurring during measurement. Furthermore, if two or more input variables are closely related due to either limitation of the equipment and/or physical constraints of the system, the individual effect of these variables will be very difficult to determine. The influence of the level range that will be used is also critical. A short range can lead to error due to the variance of the parameters while a wide range entails the danger of invalidating the assumption of linearity presumed for most data analysis. These considerations reveal the importance of a proper strategy in planning and performing the experiments in order to maximise the amount of the useful information that can be obtained.

The three basic techniques in statistical design of experiments in order to avoid systematic error of the results and thus increase their precision are:

- Replication,

- Randomisation,
- Blocking.

Replication (i.e. the repetition of trials), provides the required number of observations of the same factor and level for estimation of the experimental error. The precision of the estimates of the effects can also be increased. *Randomisation* is, according to Montgomery [206], the cornerstone underlying the use of statistical methods in experimental design. By randomisation both the allocation of the experimental material and the order in which the individual runs or trials of the experiment are to be performed are randomly determined. This assists in “averaging out” the effects of extraneous factors that may be present. Furthermore, observations and errors behave as independently distributed random variables, something that statistical methods require. *Blocking* is a very important technique used to increase the precision of an experiment and involves division of the experiment into groups (blocks) which are more homogeneous. For example, measurements made using the same batch of electrodes, or on the same batch of raw materials, or measurements made by the same operator.

Two approaches for the design of experiments are used to construct the models; parallel and sequential. They both share the common feature of varying many or all of the equipment settings simultaneously.

In sequential design of experiments, each new data point is used to help design the next experiment. Models are updated as each new data point is added and are used to design the next run for further improvement of the process. Thus, selection of the next test to be carried out is an important issue, because it directly relates to economy and efficiency. According to Galopin et al the starting of the experiment may be a difficult stage, especially if you do not know what region to explore first. A minimum of acceptable points before attempting the principal components analysis might be required. Published data, similar procedures, general knowledge of the process and available expertise would be very helpful in selecting the first tests. Another good practice would be to begin with a fractional factorial design [209]. The Simplex method, the Ultramax method and the Evolutionary Operation are examples of the sequential design of experiments.

According to Guo and Sachs [210], in the parallel design of experiments, all experiments are designed at the beginning and then performed. The construction of

models follows the collection of all data and are subsequently used for process optimisation and control. Examples of the parallel design of experiments include full and fractional factorial designs, central composite designs, and Taguchi's orthogonal array with factorial designs more frequently used.

It has been found that for designing experiments in welding applications factorial design is one of the most suitable techniques (e.g. 203, 204, 211-214). In general, it is commonly used in experiments involving several factors where the cumulative effect of these factors on the response is to be studied. In this approach, the distinguishing characteristic is that each level of any factor occurs at every level of every other factor, permitting investigation of complicated effects, also providing the smallest number of trials with which several factors can be studied. Furthermore, it allows not only the detection of the effects of individual parameters (called the main effects) but also of the effects of the interactions of the variables at several levels.

Factorial design is more effective to investigate the behaviour of a response in a small region of the factor space, where a linear relationship among the factors usually successfully describes the response. Where non-linearity is suspected, a slightly modified factorial design approach, such as the planning of the experiment around a central point, enhances the ability to model successfully. However, the use of more levels is another way of dealing with such conditions.

The simplest factorial design is that in which each of the factors is used at only two levels, i.e., a "high" and a "low" level, and is called 2^k Factorial Design, where k is the number of variables. It is particularly useful in the early stages of an experimental program, when the number of factors investigated is likely to be large. Many statistics text books have examined the application of factorial designed experiments (e.g. 206, 207, 215, 216). However, it must be noted that in welding applications the physical combination of some parameters might lead to defect formation and instability. This fact can be restrictive in developing models describing a process operating range using factorial design techniques.

Hahn [217] noted that a proper experimental design is often more important than sophisticated statistical analysis. Results from a well-planned experiment are frequently evident from simple graphical analyses. It must always be remembered that the mark of

a well-designed and executed experiment is often that formal statistical analysis is superfluous.

2.6.2 Analysis of Data

Data collected from the experiments are treated with the support of statistical analysis techniques in order to meet the main objective which is to build the appropriate models. A number of well established techniques are presently available for data analysis depending on the experimental design and/or the complexity of the phenomenon. The Table of Contrast Coefficients, the Yates' algorithm and the Response Surface Method are all typical approaches that can be used to calculate the effects without complex computational assistance. However, the significant development in computer technology made the analysis of complex experimental data and increased numbers of variables more accessible. A brief introduction on regression analysis including only the basic concepts and techniques associated with the method is presented below.

2.6.2.1 Regression Analysis

Regression analysis is a procedure used to fit models relating one dependent variable or response on k independent or regressor variables by minimising the sum of the residuals for the fitted line. The relationship between these variables is characterised by a mathematical model called a regression equation and the regression model is applied to a set of sample data [206].

Several regression methods can be employed depending on the number of factors involved and the significance of the relations between factors and responses. In *Simple Regression* the relationship between a single regressor variable and a response variable is determined. However, many regression problems involve more than one regressor variable and in this case the relation is widened to many factors and is called *Multiple Regression*. If the response variable is linear in the independent variables the resultant model is called *linear*. Since non-linear functions of variables are common in engineering *non-linear* regression analysis techniques can also be used where least square estimates of the parameters are obtained. For most practical welding situations, multiple linear regression analysis seems to be the most commonly adopted technique.

2.6.2.2 Linear Multiple Regression Analysis

The general problem of fitting the model can be described with the use of the following first-order polynomial model:

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \dots + \alpha_k x_k + \epsilon$$

is called the multiple linear regression problem.

There are several other model structures which can be used in a multiple regression analysis. The most common are [218]:

1. Second-order polynomial model

$$y = \alpha_0 + \sum \alpha_{kk} x_k + \sum \alpha_k x_k^2 + \sum \alpha_{k-1,k} x_{k-1} x_k + \epsilon$$

2. Intermediate model

$$y = \alpha_0 + \sum \alpha_{kk} x_k + \sum \alpha_{k-1,k} x_{k-1} x_k + \epsilon$$

3. Multiplicative model

$$y = \alpha_0 x_1^{\alpha_1} x_2^{\alpha_2} \dots x_k^{\alpha_k} + \epsilon$$

4. Exponential model

$$y = \text{Exp}(\alpha_0 + \sum \alpha_{kk} x_k) + \epsilon$$

where

y is the model output;

$x_1, x_2, \dots, x_k$ are the independent variables (or regressors);

$\alpha_0, \alpha_1, \dots, \alpha_k$ are the regression coefficients to be determined from the data;

k is the number of independent variables.

The multiplicative and exponential models are not linear, but a logarithmic transformation can easily transform them into a linear form. It must be noted that in all the above models there are no interacting effects between the independent variables which means that the effect of x_a on the mean response does not depend on the level of x_b , and correspondingly the effect of x_b does not depend on the level of x_a , where x_a and x_b are random independent variables. If interaction between independent parameters is observed this can be described by the following model structure which includes cross-product terms [202]:

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_1 x_2 + \dots$$

where $x_1=x_{i=1}$, $x_2=x_{i=2}$ and $x_1x_2=x_{i=3}$

It should be clear that the term linear model refers to the linearity of the parameters that are included in the general equation, and not to the shape of the response surface.

2.6.2.3 Selection of Independent Variables and Estimation of Regression Coefficients

Variable selection for the regression equation is one of the most difficult problems in regression analysis. It must be noted that usually there is a big difference in selection of the factors to be present in an experimental design and in a model. Neter et al [219], suggested that there is no unique way of searching "good" subsets of x , and subjective elements play an important role in the search process. Exclusion of variables that do not contribute significantly to the process output is preferable in regression analysis since retaining these terms results in inflation of the prediction error to the regression model. However, it turns out that omission from the model of one or more relevant variables usually violates the first assumption required for statistical inference in regression, which is that errors (ϵ) are assumed to have mean zero and constant variance [220]. Therefore, Ogata noted that in model building it is very often necessary to make a compromise between the simplicity of the model and the accuracy of the results of the analysis which requires decision making about which physical variables are negligible and which are crucial to the accuracy of the model [221].

The various procedures available for variable selection differ solely in the criterion that each uses for selecting a "good" set. Montgomery and Peck suggested the following grouping for variable selection procedures [222]:

- *All possible regressions* All possible regression equations encompassing all possible combinations of regressors are carried out. The best model is selected with the support of a suitable statistical criterion.
- *Forward selection* the procedure starts without any regressors but the intercept. The predictor variable having the highest correlation with the criterion variable is then added and the procedure continues adding variables based on the largest partial

correlation with the response. At each new stage the significance of the previously selected variables is also checked, and insignificant parameters are removed. Computation ends when all statistically significant variables have been included.

- *Backward Selection* the procedure begins with an equation that includes all of the predictor variables in the analysis and sequentially deletes variables, with the variable having the smallest partial correlation with the response dropped first. A variation of this form is a method called "*Backward Selection with Addition*" where at each step all variables that have been deleted are checked again for statistical significance; if any variable that was previously deleted is found to be significant, it is added back into the equation.
- *Stepwise Selection* this procedure is probably the most widely used amongst the automatic search methods. It is a modification of forward selection and can also be found as "*stepwise regression with deletion*". At each step those variables that are already included in the equation are reassessed usually by their partial F ratio to ensure that they are still statistically significant. Other criteria for adding or deleting a variable can also be employed such as *error sum of squares reduction* or the *coefficient of partial correlation*.

It must be emphasised that the stepwise regression procedures do not guarantee that the best subset model will be identified. The result of a stepwise regression analysis, is likely to overstate the model's explanatory power, and the user may fail to recognise the possible existence of systematic variation in the residuals if the functional form of the relations is not considered and diagnostic tests based on residuals are not carried out. Furthermore, there is a tendency for regression users to hide much of the data analysis and report only the final result pretending that only one regression analysis was conducted. Hiding the actual procedures used makes it likely that the users overstate results, causing other users to be disappointed when the results are applied to making decisions [220]. However, the adequacy of the regression model is a problem that has long plagued the practising statistician. The decision on whether or not a developed model is adequate for its intended use is somewhat subjective. According to Suich and Derringer, in this decision, judgements must be included about the relative costs of further observations versus the additional benefits, the amount of time and effort which should be expended, on the problem, etc. [223].

2.6.2.4 Statistical Parameters for Regression Models Adequacy Checking

After a multiple regression model has been formulated, the next step is to estimate and test its adequacy, in other words "*how well does the linear model represent the observed data?*" Several criteria can be used in answering this question.

R^2 , often referred to as the *coefficient of determination* can be used as a measure of how well the developed regression equation fits the data, although in general this is a poor basis for judging the quality or usefulness of a regression result [220]. It represents the fraction of the total variation that is related to the predictor variables in the regression equation. This ratio is a number always between zero and one, with a value of zero indicating that the response variable is not related to any of the predictor variables. On the other hand a large R^2 does not necessarily mean that the fitted model is a useful one. Addition of more independent factors will only increase R^2 and never decrease it, but this does not always mean that the new model is superior to the old one. It is defined by the relationship:

$$R^2 = (Syy - \sum r_i^2) / Syy$$

where:

$$r_i = y_i - \hat{y}_i$$

$$Syy = \sum (y_i - \bar{y})^2 \text{ and,}$$

y_i : the actual value for the I observation,

$\hat{y}_i$: the fitted value for the I observation,

$\bar{y}$: the sample mean.

However, R^2 is easily misunderstood because it can only increase as more explanatory variables are added. Therefore, R^2 adjusted is usually used which is defined as:

$$R^2_{adj} = 1 - s^2 / [Syy / (n - 1)]$$

where:

$$s^2 = \sum r_i^2 / (n - k - 1) \text{ and,}$$

n : the number of observations,

k : number of parameters in the model.

The F ratio is a common parameter to determine whether or not the criterion variable is significantly related to the predictor variables that have been included in the equation. If the calculated F ratio value exceeds the expected value from an F ratio distribution table at a specified significance level, the entire model is significant and one or more of the predictor variables are statistically related to the criterion variable. Otherwise, it is not possible to have confidence in the initial model nor in a simplified model using a subset of the predictor variables. The significance level of the F ratio is given by the P value. The F ratio is defined as:

$$F_{ratio} = \frac{R^2(n-k)}{(1-R^2)(n-k)}$$

The standard error of estimate S_e is another index that can be used to select a model and is defined as the square root of the sum of the errors divided by the degrees of freedom [224]. At each step of a model development, S_e must be less than S_y (the standard deviation of the criterion variable), with a value relatively close to zero being ideal. With only few exceptions, a value of S_e that is relatively close to S_y indicates a model with relatively poor accuracy. The mathematical definitions for these two terms are given below:

$$S_e = S_y \sqrt{\left(\frac{n-1}{n-k-1}\right)(1-R^2)} \text{ and,}$$

$$S_y = \frac{1}{n} \sum_{i=1}^n (y_i - \bar{y})^2$$

Computational routines used for regression analysis usually present, along with the model fitting results, an Analysis of Variance (ANOVA) table. After regression ANOVA is probably the second most widely used statistical technique in engineering analysis. It indicates whether one variable has a significant effect upon another and also, when two or more variables are analysed for their effect upon another one, can detect the presence of interactions among those independent variables. The ANOVA technique

is a comparison of means, the comparison made using F statistics. It must be noted that regression analysis is similar to ANOVA in that it tests for significance by way of F ratios, but it improves upon ANOVA in that it quantifies the effect [225].

An important parameter to assess whether a variable should stay in the model or not is the Confidence or Significance Level, which is a probability of occurrence measured by a Significance Test for each variable after the variable selection. Usually, significance levels lower than 0.05 are accepted. However, it must be noted that significance does not imply importance, it means real effects not due to random fluctuation.

Residual analysis plays a very important role in judging model adequacy since residuals represent the variation in the criterion variable that is not explained by the predictor variables. An incorrect model structure or the need to consider another predictor variable may be revealed by plotting of the residuals. In general, there are several types of residual plots that can also be used to check for violations in the assumptions of the model, or to identify extremely large residuals referred to as "outliers", which may indicate problems with certain observations. The most common are the probability plot of the residuals and plots of the residuals against the fitted values and independent variables.

A linear dependency between the regressors, however, may lead to unacceptably high standard errors and the problem of multicollinearity is said to exist. In regression modelling this phenomenon can induce a number of problems such as to inflate and change the sign of the coefficients estimates and prediction of unreasonable variables. The simplest way to detect it is the examination of the correlation matrix where large coefficients of correlation between pairs of independent variables (near to unity) indicate linear dependency. However, the ability to obtain a good fit to the data is not inhibited by this phenomenon and several remedial measures can be used once detected.

2.6.2.5 Fuzzy Regression

The exact quantitative measurement of some weld quality criteria, such as undercut, is sometimes quite difficult. For that reason they are usually classified with the support of Boolean logic as "present or not present", "yes or no", "true or false",

although in most of the cases somebody has to deal with the intermediate range between true or false, that is, the seriousness or level of defects [204].

The application of fuzzy logic allows for the intermediate levels to be "quantified". It is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth. According to Hubanks, fuzzy logic is a mathematical model for capturing ill-defined process relationship [226]. It allows engineers to tackle problems where a rigorous mathematical model does not exist or where they are too complex to evaluate for real-time operation.

Many systems may be modelled, simulated, and even replicated with the help of fuzzy systems, not the least of which is human reasoning itself. Fuzzy logic has successfully been employed for many welding applications [204, 227, 228].

The benefits of regression analysis can be expanded into modelling non-numerical attributes coded in binary forms and is referred to as fuzzy regression [229]. The key benefits of fuzzy regression are:

- that it provides a mean for fitting data when the relationship between the independent and dependent variables is imprecise. The data imprecision is represented by the residuals,
- it simplifies and reduces the development cycle,
- it is easy to implement and
- can provide more "user-friendly" and effective performance;

2.6.3 Model Validation

After a model has been formulated and checked for adequacy, it must be tested to ensure that it is sufficiently sensitive to the concepts that form the basis for the experimental hypothesis, that is, a model is valid when it measures what is intended, in its intended operating environment.

According to Montgomery and Peck, three types of procedure are useful for validating a regression model [222]:

- Analysis of the model coefficients and predicted values with prior experience, physical theory, and other analytical models, or simulation results.
- Collection of fresh data with which to investigate the model's predictive performance.
- Data splitting; that is, setting aside some of the original data (called the holdout sample) and using these observations to get a measure of the model's predictive validity.

2.7 Procedure Development

The selection and/or development of a welding procedure is the principal function of a welding engineer. The complex nature of the production processes involved makes the successful fulfilment of this task quite difficult. According to Galopin et al [209], a procedure development consists of specifying how the welding operation should be carried out, in order to produce the weldment within given specifications. Paranhos suggested that a complete scheme able to predict and select welding procedure should contain two main components [203]:

- i. a model capable of describing weld bead geometry;
- ii. the specifications and constraints to comply with.

Traditionally the development of an arc welding procedure is made by a trial and error approach. The identification of a presumed good working condition/quality is followed by a small number of runs to confirm the results [211]. However, this approach contributes very little to the understanding of the problem and it yields a solution which is not necessarily optimised in terms of cost, quality or productivity and can also be time consuming and expensive [205].

The so called "tolerance box approach" was developed to provide a more systematic technique for procedure selection and relates to sequential experimentation, starting from a widely spaced framework of experiments and moving gradually to a more focused experimental lattice containing acceptable welds. The experimentation will continue until the required degree of precision is obtained and the procedural field or tolerance box is defined for the variables under study [203]. The major limitations of this approach, (which is basically a graphical one) are the volume of the collected data

which is usually very difficult to deal with efficiently when considering more than three variables, and the lack of any quantitative information regarding the model accuracy.

Salter and Doherty [201] presented a new method to implement the "tolerance box approach". Having established the working area under study and the quality standards to be used, small factorial or partial factorial designs were made around the working area, reducing considerably the required experimental data. Furthermore, with the application of statistical analysis techniques, multiple regression analysis equations were obtained relating the geometric parameters of the weld to the input parameters of the welding procedure. This gave the additional benefit of controlling the welding procedure and study the influence of process variables modifications on the procedural fields without further experimentation [203]. McGlone [131] and Paranhos [203] suggested that having established a set of equations which relate procedural parameters to weld bead geometry, development of suitable welding procedures can be achieved more conveniently by incorporating the equations into an interactive computer programme. In this approach the computer prompts the user for the required information and then lists the technically acceptable procedures.

Galopin et al [209] suggested a new method to implement the "tolerance box approach" to welding procedure selection. It models the procedural field as an n th dimensional ellipsoid which discriminates between tests inside and outside user's specification, thus allowing to select the next most significant test and making the experimentation very efficient. Multiple regression analysis has been employed for model development and computer algorithms have been used for selection of optimum sets of welding conditions.

Lack of model development associated with plasma welding made impractical, until now, the implementation of computer technology in procedure development for plasma welding operations, something that can be inferred from the lack of literature associated with the subject.

2.7.1 Optimisation of Welding Procedures

One of the most important problems to be solved in welding engineering is to identify the optimum process parameters from a collection of alternatives which result

in the same output target value, but with considerable difference in operating conditions [204].

Optimisation might be defined as the science of determining the “best” solutions to certain mathematically defined problems, which are often models of physical reality. It involves the study of optimality criteria for problems, the determination of algorithmic methods of solution, the study of the structure of such models, and computer experimentation with methods both under trial conditions and on real life problems [230].

Probably the most important step in all optimisation techniques is to define and express precisely the objectives in which the optimum will be found in terms of easy to control independent variables. In a complex multi-factor process like welding, the optimisation criterion is normally complex too, that is it includes requirements relating to the different properties of welded joints. Furthermore, requirements related to cost, production rate, heat input and defect formation can also be included. Kasatkin noted that in addition to this, the optimisation criterion is not constant: it requires adjusting according to the requirements made of particular welded products something that makes insufficient the development of only a single optimum variable of the welding procedure [200]. He also noted that in order to solve effectively the problems involved in optimising a welding procedure the existence of appropriate and accurate models are necessary.

Another important requirement for process optimisation is the definition of all the required specifications that the weld should be in compliance with. Jones et al mentioned that for the establishment of tolerance procedures it is important that all aspects of weld geometry are provided with dimensional tolerances [176]. Loose statements such as “there shall be no undercut” are not accepted since virtually all fusion welds are subjected to some form of undercut at the weld toes.

It is suggested by Paranhos the definition of the range of tolerances that will be given for the obtained solutions when predicting and optimising welding procedures is critical, due to the fact that deterministic models is being used while the welding process cannot be described as such [203]. Thus, variations present when setting the welding parameters as well as when measuring the output variables have to be

accounted when multiple regression equations are used for prediction and optimisation of the procedure.

According to Galopin et al procedure optimisation provides a numerical description of the procedural field which may be used to design a generative type welding data base system, based on the optimisation of the appropriate responses which are expressed in mathematical models as functions of the explanatory variables. The model response estimates are used in an optimisation algorithm to arrive at the optimum set of welding conditions. [209].

As already mentioned two common problems that may be encountered in welding are that it is a problem involving the simultaneous combination of properties and that is difficult to define or measure phenomena such as undercut. Deringer and Suich developed a technique called "Simultaneous Optimisation of Several Response Variables" which can deal with such situations and is based on the desirability function approach [231]. It transforms the multiple objectives into a single objective by transforming each response output under consideration to a desirability value and combining all of them to an overall assessment of desirability.

Several techniques have been utilised for procedure generation and optimisation, most of them associated with GMAW and SAW [e.g. 143, 203, 209]. Lack of models related to plasma welding applications makes impossible the optimisation of welding procedures that uses the plasma welding technique.

2.8 Summary

The literature survey indicates that although improvements in computer technology made it possible to control and synchronise a large number of parameters associated with plasma welding (see section 2.2.9), and therefore made plasma welding a more reliable process for a wide range of applications (see section 2.3), orbital plasma welding of tubular components is not usually practised (see section 2.5.1). This is mainly attributed to the high cost and complexity of the equipment (particularly of the plasma torch) along with the requirement for high precision and extensive control of the process, especially when the keyhole mode is applied (see sections 2.2.9, 2.2.10).

The complexity of the plasma torch is probably the major drawback for the exploitation of the process for orbital welding of small bore tubes in a totally enclosed head which provides the best environment for clean, even weld beads. This is mainly attributed to the need to absorb large amounts of heat (cooling of the torch) (see section 2.2.10), the need for introduction of both plasma and shielding gas (see section 2.2.1) and the need for a reliable arc starting (see section 2.2.5). These requirements result in a rather bulky and complex torch and which is unsuited to operations within a confined space (see section 2.5.1). Furthermore, the keyhole welding technique which offers the most significant advantages, is usually associated with higher current applications (see sections 2.2.4.3, 2.3.3). The latter makes GTAW the most widely used technique for orbital welding of small bore tubes, since in most situations it can provide a reliable solution, while the low cost and simplicity of the equipment make the process even more attractive (see section 2.5.1). Nevertheless, the several special advantages that plasma welding offers, particularly in the keyhole mode, along with the need to overcome specific problems in some materials has attracted industrial interest in the application of plasma welding (see section 2.5). Furthermore, microprocessor controlled equipment currently available for the orbital GTAW applications, makes it easier to control the larger number of parameters required for plasma welding to accommodate factors such as heat build-up, change in welding position and initiation and closure of the keyhole (see sections 2.5.2, 2.4.3.7). The larger number of plasma variables and modes of operation also offer greater flexibility for control of both defects and weld bead characteristics (see sections 2.4.1 and 2.4.3), an advantage which can only be exploited however through extensive mechanisation of the process.

The literature survey also indicates that process modelling can provide the necessary framework to reduce the number of problems associated with the large number of control variables in orbital plasma welding (see section 2.6). Modelling of the process can provide the relationship between weld bead shape and welding parameters, and therefore, can reduce the number of trials required to achieve an optimised weld. To achieve this by empirical means, a systematic approach must be followed. Several statistical analysis techniques are currently available which can handle the large number of parameters and data generated in orbital plasma welding and reduce the number of experimental trials required (see section 2.6.1). Although factorial design has proven in the past to be one of the most suitable techniques for welding applications, sequential design of experiments offers the possibility of a more effective and efficient exploitation of the operational envelopes and may be used to develop new procedures

for a relatively new application like orbital plasma welding (see section 2.6.1). In data analysis, the regression analysis is without any doubt one of the best and simplest techniques to fit models relating one dependent variable (weld bead characteristic) on k independent variables (weld control parameters) (see section 2.6.2.1). Although there are a number of techniques for selection of the independent variables, subjective elements also play a very important role in the formulation of the final model structure (see section 2.6.2.3). Models can handle both, quantitative and qualitative data, which is very important for certain plasma weld bead characteristics such as undercut (see section 2.4.3.5) which is very difficult to be measures quantitatively (see section 2.6.2.5). The development of accurate welding models makes the selection of the appropriate welding procedure with the use of computer technology (off-line control) easier, and therefore reduces the likelihood of defect occurrence. However, to date, lack of model development associated with plasma welding until has made it impractical to implement computer based technology in procedure development (see section 2.7). As a consequence, the optimisation of welding procedures, which is one of the most important problems associated with the plasma welding process, is very difficult (see section 2.7.1).

In conclusion, the review of the literature indicates that for the successful application of the plasma process to orbital welding of small bore tubes, it is necessary to develop the appropriate equipment and methodology which can subsequently be used for procedure development and optimisation of the process, providing an integrated treatment for the main quality problems primarily associated with GTA welding of small bore tubes.

3. Experimental Design, Equipment and Procedures

3. EXPERIMENTAL DESIGN, EQUIPMENT AND PROCEDURES

3.1 Introduction

The principal objective of this study is to produce consistent, good quality welds by preventing critical defects such as lack of fusion, burn-through, undercut, contamination and excessive porosity, through exploitation of the advantages of the plasma welding process for the orbital welding of small bore tubes. To meet this objective, the research work was undertaken in a two stage programme which has been outlined in section 1.2.

In this chapter, a general description is given of the materials and equipment used, other than the developed torch design which is discussed in chapter 4. The experimental strategy and procedures adopted for the different stages of this work are also presented.

3.2 Equipment

The main equipment used was an Adaptive Modular Orbital System (AMOS) capable of controlling and synchronising all major plasma welding parameters (i.e. welding current, travel speed, gas flow rates) (figure 35), a 9-4500 Arc Machines welding head (figure 36), a Migatronix Commander BDH 320 power source (figure 37) and an Arcwatch data monitoring system (figure 38). The experimental set-up is presented in figures 39 and 40.

3.2.1 The AMOS Welding System

The AMOS welding system is a highly sophisticated control system developed for orbital welding operations, as part of a BRITE-EURAM project [232]. It consists of a modular VME-bus control rack and two control stations (namely the top and bottom station). The bottom station controls all the hardware of the orbital welding system in real time. The parameters for a particular weld are downloaded from the top station and implemented on the hardware by the bottom station.

Woodward reported that the rack provides control for all motion axes on the orbital heads as well as the gas flow valves [94]. It also remotely programmes and controls an independent welding power source in real-time. Serial links are used to interface the control computer with the control rack, and the control rack with the power source CPU. Initially several problems were experienced with the communication links as a result of the high frequency (HF) arc ignition used for GTAW/Plasma welding. However, these were overcome by replacing the serial cables with optical communication cables. All the welding and orbital motion parameters are configured and stored in a database on the control computer [94].

AMOS allows precise regulation for the current, head rotation, plasma and shielding gas flow rates, allowing their precise pre-programming in up to 16 different segments if necessary. Furthermore, it embraces functions for the independent control of the welding parameters in all different phases of the welding cycle (i.e. pre-purge, arc ignition, slope up, welding segment control, slope down and post purge), all synchronised directly to the relative position of the torch with regard to the workpiece. All required parameters are introduced by digital settings on a user-friendly, multiple menu computer interface.

It must be noted that for rapid current pulsing (pulses less than 100ms) the pulse parameters are controlled by the power source CPU and that there is a problem with choosing pulse duration 100ms in which case the system seems to ignore completely the segment parameters.

During the progress of this study the AMOS system was continuously under development. However, a detailed description of the changes is not considered necessary in the context of this study.

3.2.2 The Welding Head

All the experiments were performed in a AMI 9-4500 totally enclosed weld head modified for plasma operations. It is a standard weld head having a clamp housing on both sides of the head with the tungsten electrode placed in the centre of the rotor. The rotor is driven by an electric motor and rotates around the stationary tubes by means of a precision gear system. Tube clamp inserts are placed on both sides

of the head for welding tube-to-tube, pipe-to-pipe or fittings with sufficient straight section as shown in figure 41. The weld head cable connects to the adapter or extension cable. From there the ground and the electrode cables are connected directly into the power source while the shielding gas cable is connected either straight to the shielding gas bottle or to the output of the shielding gas valve of the ISOTEK control rack. Water is supplied to the head for cooling of the rotor through the ground and electrode cables.

3.2.3 The Power Source

The power source employed for the purposes of this study was a Migatronix Commander BDH 320 TRIPLE power source, fully compatible with the ISOTEK control rack utilised. It is an inverter based machine which has been designed to provide an extremely versatile and accurate supply for high performance GTAW, GMAW and MMA welding. It switches at a frequency of 100kHz, which makes it one of the fastest inverters on the market. The latter is particularly beneficial since current pulsation which requires very fast dynamic response time for enhanced performance is utilised during this research work [41]. It has an 80 volts open circuit voltage which enables the high voltages required for the plasma applications to be achieved, and a current range of 5-320amps with a 60% duty cycle at 320amps. The inverter, like all other components in the machines, is controlled by a central microprocessor, which makes it possible to achieve advanced welding control combined with straightforward operation and ease of use. The power source also provides the necessary constant current output characteristics required for plasma welding, thus achieving independent and accurate current control. Further details of the power source are provided in Table 10. As noted in section 3.2.1 all the functions of the power source are controlled through the ISOTEK AMOS rack. Details of all connections are presented in figures 39 and 40.

3.2.4 The Weld Data Logging System

Two welding parameters were monitored during this study; welding current and arc voltage, the basic electrical signals of the arc. These were examined in an attempt to determine whether there is any relationship between arc voltage and keyhole formation or weld bead appearance, in order to develop a real time quality

control system. The welding speed was calibrated and checked during the initial phase and at frequent intervals throughout this research work by timing the rotor and was always found to be the same.

The Arcwatch data logging system, a computerised unit developed at Cranfield for monitoring and analysis of the weld signals was used for the main monitoring purposes. It is a PC compatible system, consisting of a standard PC (286 and PENTIUM computers were used during this study), a 12 bit 12 channel Analogue-to-Digital converter plug-in board which provides facilities for the simultaneous monitoring of several welding parameters, a four channel signal conditioning unit and a dedicated data acquisition software package. The data acquisition parameters (such as calibration factors, sampling rate, sample size and sampling interval) can all be varied. The acquired data can be numerically and graphically displayed. Furthermore, the data obtained can be treated using numerical and statistical techniques.

Temperature measurements of the developed welding torch were also performed with this system, in order to examine the efficiency of heat absorption and dissipation from the tip of the torch.

In addition integral digital meters, measuring the average current and voltage were available on the power source.

3.2.4.1 The Sensor Specification

Current, voltage and temperature sensors were used in this experimental study. Their basic characteristics are summarised below.

a. Voltage Sensor: Welding Voltage was measured directly between the workpiece and the electrode through special sockets on the welding head.

b. Current Sensor: Current measurements were taken using a Hall effect probe to supply the signal, by placing it around the main current conductor. Two current probes were used during this experimental study, a 400 A a.c. current transducer and a 400A d.c. transducer. Their specifications are presented bellow:

	<u>400A a.c. probe</u>	<u>400A d.c. probe</u>
Rating:	0-400A a.c.	0-400A d.c.
Calibration accuracy at 23°C:	±1% of range	±1% of range
Zero offset (23°C):	typ. ±0.1% of range	typ. ±0.1% of range
Zero drift (0-60°C):	typ. ±0.1% of range	typ. ±0.1% of range
Gain variation (0-60°C):	0.05% reading/°C	0.05% reading/°C
dI/dt following:	200A/μs	200A/μs
Operating temperature rating:	0°C to +60°C	0°C to +60°C

c. Temperature Sensor: A K Type thermocouple was used for measuring the temperature of the welding torch. It consists of K type thermocouple wire insulated with varnish-impregnated glass fibre sleeving. Its hot junction tip is welded in an argon atmosphere to eliminate any oxidising of the junction and its operating temperature range is -50°C to +400°C.

An important issue to be considered with thermocouple measurements is that the signals produced are of the order of millivolts or even microvolts. Amplifying these low-level analogue signals directly in the data acquisition system also amplifies any noise picked up from the signal leads or from within the computer chassis. When the input signal is small, noise can drown out the signal, leading to meaningless data. A simple method was adopted for reducing noise effects for these experiments. A device was used which amplified the signal as close to the source as possible, thus boosting the analogue signal above the noise level before noise in the lead wires or computer chassis could corrupt the signal.

The experimental set-up for temperature measurements is presented in figures 41 and 42. Its only difference with the set-up described in figures 39 and 40 was that a thermocouple was in touch with the torch body, inserted through a hole open in one of the brass clamps.

3.3 Materials

3.3.1 Base Metal

The following materials in the form of tubes were used during this experimental study:

Tube	Outside Diameter (OD) in mm.	Wall Thickness in mm.
1) Ti-3Al-2.5V	10	0.60
2) 316L Aust. S.S	12.7	0.71
2) 316L Aust. S.S	12.7	1.25
3) 316L Aust. S.S	12.7	1.22
4) Water cooled, oxygen free copper tube (10mm OD) for investigation of torch and arc characteristics, on which anode melting did not occur.		

The chemical compositions of the tubes are given in Appendix A.

3.3.2 Plasma, Shielding and Purging gases

Commercially pure argon was utilised as the plasma gas throughout this study due to its excellent ignition capability and its minimal electrode erosion properties. A rubber hose was fixed to the end of a separate PVC tube used to deliver the plasma gas within the torch due to the flexibility required during the rotation of the torch.

Commercially pure argon was also the only gas employed as purging gas for protection of the weld root. A vinyl hose was used for gas distribution, while a simple and effective method of confining the gas under the weld was practised. Plastic covers, readily removed, were placed at each end of the tube, allowing gas to circulate from one end to the other through a small hole at the centre of the cover. At the same time, the view of the inner bead while welding, was not restricted.

Three different shielding gases were used, these were commercially pure argon for titanium melt-in mode welding and austenitic stainless steel melt-in and keyhole mode welding and Ar+5% H₂ and Ar+10% H₂ for austenitic stainless steels keyhole welding.

The various gas combinations employed during this experimental study are presented in Table 11.

3.3.3 Electrode

A 2% thoriated tungsten electrode of 24mm diameter was utilised throughout this study, as only d.c electrode negative operation was envisaged. A 20° vertex angle was used after a preliminary investigation revealed that this angle offered optimum ignition and arc stability characteristics. Before installation, electrodes were cleaned with fine polishing paper (1200 grit SiC) and washed with acetone (CH_3COCH_3).

3.3.4 Constricting Orifice

Thermal Dynamics parallel sided constriction orifices were employed. Orifice diameters used depend upon the tube wall thickness and the current value required. Manufacturers suggested current ratings for different orifice diameters are:

Orifice Diameter	Current Rating (maximum value)
0.56mm	15A
0.79mm	30A
1.17mm	50A
1.63 mm	75A

Fine polishing paper (1200 grit) and acetone were utilised again for cleaning the orifices before their installation and between welding trials.

3.4 Procedures

As already stated this project was performed in two stages; the first one concerns the development of an orbital plasma welding head and is covered in chapter 4, and the second is related to welding, modelling and procedure development.

Test carried out in the second stage could be divided into two distinct phases:

a. Bead on tube autogenous weld tests were carried out throughout the experimental programme, since they simulate closely a real welding joint and also provide accurate results on the influence of welding parameters on weld bead formation and

appearance. Furthermore, such trials are cheap and easy to prepare, and only simple control of the welding torch position is required.

b. Optimised results obtained during the first phase of the experimental work were subsequently transferred to butt joint situations.

3.4.1 Test Tube Preparation

All tubes used for bead on plate trials were cut into approximately 30cm long specimens using a hacksaw. Square groove butt joints were used for the joint trials. Very careful milling was employed for the latter in order to ensure accurate fit. Figure 43 illustrates the joint designs used.

All surfaces were originally abrasively cleaned with fine polishing paper (800 grit) and degreased with acetone before fixing in the orbital head. Cleaning procedures are particularly important for the very small thicknesses employed. Even minor contamination (such as fingerprints) can alter the arc behaviour to such an extent that fusion actually stops in that zone.

Titanium and its alloys are particularly sensitive to adsorbed impurities from the metal surface and to machining finish of the base metal before welding, since investigators discovered that to a large extent porosity depends on these two factors. The presence of hydrogen or oxygen gases can lead to porosity and it has been shown that defects caused by machining the end surfaces of weld edges may trap pore forming contaminants [233-237]. As a control over porosity, the edges to be joined are given special treatments which include draw filling, or abrading the joint edges and adjacent surfaces prior to fit-up, and an acetone or alcohol wash just prior to welding [238]. Such control techniques were adopted during this investigation.

3.4.2 Fitting and Tacking

In butt joints, accurate fitting is essential. Poor fit-up not only increases the possibility of air contamination by making purging more difficult but also increases the possibility of molten metal drop through, particularly when the keyhole welding mode is adopted.

In butt joints, tubes were first tacked at approximately 180° intervals around the tube using GTAW, in order to retain the components in alignment during welding. Special care was taken to avoid any oxidation of the penetration root bead by using argon as backing gas for all materials used, and also surface contamination in titanium by using prolonged post-weld gas flow over the tack weld. Argon was utilised as the shielding gas in all cases.

3.4.3 Clamping

A clamping device incorporating split brass rings to hold the pipe in proper alignment was used (figure 44). Different ring diameters were utilised according to the outside diameter of the tube to be welded.

3.4.4 Electrode Set Back Adjustment

A gauge and wrench assembly was used to adjust the electrode set back. After selecting the proper gauge on the assembly, the gauge is inserted into the front of the torch and pressed until the shoulder of the gauge contacted the torch. The electrode was pressed into contact with the gauge and tightened securely. The above procedure is illustrated in figure 45 for a common plasma torch.

Another procedure adopted, where necessary, was the use of a micrometer to measure the distance between the torch shoulder and the tip of the electrode. The set back distance can be determined by subtracting the measured distance from the orifice thickness.

3.4.5 Electrode Centralisation

The importance of proper electrode centralisation for process stability and performance has been noted in section 2.4.2.6. Failure to properly centralise the electrode led primarily to severe undercut in one side of the weld and also affected the consistency of the obtained results (also discussed in section 5.3.2). An attempt was originally made to obtain accurate alignment with the use of a ceramic sleeve. This proved only partially successful since the high temperatures developed in the electrode resulted in damage to the sleeve after a number of trials. Finally a provision

for pivoting the copper torch around its seat was incorporated in the developed system which allowed electrode centralisation to be accomplished by visual observation of the electrode's position in relation to the orifice duct. It must be noted though that the technique adopted did not provide appropriate accuracy and consistency resulting in the need to frequently check the electrode's position within the nozzle.

3.4.6 Arc Ignition

For all experiments arc initiation was achieved by means of a high frequency discharge, between the electrode and the base material. The use of a pilot arc was avoided after initial experimentation showed that consistent arc ignition was experienced in an enclosed chamber without the use of a pilot arc, even for low current values (e.g. 7A). The power was derived from the main power source which proved to be sufficiently stable for arc ignition at low currents. Using this technique, electrode damage or contamination was eliminated and prolonged electrode life was experienced. This may be attributed not only to the avoidance of touch striking, but also to the inert atmosphere which protects the electrode, while high voltage values required for arc initiation in an open atmosphere due to its high ionisation potential are at the same time reduced. Furthermore, this avoided the additional complexity of a plunger movement required for a touch starting system (see also sections 2.2.4.1, 2.2.5 and 2.2.8 for further information about arc stability, arc starting techniques and arc ignition requirements for low current plasma arcs).

Difficulties did not occur even when the total arc length was set high or the orifice diameter was very small. However, it was found that although the control rack was electronically protected from any damage caused by the high frequency, still such discharge could occasionally affect the control electronics causing the system to crash. Failure to strike an arc was rare, and it was generally associated with failure to achieve a proper argon atmosphere in the head.

3.4.7 Welding Operation

Before starting each trial all relevant process parameters were set (figure 46), including:

- Plasma Segment Details (figure 47)
 - ⇒ Welding Current
 - ⇒ Plasma and Shielding gas flow rates
 - ⇒ Welding Speed
 - ⇒ Duration of each segment
- Electrode set back and torch stand off distances
- Plasma, Shielding and Purging gas compositions
- Purging gas flow rate was the only parameter regulated directly from the gas bottle
- Constriction nozzle diameter
- Plasma Start Details (figure 48)
 - ⇒ Current (Step Current, slope up delay and time)
 - ⇒ Plasma and Shielding gas (Prepurge time, slope up delay and time)
 - ⇒ Rotation (Delay, speed and duration)
- Plasma Stop Details (figure 49)
 - ⇒ Current (Final value, slope down delay and time)
 - ⇒ Plasma and Shielding gas (Postpurge time, slope down delay and time)
 - ⇒ Rotation (Delay, final speed and duration)

Furthermore, a special screen existed in the control software for arrangement of the ignition details (figure 50). Throughout the experimental work plasma ignition details remained the same. These were:

Ignition type:	HF strike
Current:	15A
Arc check time:	0.3sec

The latter is the duration of time after which the system checks to confirm the arc ignition. In the event of ignition failure the weld sequence is aborted.

Up to 16 different segments could be employed, although usually no more than 3 segments were utilised during this study.

After setting the parameters the tube was positioned in the welding head and the torch was moved to the weld start position. The latter remained constant throughout the experimental work (10 o'clock position). All welds were carried out in the 5G position with the torch always moving in the anti-clockwise direction. The "Run Weld" option was chosen from the menu in the control software and the "Select Pass to Run" screen appeared, where the direction of the head rotation was chosen along with the desired pass from a pass list (figure 51). Following that, the screen illustrated in figure 52 was the next to appear, with a summary of the current and welding speed parameters employed in the first segment of the welding sequence. Pressing of the "Go" button resulted in starting of the welding sequence. The placement of voltage sensors on the head and logging of voltage and current transient signals followed arc ignition in most of the experiments, so that the possibility for any damage to the signal conditioning system that can be caused due to the use of the HF ignition was minimised. Figure 53 presents a summary of these sequences.

3.4.8 Test and Analysis Procedures

Inner and outer weld bead measurements were carried out using a Vernier gauge on welded tubes at specific positions along the weld bead, depending on the diameter of the tube under investigation. Undercut was also classified using a number of labels describing different undercut levels.

Metallographic examination was performed on a number of samples in order to determine the soundness of the resultant welds. Specimens were mounted in bakelite and polished on rotating polishing paper (120, 220, 1200 grit SiC) originally and 6, 1, micron diamond dust paste rotating cloth subsequently. Kroll's etchant (1-3ml HF, 2-6ml HNO₃, H₂O to 1000ml) was used for etching Ti-3Al-2.5V specimens, while Marble's etchant (4g CuCl₂, 10ml HCl, 40ml H₂O) was used for austenitic stainless steel specimens. Specimen hardness profiles were evaluated, which is particularly significant due to the sensitivity of titanium welds to contamination and consequent embrittlement. A large hardness increase can be an indication of excessive contamination.

In titanium the colour of the welds indicates, to some extent, the degree of contamination that has occurred, colour was therefore used as an initial indication.

Table 12 indicates the significance of weld colour and the suggested remedies. In all the welding trials only silver colour finish was acceptable. The selection of plasma, shielding and purging gas compositions, shielding and purging gas flow rates, pre and post-purging times was made in order to avoid any surface discolouration.

3.5 Experimental Strategy

Following the design and fabrication of totally enclosed plasma welding head and the investigation of its main characteristics, plasma welding was adopted for treatment of the main quality problems encountered in welding of small diameter titanium and austenitic stainless steel tubes, which are porosity weld variability respectively. In parallel, and in addition to deriving optimum parametric settings, the investigation has been extended to investigate in a systematic manner the influence of the major parameters on the following quality objectives:

- Prevention of inadequate penetration.
- Prevention of contamination.
- Elimination of porosity.
- Prevention of undercut formation.
- Control of weld bead geometry with particular emphasis in the production of controlled internal bead widths.
- Assessment of arc stability for microplasma operations.

Procedural (i.e. off line) control was adopted for identification and optimisation of welding parameters. Since no procedure was available for the proposed welds it was necessary to generate the parameters required for the production of consistent weld profiles.

All experiments were designed with a view to developing mathematical models to correlate independently controllable welding parameters. The first step though, before any experimentation could be planned was to define the quality acceptance criteria. These can be geometrical, mechanical or metallurgical in nature, and analysis can become complicated by their number and variety.

In this study primarily geometrical criteria were utilised, although a large number of specimens were subjected to metallurgical control as well. Furthermore, the geometric profile of the weld bead was used to assess the geometric changes of the bead under different welding conditions, by exploring the relationships between the process variables and each of the geometric performance variables. In practice, these parameters are the control objectives, the responses of the system to the variation of the welding inputs. Two main quality acceptance criteria were used:

- 1. Weld bead dimensional accuracy.**
- 2. Type and seriousness of defects present (full penetration, no burn-through, no porosity, minimum undercut).**

A quantitative approach was used to estimate weld bead dimensional accuracy through inner and outer bead width measurements. Such an approach seemed too difficult to adopt for defect related criteria, where a more subjective qualitative approach was followed. In particular, undercut was very difficult to measure quantitatively due to the different types of undercut that exist and the very small thickness of the examined tubes. The qualitative approach adopted for undercut classification is more extensively described in section 5.3.3.3. However, it was very difficult to give definite defect limits and groupings for the range of thicknesses and diameters employed in the current investigation. A typical industrial weld quality specification from different industrial sources was constructed. This specification, presented in figure 54, was used to assess the quality of the welds produced.

Based on the literature survey, previous experience and initial experimentation, the next step was to identify all those input factors that may affect the process output parameters, which in this case are primarily the quality parameters together with the measured transient signals. Twenty six potentially significant process variables were identified (Table 13), several of them interacting with each other in their effects (see section 5.4 for more information associated with the effect of welding parameters on weld quality in plasma welding). In order to simplify the problem, these parameters were further classified into two main categories:

a. Preset or Background Variables These were decided at an early stage prior to welding and did not vary during the welding operation. They set the framework

within which subsequent experimentation took place. Since these parameters can only be changed in discrete steps they are not prone to unexpected variations during welding.

b. Explanatory Variables. Included in this group were those variables which combined with the preset variables result in full definition of the welding operation and explanation of output variation. These were further divided into "directly controllable" parameters and "observable".

The *directly controllable* parameters are those that can readily effect change in the weld quality, output rate and transient signals (mainly voltage waveforms). *Observable* on the other hand are those that can not be modified on-line during welding.

Another important classification was used for explanatory variables during this study. They were grouped into primary and secondary parameters. *Primary* variables include those factors that exert a major influence on the weld quality and output rate while *secondary* variables are these which have to be changed significantly before they have any major effect on the output parameters.

Grouping of the parameters based on the above classification is illustrated in Tables 14a and 14b. It must be noted that this classification was made for the purposes of the specific investigation and was based on subjective judgement and production practice.

The next step was the development of the actual models which are based on multiple regression analysis techniques in order to gain a better understanding of the process characteristics, three different conditions were examined:

- a) Orbital plasma welding using the melt-in-mode technique on Ti-3Al-2.5V tubes.
- b) Orbital plasma welding using the melt-in-mode technique for 316 austenitic stainless steels tubes.
- c) Orbital plasma welding using the keyhole mode technique for 316L austenitic stainless steels tubes. In this case, a detailed examination on the influence of the shielding gas employed on the resultant weld was also conducted.

The independent process variables chosen as more likely to control the output characteristics described above, were the following:

1. Average Welding Current Employed During the Torch Rotation (HI_1).
2. Welding Speed (WS).
3. Plasma Gas Flow Rate (PGFR).
4. Electrode Set Back (ESB).
5. Orifice Diameter (OD).
6. Heat Input During the Starting Segment (HIS) (Time Period Between Arc Initiation and Initiation of Torch Rotation).
7. Shielding Gas Composition (SGC).

Process variables No: 1, 2, 3, 4, 5, 6 were investigated during model building for Ti-3Al-2.5V tubing while for the other two conditions No: 1, 2, 3, 4, 7 were examined.

Since no procedures were available for the proposed welds a combination of procedure development and model building was carried out. A step-by-step strategy based on "the tolerance box approach" was adopted which made the selection of the next experiment to be carried out important because it was directly related to efficiency and economy. After identifying a suitable plasma gas flow rate and the appropriate current modulation, based on

a: a limited number of pre-screening experiments which revealed acceptable points and, b: experience gained during the course of this study and feasibility studies,

suitable parameter combinations were developed in terms of average current/welding speed combinations. The starting point of the experiments could have proven difficult if the regions to explore first were completely unknown. Consequently, within the developed operational envelopes the influence of other parameter variations (such as plasma gas flow rate, electrode set back distance, shielding gas composition and delay time) on the stability of the process and the quality of the resultant weld were also examined. In addition, further experiments were made in areas containing acceptable welds until the required degree of precision and continuity were obtained and the procedural fields were defined. This approach was considered more efficient than the adaptation of other statistical techniques such as fractional factorial designs, due to

the prototype nature of the system and the consequent lack of any relevant experience related to parameter development using such a system.

It must be noted that only one set of parameters was originally employed at this stage of the research work, in all three conditions examined. Experimental results from parameter combinations which lay within the defined process field were used to provide data for the estimation of the regression model parameters.

In each weld, measurements were taken from predetermined positions in the inner and outer bead depending on the tube diameter (normally every 5mm from the start of the weld), and a group of models were developed, one for every position, providing an accurate representation of the inner and outer bead width along the weld. Observation of these results offered an indication of the programming requirements for a consistent penetration bead size. All models were introduced into a common software package (Excel 5.0) which was used not only to provide a numerical description of the procedural field but also as a welding data base system for optimisation of the appropriate responses under any constraint combination within the developed procedural field.

At the same time, regression models based on subjective qualitative judgement of undercut indicated the expected seriousness of the defect, allowing a further appraisal of the final result to be made.

The flexibility of the software used along with the precise representation of the weld outcome permits the welding engineer to make his own choice for the stringency of the constraints that he wants to apply, as well as the field of the parameters that he wishes to use within the procedural field, for a predetermined desired outcome. Figure 55 illustrates the general concept utilised for model development and process optimisation.

4. Design, Construction and Testing of An Orbital Plasma Welding Head

4. DESIGN, CONSTRUCTION AND TESTING OF AN ORBITAL PLASMA WELDING HEAD

4.1 Introduction

At the beginning of this research work, no research related to totally enclosed-orbital plasma welding head systems had been reported as indicated in the literature survey. Since plasma welding could offer a reliable solution to a number of problems (e.g. porosity in titanium, weld variability in austenitic stainless steels), the possibility of developing such a system, initially for small bore tubes, was investigated.

4.2 Basic Concepts and Constraints in the Design of the Plasma Welding System.

Since a lot of work has been put into developing totally enclosed GTAW orbital welding heads, the main target of this research work was to modify for plasma operations an already existing GTAW head. This would combine the benefits that these systems offer in precise pre-programming and atmosphere control with the advantages offered by plasma welding.

The following criteria were used for the development of the modification:

1. *Weld in all positions (360° positional welding).*
2. *Consistent weld quality*
3. *Simplicity of the modification*
4. *Ease of manufacture*
5. *Minimum alteration to the already existing GTAW heads*
6. *Improved productivity*

Criterion No 5, imposed at the beginning of the investigation proved to be the most important constraint upon the design of the modification and is associated with the fact that the welding head is not property of the University and therefore it was not allowed to pursue permanent head modifications this time. It did not permit the introduction of water cooling channels for cooling of the plasma torch body since this would have required extensive machining and could have caused irreversible damage

to the head. Moreover, the limited space already available for the introduction of the plasma modification, made any external cooling of the rotating torch impracticable and very complicated.

Following this, the two options described below were investigated:

- a) the use of heat pipes and,
- b) the construction of the torch from a material with high heat capacity.

a. Heat Pipes

According to Dunn and Reay [239] the heat pipe is a device of very high thermal conductance, similar in some respects to the thermosyphon. Figure 56a illustrates these two devices along with a representation of their basic operation which follows the same principle. A small quantity of water is placed in a tube from which the air is then evacuated and the tube sealed. The liquid vaporises when the lower end of the tube is heated and moves to the cold end of the tube where it is condensed. In the case of a thermosyphon the condensate is returned to the hot end by gravity. Considerable quantities of heat can be transported with a very small temperature difference from end to end since the latent heat of evaporation is large giving a very high effective thermal conductance to the structure. While for the thermosyphon the condensate is returned to the hot end by gravity, heat pipes have the ability to transport heat against gravity by an evaporation-condensation cycle. This can be achieved by using a wick, constructed for example from a few layers of fine gauze, which is fixed to the inside surface and capillary forces return the condensate to the evaporator. Other forces for condensate return can also be employed in heat pipes, for example centripetal, electrostatic volume and osmotic forces etc.

The performance of a heat pipe is often expressed in terms of "equivalent thermal conductivity". A tubular heat pipe of the type illustrated in figure 56b, using water as the working fluid and operating at 150°C would have a thermal conductivity several hundred times that of copper. By suitable choice of working fluid and container materials it is possible to construct heat pipes for use at temperatures ranging from 4K to in excess of 2300K.

Although this option looked very promising for an orbital plasma welding head since it eliminates the need for an external cooling circuit without any increase in torch size it was considered that extensive evaluation trials were required to decide upon the design and placement of the heat pipes in the torch, while manufacturing the torch would become complicated. Furthermore, the low power levels to be handled at that stage led to the decision to seek more simple ways for effective cooling of the torch. However, it was decided not to exclude the evaluation of such a solution in the future.

b. Use of high heat capacity material

The second available option, was to consider the construction of the torch body from a material that can absorb and extract the heat rapidly and efficiently, thus providing the necessary effective cooling of the outer sheath of the plasma arc. Copper and tungsten are two materials that satisfy the above requirements and could be used as a heat sink, especially when considering that originally, the prototype torch was intended to be used for small bore, small-medium thickness tubes which normally do not require current values greater than 25 amperes. Copper was finally preferred, mainly due to its machinability along with its excellent electrical conductivity which makes it suitable if a pilot arc becomes necessary.

However, it was not known whether the torch tip, which was likely to experience the highest temperatures, was going to be capable of "seeing" the copper mass surrounding it, and which was expected to control its effective cooling. Research work conducted at the same time in the Technical University of Denmark [240] for higher current plasma applications had revealed, through simulation of different torch designs, that cooling of the torch is primarily controlled by the flow rate and the type of cooling media and not by the amount of copper used in the main body. However, the low current requirements for the proposed applications along with the short welding times required for the small bore tubes, led to the decision to perform a low level modification based on the use of copper mass as a coolant and subsequently consider other options (introduction of water cooling channels or heat pipes) if this proved to be necessary.

4.3 "Copper" Cooling of the Orifice.

Before proceeding to the design of the modification an approximation of the required amount of copper had to be made. The estimation was based on a simplified calculation of the heat needed to be extracted by the copper torch body, in order to avoid any orifice damage.

The worst case scenario was examined in which the whole amount of the generated heat would be absorbed by the torch, although previous research work had proved that approximately one third or less of the arc energy was absorbed as heat by the torch. Calculations were based on average parameters identified for circumferential keyhole welding of Ti-6Al-4V tubes (25mm X 1.6mm), which were also considered to be representative for the materials under investigation. These were:

Average Current: 14A
Average Voltage: 26V
Total Arcing Time: 20sec

Using the above parameters the total heat input was found to be:

$$\begin{aligned} \text{Total Heat Input} &= \text{Av. Current} * \text{Av. Voltage} * \text{Total Arcing Time} = \\ &14A * 26V * 20\text{sec} = 7280\text{Joules} \approx 8\text{kJ}. \end{aligned}$$

To assess the amount of copper mass required to absorb that heat the following equation was applied:

$$Q = m * c * \Delta\theta \quad (3)$$

where:

Q: the energy absorbed by the coolant (in J), (8kJ in the current investigation),

m: the required mass of coolant (in kg),

c: the specific heat of the coolant (in J/(kg*K), which is 385J/(kg*K) for copper,

$\Delta\theta$: the temperature difference. It was assumed that the initial temperature was the ambient temperature (approximately 20°C), while the end temperature was arbitrarily considered 600°C. Hence, $\Delta\theta=580\text{K}$.

By replacing the above values to equation (3), it was estimated that the copper mass required was approximately 36g. Since the density of copper is 8.94g/cm^3 , the volume of the necessary copper was estimated to 4.03cm^3 .

The design for the copper torch body is illustrated in figure 57 while figure 58 presents the torch body finally developed and adapted to the orbital welding head. A number of issues related to the characteristics of the torch under development were also examined before proceeding to the fabrication of the modification shown in figure 58, and these are presented below.

4.4 Plenum Chamber

As already mentioned in section 2.2.1 the geometry of the plenum chamber affects the arc through its influence on the flow of the plasma gas. It was decided to use a cylindrical plenum chamber since no other geometry would be more beneficial at that stage. Furthermore, designs other than cylindrical would introduce an extra, unjustifiable manufacturing complexity.

4.5 Introduction of the Plasma Gas in the Plenum Chamber

It was decided to introduce the plasma gas from the side of the torch body for the following two reasons:

- The flexible tube chosen to introduce the plasma gas had to rotate around the metal tube as the weld progressed. Thus, it had to be located in a position which could reduce the possibility of it coming into contact with the hot metal tube for prolonged periods.
- Sidewise introduction of the gas in the plenum chamber was more likely to give a vortex plasma gas flow which, as illustrated in section 2.2.6.1, is beneficial for arc stability.

4.6 Electrical Insulation of the Torch

One of the most important requirements that was originally considered concerned the electrical insulation of the torch from the electrically charged rotor.

Failure to achieve this would result to the torch body being electrically charged, having the same polarity as the electrode. This could not only enhance double arcing conditions but also arc striking between the base metal and various edges based on the torch body, thus leading to serious damage of the torch.

To avoid this, a "Tufnol" layer was placed between the torch body and the rotor. This material combines first class quality electrical insulation for high working temperatures along with good mechanical strength and machinability, all properties necessary for the specific application. Its physical properties are presented in Table 15.

4.8 Torch Assembly Procedure

Different Tufnol thicknesses were machined in order to allow for approximate adjustments of the stand-off distance required for different tube diameters. The selected Tufnol layer was screwed firmly in the rotor. Subsequently the torch body was screwed securely in the Tufnol layer. After selecting the appropriate electrode set-back distance using the procedure described in section 3.4.4 and mounting the electrode tightly in the rotor, a suitable orifice was screwed in the torch body. A screw-in type orifice was used because it can easily be replaced without need for re-centralisation of the electrode, although the heat transfer across such a physical interface was lower than through solid metal. As already mentioned in section 3.4.5, the torch body mounting system gave sufficient clearance to enable accurate x-y position control and hence accurate centralisation of the electrode, which solely relied on the torch assembly procedure. Furthermore, the relative tightness of the tension bolts could be adjusted in order to support the centralisation of the electrode tip in the nozzle. Figure 59 illustrates the whole torch assembly sequence along with the complete design of the modification. In order to extend the diameter range of the tubes that can be investigated with the developed modification very thin Tufnol layers had to be constructed. For these an alternative torch assembly procedure had to be followed, where the torch body was mounted directly to the rotor, using ceramic sleeves to prevent any electrical contact between the rotor and the torch body. This procedure is also illustrated in figure 59. Furthermore, all the parts used for the developed modification are illustrated in figure 60.

4.9 Testing the Torch

4.9.1 Gas Tightness of the Construction

Following the completion of the modification the head was integrated with the recently developed AMOS - Orbital Welding System. Before proceeding to torch testing the assembly was examined for possible gas leakage through the various interfaces of the construction, after establishing that the gas flow delivered from the ISOTEK rack gas controllers was precise. The experimental set-up utilised is presented in figure 61. A calibrated gas flow meter was used for measurement of the actual output flow rate while the gas flow value was set through the control software for a 60sec period. The torch remained in a fixed position (8 o'clock) throughout the experimentation. Significant gas leakage was originally observed, with approximately 65% of the gas escaping through the various interfaces. Results from this investigation are presented in figure 62.

In order to enhance the gas-tightness of the construction a pure PTFE tape designed for sealing threaded joints was placed in the interface between the Tufnol layer and the copper torch body. As this material is chemically inert and can withstand a temperature range of -200°C to $+260^{\circ}\text{C}$ it was suitable for the specific application where particularly high temperatures were expected to be reached. In addition, a PVC electrical insulation tape with good high temperature ageing properties (-5°C to $+105^{\circ}\text{C}$) was placed sidewise at the same interface as illustrated in figure 61. Using the same experimental set-up, new gas flow measurements were conducted. Results obtained indicated that gas losses were reduced to approximately 10% of the nominal input value. The improved results are also illustrated in figure 62.

It must be noted that the indication of the flowmeter was fluctuating ± 0.2 units during the 60sec trial time which in gas flow rate terms is approximately $\pm 0.14\text{l/min}$ fluctuation.

To assess whether the normal flow of the plasma gas was affected by the rotation of the plastic tube during the rotation of the torch, the same experimental set-up was used and the output gas flow rate was observed while the torch rotated.

Significant plasma gas flow rate fluctuation, other than the one originally observed with the stationary torch, was not detected.

It must be noted that the PGFR was regularly calibrated during the course of the investigation (approximately every 100 trials) in order to eliminate gas leakages as possible causes of error.

4.9.2 Effectiveness of Gas Shielding

The effectiveness of gas shielding was not only associated with the shielding gas flow rate but also with the pre-purge and post-purge times. Preliminary trials conducted on titanium and austenitic stainless steel tubes revealed that a minimum of 5l/min shielding gas flow rate along with a 30sec pre and post-purge time was sufficient to produce contamination free outer surfaces providing that all other tube preparation procedures were also followed.

4.9.3 Investigation of the Characteristics of the System

Two major areas related to the characteristics of the modified head were investigated. These were:

1. The temperature rise of the torch very close to the nozzle (see figure 63), along with the influence of the major welding parameters on the heating and cooling of the torch.
2. The relationship between arc voltage and the major welding parameters.

All experiments were conducted using a 10mm outside diameter water cooled copper tube as base metal and with the torch stationary at the 12 o'clock position. The experimental set-up used for these experiments is illustrated in figure 63. Details about how the above characteristics can be related to the design of the torch and the performance of the nozzle along with more details about the torch design are discussed in sections 5.2, 6.2 and 6.3.

Fractional factorial design techniques were used and equations were produced using regression analysis, for the temperature at the tip of the orifice after 60sec arcing time and 60sec and 120sec after the extinction of the arc. Using the results

obtained, heating and cooling curves have been drawn while heating and cooling rates were estimated and compared.

Because arc voltage values can be used as an indication of the energy status of the arc, a whole series of systematic tests were also conducted using the same experimental set-up in order to investigate qualitatively the dependence of arc voltage on:

- Torch Temperature.
- Welding Current.
- Plasma Gas Flow Rate.
- Orifice Diameter.
- Electrode Set Back Distance.
- Shielding Gas Flow Rate.
- Shielding Gas Composition.
- Electrode Angle.

With the exception of the investigation on the influence of torch temperature on arc voltage where a 60sec arcing time period was employed, a 10 sec arcing time was used for all the other conditions, while voltage and current values were continuously recorded. Each trial started only after the head had cooled down to room temperature. Results obtained are presented in both diagrammatic and tabular format in order to determine the influence of the operating parameters on measured voltage. It must be noted that results obtained are only valid for the given geometric arrangement due to the complex interaction between weld torch geometry and gas flow behaviour.

Furthermore visual observation of the arc during the experiments revealed that heating of the torch had minimal effect on the shape of the arc. After each trial the condition of the constricting orifice was also assessed and it was found that unless a procedural error was made its condition remained unaltered. Three such errors were noted, these were:

- a) The use of currents in excess of the suggested operating level for the specific orifice diameter (see figure 64).
- b) The use of an asymmetric arc caused by improper electrode centralisation, which could result in damage of the orifice at the exit and.
- c) Accidental damage.

5. Results

5. RESULTS

5.1 Introduction

This chapter is split into two major parts. The first part (section 5.2) describes the characteristics of the developed plasma torch modification and includes results from the torch testing experimental work (torch temperature and arc voltage measurements and analyses). The second part (sections 5.3 to 5.8) presents the modelling procedure developed for optimisation of the bead geometrical characteristics and the results obtained from its use in three different applications.

5.2 Torch Characteristics

The unique characteristics of the orbital plasma torch (particularly those related to cooling and gas shielding) provoked an extensive investigation of its main features in order to gain a better understanding of the plasma arc properties produced with this modification. Testing procedures have already been described in section 4.9.3.

5.2.1 Temperature Measurements and Analyses

In order to avoid excessive experimentation only the effects of the major process parameters on torch temperature very close to the orifice were investigated using fractional factorial analysis (see section 2.6.1 for more information about factorial design). The collected experimental data were used to develop models by applying regression analysis techniques. Correlation analysis was initially performed in order to identify the potentially significant linear and second order interactions of the input variables, while third order interactions were neglected. However, interacting and power terms which capture possible non-linear characteristics were not included in these models since preliminary statistical investigation indicated that such effects did not exert a significant influence on torch temperature.

Based on observations made by a number of researchers (see sections 2.2.4.1, 2.2.6.1), the following factors were originally considered to be the parameters that exert the greatest influence on the torch heating and therefore, were chosen as independent input variables:

- welding current (HI_1 in A),
- orifice diameter (OD in mm),
- plasma gas flow rate (PGFR in l/min),
- shielding gas flow rate (SGFR in l/min),
- electrode set back distance (ESB in mm),

The following operating parameters were held constant at the levels indicated below:

- | | |
|---|-------------------------------------|
| • Free arc length (torch stand off distance): | 17mm |
| • plasma and shielding gas composition: | commercially purity argon |
| • Polarity: | DC Electrode negative |
| • Prepurge time: | 30sec |
| • Postpurge time: | 60sec |
| • Prepurge shielding gas flow rate: | same as the SGFR during arcing time |
| • Prepurge plasma gas flow rate: | same as the PGFR during arcing time |
| • Postpurge shielding gas flow rate: | 10l/min |
| • Postpurge plasma gas flow rate: | 2l/min |
| • Arcing time: | 60sec |
| • Data logging time: | 4min. and 5sec. (245sec) |

One-fourth of the replica of the full factorial experiment 2^5 was performed. Two levels were chosen because preliminary trials indicated that a linear response was expected over the range of the factor levels chosen. The experimental planning matrix is presented in Table 16. Two trials were made with each set of operating parameters and the tests were performed in a random order as illustrated in Table 17.

A continuous temperature measurement was taken for each trial using the Arcwatch data monitoring system. The data captured comprised 96 windows of temperature measurements in blocks of 512 values. The average recorded temperature

measurements for the two trials taken at 10sec intervals after arc initiation are shown in figure 65.

Correlation analysis results between factors and responses, based on the average temperatures obtained, are presented in Table 18. The positive correlation coefficient for current indicates that it varies in the same way with temperature, in other words current increase results in torch temperature increase. The negative correlation for all the other factors suggests that their increase results in reduction of the torch temperature. Moreover, the very strong correlation between welding current and measured temperatures indicates that current is the predominant parameter in torch heating (as expected). Shielding gas flow rate and electrode set back distance appeared to have the smallest, although still a significant, influence on torch temperature. The qualitative effect of the independent variables on the torch temperature were as expected:

• increasing current	torch temperature increase
• increasing orifice diameter	torch temperature decrease
• increasing plasma gas flow rate	torch temperature decrease
• increasing shielding gas flow rate	torch temperature decrease
• increasing electrode set back	torch temperature decrease

Temperature values were also utilised for the development of mathematical equations which can relate temperature to the independent variables selected. Models have been developed for the following time periods using regression analysis techniques, based on the "least squares" method in order to fit the best line through the set of temperature measurements obtained:

1. 10sec after arc initiation,
2. 20sec after arc initiation
3. 30sec after arc initiation,
4. 60sec after arc initiation, (maximum recorded temperatures),
5. 30sec after arc extinction, (90sec after arc initiation),
6. 60sec after arc extinction, (120sec after arc initiation),
7. 120sec after arc extinction, (180sec after arc initiation),

8. 180sec after arc extinction, (minimum recorded temperature, 240sec after arc initiation).

The following intermediate model structure (see section 2.6.2.2) was adopted for all of the 8 models developed:

$$\text{TEMP}(i) = a_{0i} + a_{1i} \text{WI} + a_{2i} \text{OD} + a_{3i} \text{PGFR} + a_{4i} \text{SGFR} + a_{5i} \text{ESB}$$

where i , which represents the time index in seconds takes values: 10, 20, 30, 60, 90, 120, 180, 240).

The regression coefficients estimated using a 95% significance level are presented for all temperature models developed in Table 19.

5.2.1.1 Testing the Torch Temperature Models

The plot of the residuals against fitted values for all the developed models was initially used to assess the validity of the regression equations. Although a limited number of experiments were employed the assumptions of zero mean, constant error variation, independence, and normality were not violated in any case. Sample plots are illustrated in figure 66. In order to further check the adequacies of the developed models the standard error of estimates (SE), the adjusted coefficients of multiple correlation (R_{adj}), the square of the correlation coefficients (R^2), the F-ratio values and the P values were estimated and are also illustrated in Table 20 (see section 2.6.2.4 for the definition of quantities).

After testing the model against the data used for parameter estimation, it was considered useful to test the validity of the model on new data (the validation samples). The input parameters utilised for the validation sample are presented in Table 20. Temperature measurements obtained using the same data monitoring procedure and technique are illustrated in figure 67 along with the predicted values and the prediction error. It can be observed that the models could predict the torch temperature to an accuracy of $\pm 5^\circ\text{C}$.

5.2.1.2 Prediction of the Torch Temperature Cycle

In order to visualise the effect of the welding parameters on torch temperature cycle, all models were integrated in an Excel 5.0 spreadsheet, where temperatures for intermediate times were calculated by linear interpolation. A representation of the torch temperature field as a function of time was thus obtained for the range of the parameters utilised. Graphical display of the temperature cycle was also provided. Based on observations made from the temperature cycle graphical display, rise and fall temperature rate values were estimated and included in the spreadsheet for four different time periods, over which a noticeable change was identified. Furthermore, the temperature rise and falling rates for the whole arcing period were assessed. All estimated rates are presented below:

1. General rise rate for the whole arcing time.

$$R_t = (T_{60} - T_0) / 60$$

2. For the first 20sec of the arcing time.

$$R_{20} = (T_{20} - T_0) / 20$$

3. For the final 40sec of the arcing time.

$$R_{60} = (T_{60} - T_{20}) / 40$$

4. General falling rate for the whole post-arc period (180sec).

$$F_t = (T_{240} - T_{60}) / 180$$

5. For the first 60sec of the post-arc period (the postpurge period).

$$F_{60} = (T_{120} - T_{60}) / 60$$

6. For the final 180sec of the post-arc period where there is no gas flow rate.

$$F_{180} = (T_{240} - T_{120}) / 120$$

Sample screenshots from the developed spreadsheet are illustrated in figure 68.

5.2.1.3 Influence of the Major Input Parameters

Using results obtained from the developed models the individual influence of the five input parameters investigated was further assessed (see figures 69a to 69d). It could again be identified that welding current is the predominant influential factor on torch temperature. This was also indicated from the way that rise and fall rates varied with current variation (see figure 69a). Orifice diameter also exerted a significant

influence on torch temperature, with higher temperatures recorded when the smaller orifice diameter was used (0.56mm). Although torch temperature falls as PGFR, ESB and SGFR increase, the influence of all these parameters on the torch temperature cycle is very small (see figures 69b, 69c and 69d respectively).

It was also noticed that as the torch heated up the temperature rise rate was gradually decreasing which can be considered an indication of decreasing heat absorption efficiency which can subsequently result in double arcing conditions.

A final general remark was that cooling rates were very small, particularly after the end of the post-purge period and prolonged periods were required for torch cooling to room temperature, thus significantly reducing the duty cycle of the modification.

Two trials were also performed using Ar+5%H₂ as shielding gas in order to investigate the influence of shielding gas composition on torch temperature cycle. The torch temperature was recorded for 130sec (60sec arcing time, 70sec post purge period). Results obtained (illustrated in figure 70) indicate that, although some of the most adverse welding conditions were employed, recorded temperatures were within reasonable limits and did not exceed 220°C, which is well below the melting point of the copper.

During the course of the experimentation, visual observations of the arc stability along with the appearance of the orifice and torch modification were made. In general no problems were encountered for the range of parameters that were employed. A very stable arc was obtained, while the general torch and orifice appearance remained unaffected.

5.2.2 Voltage Measurements

Before proceeding to the presentation of the results it must be noted that results are repeatable to within about ± 0.5 Volts. The variations may be attributed to electrode and orifice condition as well as small variations of the torch stand off distance, due to abnormalities on the water cooled copper tube.

Two different shielding gas compositions (pure argon and Ar+5%H₂) were investigated in a manner already described in section 4.8.3. Due to limited gas supply the investigation of Ar+5%H₂ was restricted to two orifice diameters (0.56mm and 0.79mm) while only the influences of welding current (HI_1) and shielding gas flow rate (SGFR) were investigated.

5.2.2.1 The Arc Voltage-Torch Temperature Relationship

The influence of torch body temperature on arc voltage was examined; three trials were made, using a 30sec arcing period and fixed operating conditions. The results obtained (presented in figure 71), revealed a small gradual reduction in the arc voltage during the arcing period for both shielding gases which was less than 1V in any case.

5.2.2.2 The Arc Voltage-Orifice Diameter Relationship

Although there is a wide range of orifice diameters available, four different orifice diameters suitable for the current range of the developed equipment were examined with pure argon as a shielding gas. The major problem encountered was that with the present experimental set-up simultaneous adjustment of both set-back (ESB) and stand-off distance (SDT) was very difficult and needed alteration of the Tufnol layer utilised. Frequent changes and re-adjustments of the torch could affect the consistency of the measured values mainly due to the need for re-centralisation of the electrode. Therefore, all trials were performed using the same torch configuration and the same total arc length and, since variations of the ESB and SDT were marginal for three out of the four orifices employed (as illustrated in figure 72) comparative results could be acquired.

The results obtained are presented in figure 73. It can be observed that arc voltage decreases as orifice diameter increases. The influence of the orifice diameter was, as expected, significant. The limited number of the results obtained indicated a non-linear relationship between arc voltage and orifice diameter.

Plasma gas flow rate did not have a significant effect on the voltage-orifice diameter relationship (as also shown in figure 73). However, a slight systematic increase in the arc voltage value could be noticed with PGFR increase.

5.2.2.3 The Arc Voltage-Electrode Set Back Relationship

Richardson showed for electrodes placed inside the parallel sided portion of the orifice that ESB distance exerts a significant influence on the effective nozzle constriction and resultant plasma gas flow patterns and therefore suggested that it is not possible for this parameter (and electrode angle too) to be independently examined [37]. However, since the electrode was consistently placed outside the parallel sided portion of the orifice, the variation of electrode set back could also be examined.

Results obtained are presented in figure 74. Although, for the reasons mentioned above, it was not possible to draw any general conclusions it could be observed that an almost linear relationship between arc voltage and ESB exists. The results also indicated a small influence of the PGFR on arc voltage for the ESB distances utilised. A slight arc voltage increase could again be observed with PGFR increase.

5.2.2.4 The Voltage-Electrode Angle Relationship

Two electrode angles were examined as can be seen from the results presented in figure 75. However, based on the same arguments presented in 5.2.2.3, only qualitative results could be extracted.

From the diagram illustrated in figure 75, a slight decrease of approximately 0.5V in the arc voltage value for both orifice diameters examined can be noticed as electrode angle (EA) increases. Also a small but nevertheless systematic voltage increase was observed as PGFR increases. However, it was once more observed that PGFR did not have any significant influence on the recorded voltage values.

5.2.2.5 The Voltage-Welding Current Relationship

Results reported here refer to investigation conducted on two different orifice diameters (0.79mm and 1.63mm). The parameters used and results obtained for pure argon are illustrated in figure 76.

It can be observed that the curves have similar forms to those of GTAW arcs. A minimum is apparent at approximately 20A, with a negative gradient for lower than 20A current values and a positive for higher than 20A current values also evident. It can also be observed that the gradient of the positive arm of the curve is smaller than that for the negative arm for both orifices. Also both positive and negative arm gradients of the 0.79mm diameter orifice are slightly greater than the 1.63mm diameter orifice gradients.

Finally, the limited number of the available data (mainly due to orifice current limitations) makes any assessment concerning the linearity of all arms difficult, although the higher current arm seems to follow a more linear behaviour.

Figure 76 also illustrates the results obtained with the use of Ar+5% H_2 and the 0.79mm OD. The curve has the same general form as the one produced with pure argon as shielding gas (i.e. negative slope for low currents, positive slope for high currents), with a weak minimum appearing at about 20A in each case. A comparison between results obtained with both Ar and Ar+5% H_2 as shielding gases indicated an approximately 5V increase when the latter was used although direct comparison of the results was not possible since some of the control parameters varied (see also figure 76).

An approximately 5V arc voltage increase was also noticed compared to experiments made with pure argon as shielding gas when the 0.56mm OD was utilised with the Ar+5% H_2 (see figure 76). The limited number of data that were acquired due to the narrow current range of this orifice (15A maximum permissible current value) also revealed a minimum at about 10A.

5.2.2.6 The Voltage-Plasma Gas Flow Rate Relationship

Four different orifices were examined during this investigation and results obtained resemble those acquired during the "Voltage-OD", "Voltage-ESB" and "Voltage-EA" investigations, with the influence of PGFR also assessed.

The results obtained (illustrated in figure 77) show an approximately linear dependence of voltage on plasma gas flow rate for all four orifices. Arc voltage increased almost linearly as PGFR increases for all orifices utilised. Although differences obtained were very small and within the range of the experimental error, their systematic nature allowed the above general conclusions to be extracted.

Finally, it was noticed that the copper orifices were sufficiently thermally protected with the PGFR levels utilised. Moreover, the arcs produced were reasonably stable even for prolonged arcing periods, particularly when the lower PGFR values were employed.

5.2.2.7 The Shielding Gas Flow Rate-Arc Voltage Relationship

Two shielding gas flow rates (10 and 15l/min for pure argon and 7 and 14l/min for Ar+5%H₂) were investigated using two different orifice diameters (0.79mm and 1.63mm) and a number of current values. The acquired results indicated that the SGFR did not have any significant effect on the arc voltage (see figure 78). The same trend was followed with current variation for both SGFRs examined (see also figure 78). Furthermore, the influence of welding current on arc voltage could again be examined and similar results were obtained to those acquired in section 5.2.2.4. Due to the characteristics of the torch design this aspect is discussed in more details in section 6.3.6.

Results obtained using Ar+5%H₂ as shielding gas also the influence of SGFR was insignificant when the 0.79mm OD was employed. However, a notable voltage decrease as SGFR increases was observed for all three different current values used when the 0.56mm OD was utilised (see figure 78).

5.3 Model Development for Plasma Welding

5.3.1 Limitations and Sources of Error of the Equipment Utilised.

Before proceeding to the actual model development it is considered necessary to describe and assess some limitations and difficulties associated with the equipment, other than the accurate centralisation of the electrode and the requirement to avoid using very high current values in order to avoid torch damage (greater than 30A approximately, although there is not a definite maximum upper limit) due to the characteristics of the plasma torch.

- One of the major problems encountered was the sudden, small decrease of the stand-off distance at the 2 o'clock position (approximately 0.2mm) also linked with a small delay of the motion of the rotor. The effect of stand-off distance on weld bead characteristics is discussed in more details in section 2.4.2.8. It was estimated that the stand-off distance was gradually recovered reaching its original value at the 10 o'clock position approximately (for an anti-clockwise motion of the rotor). Therefore it was decided to place this part at the end of the welding sequence, only affecting the last two positions from where measurements have been taken in all the tubes examined (see figure 79).
- The accuracy of the bead width measurements obtained using a Vernier was $\pm 0.1\text{mm}$. However, it must be noted that due to the shape and the small size of the bead widths the identification of their edges was subjective and this could also lead to another source of error.
- Although ignition current was fixed at 15A, current measurements recorded indicated that in many cases much higher current values have been delivered (see figure 80).

5.3.2 Experimental Data

As already described in section 3.5 the primary objective was to collect experimental data that would be used for model development while identifying the operational envelopes and developing procedures for the proposed welds. This strategy resulted in a rather poor experimental design which nevertheless proved to be very successful in revealing the principal relationships between welding variables and bead

widths, offering at the same time a reliable prediction capability for the process (see section 3.5 for the experimental strategy).

Once the electrode was properly centralised, experimental blocking techniques were employed (see section 2.6.1) related to the investigation of the Electrode Set Back (ESB) distance, so that frequent re-centralisation of the electrode which can become a significant source of error with the current experimental set-up could be avoided. A consistent electrode centralisation proved to be absolutely vital when the keyhole mode was utilised. Even small variations could lead to completely different results for the same parameter combinations (e.g. cutting instead of keyhole welding). The melt-in-mode proved to be more tolerant to variations in electrode centralisation although variations to the bead width characteristics investigated (particularly the inner bead width) were again observed. The problem became significant when conditions close to the edge of the tolerance envelope were utilised (no fully penetrated welds instead of fully penetrated). Therefore "Experimental Blocking" was essential in order to increase the homogeneity of the experiments.

One trial was made for each set of operational parameters employed. The trial was repeated only if a malfunction of the system or an arc instability was detected during each welding sequence.

Initially, two sets of operational parameter values (two segments) were employed, the first for arc striking and tube preheating while the torch remained stationary and the second for the production of the weld bead around the tube. Sloping down of the current, welding speed and plasma gas flow rate was not employed during the model building stage of this study in order to avoid possible effects on the bead characteristics at the end and at the beginning of the weld while investigating the influence of the main welding parameters. However, it was utilised during the production of butt joints and it was more thoroughly examined during the keyhole welding investigation due to its greater influence on the final weld characteristics with this mode. Sloping up was not considered necessary during the arc initiation phase for any of the input parameters for the same reasons as described for sloping down, although it was subsequently shown that it might be very important in the keyhole mode (see section 5.3.1.3). In general, the research work was primarily

focused on developing stable and consistent welding conditions around the circumference of the tube.

Current pulsation using high thermal pulsing frequencies (of the order of 10Hz) was utilised throughout the research work due to the significant advantages offered by pulsed current in penetration, melting efficiency and tolerance of the procedures for both melt-in and keyhole mode of operation (see section 2.4.2.1). Furthermore, the use of high thermal pulsing frequencies was necessary since it has been identified during the feasibility studies that lower frequencies could not provide a uniform and smooth weld bead for the whole welding speed range examined during this investigation as intermittent stitches were obtained for the higher welding speeds.

Outer and inner bead width measurements were taken from a number of positions along the weld bead using the starting position as a reference point. These positions are illustrated in figure 81 for all three tubes investigated. In addition, a qualitative assessment of the undercut produced was also made for the keyhole welds which will be described in section 5.5.2.2.

5.3.2.1 Melt-in Welding of Ti-3Al-2.5V

High thermal pulsing frequencies (9Hz and 10Hz) were chosen for the welding procedure. The peak and background times for each pulse period were fixed at 50ms each, with only a limited number of trials using different values.

The investigation was based on the examination of the following parameters for both orifice diameters (0.56mm and 0.79mm):

1. **Average welding current used during the second segment (HI_1).**
2. **Welding speed (WS).**
3. **Plasma gas flow rate (PGFR).**
4. **Electrode set-back distance (ESB).**
5. **Total heat input during the first segment expressed as a product of the delay time and the average current value of the first segment (HIS).**

The following parameters were kept constant throughout the experimental work:

- | | |
|---|--------------------------|
| 1. Plasma, Shielding and Purging gas composition: | commercial purity argon. |
| 2. Shielding Gas Flow Rate: | 10l/min. |
| 3. Purging Gas Flow Rate: | 3l/min. |
| 4. Polarity: | DC Electrode negative. |

All the welding conditions used and the responses obtained are presented in Tables 21 and 22 for the 0.56mm OD and the 0.79mm OD respectively. Based on values from the above tables the general experimental envelopes (presented in figures 82 and 83) were plotted using the "average current-welding speed" combinations utilised. Both figures are split into two major areas, the "full penetration" and the "incomplete penetration". The "maximum welding speed" constraint occurs due to the heads characteristics and the "maximum current" constraint due to orifice characteristics (for the 0.56mm OD), and these are also illustrated.

5.3.2.2 Melt-in Welding of 316L Stainless Steels

During this investigation only one orifice diameter was examined (0.79mm). Furthermore, the influence of the "total heat input during the arc initiation phase (1st segment)" on the weld bead characteristics was not investigated since preliminary experiments revealed that prolonged "delay times" combined with relatively high current values (approximately greater than 11A) can result in rupture of the weld pool and hole formation. The latter was attributed to the fast heating of the starting area due to the relatively low thermal conductivity of the austenitic stainless steels compared to Ti-3Al-2.5V. High thermal pulsing frequency was again used (25Hz current pulsation in almost all trials, peak current time: 20msec, background current time: 20msec)

Therefore, the investigation was restricted to the following input parameters:

1. Average welding current used during the second segment (HI_1).
2. Welding speed (WS).
3. Plasma gas flow rate (PGFR).
4. Electrode set-back distance (ESB).

The following parameters were kept constant throughout the experimental work:

- | | |
|---|--|
| 1. Plasma, Shielding and Purging gas composition: | commercial purity argon. |
| 2. Shielding Gas Flow Rate: | 10l/min. |
| 3. Purging Gas Flow Rate: | 3l/min. |
| 4. Polarity: | DC Electrode negative. |
| 5. Average Starting Current: | 15A (I_p : 25A, I_b : 5A, t_p : 50ms, t_b : 50ms) |

All the welding conditions used and the responses obtained are presented in Table 23. Due to the significant influence of the material characteristics (i.e. weld variability problems) and the PGFR on the output values obtained (for the PGFR range utilised), the construction of the general experimental envelope using values from Table 23 based on the "average current-welding speed" combinations was rather difficult and of little practical value. Therefore, figure 84 presents only the general experimental grid showing the "full penetration", "incomplete penetration" and "hole formation" average current-welding speed combinations which reveal the considerable overlap between these areas.

5.3.2.3 Keyhole Welding of 316L Stainless Steels

The keyhole mode of operation did not allow the influence of the total heat input before initiation of the rotation of the torch on the bead characteristics to be examined since prolonged delay times could result in weld bead rupture while a short delay time could inhibit the keyhole formation. Thus, fixed starting conditions offering a consistent keyhole formation were developed and kept constant throughout the experimental investigation. However, the lack of current slope up during this phase of the study, resulted occasionally in the expulsion of a small amount of weld metal during formation of the keyhole. Problems related to keyhole opening and closure were examined in a subsequent stage (see section 5.5.7). Originally, the research was focused on developing stable and consistent keyhole welding conditions around the circumference of the tube.

Pre-screening experiments revealed that the appropriate current range was around 18A. Since the keyhole mode is particularly sensitive to the orifice diameter,

mainly due to its influence on arc pressure, it was decided to use only the 0.79mm diameter orifice as this offered the more suitable current range for the specific investigation (up to 30A).

Apart from the benefits described in section 5.3.2, high thermal pulsing frequency (current pulsation 25Hz) was utilised throughout the experimental work in order to obtain and sustain a stable keyhole for the whole wide range of welding speeds employed (see section 2.5.2B). Peak and background current times were fixed at 20msec. However, the influence of pulse frequency was independently investigated due to its significant effect on keyhole formation and weld bead characteristics (see section 5.5.7).

The following parameters were examined during this investigation:

1. **average welding current used during the second segment (HI_1),**
2. **welding speed (WS),**
3. **plasma gas flow rate (PGFR),**
4. **electrode set-back distance (ESB).**

The following parameters were kept constant throughout the experimental work:

- | | |
|---|--|
| 1. Plasma, Shielding and Purging gas composition: | commercial purity argon |
| 2. Shielding Gas Flow Rate: | 10l/min |
| 3. Purging Gas Flow Rate: | 3l/min |
| 4. Polarity: | DC Electrode negative |
| 5. Average Starting Current: | 16.5A (I_p : 28A, I_b : 5A, t_p : 20ms, t_b : 20ms) |

The influence of shielding gas composition was also separately investigated in section 5.5.5 using Ar+H₂ mixtures since, as already noted, hydrogen additions exert a significant influence on both weld bead and arc characteristics (see sections 2.4.24 and 5.2.25)

Welding conditions used along with the responses obtained (weld bead measurements and undercut classification) are presented in Table 24. Using these values the general experimental envelope (presented in figure 85) was plotted based on "average current-welding speed" combinations utilised. The envelope also indicates

the areas where stable keyhole welding can be achieved. It can be observed that the boundaries between the three major welding condition groups (i.e. stable keyhole, cutting, unstable keyhole - melt-in mode) are rather vague due to the influence of the material characteristics and the other welding parameters (primarily PGFR) on weld bead formation and keyhole stability respectively (see also sections 6.4.3, 6.5).

5.3.3 Modelling Procedure

Modelling equations for the inner and outer bead widths were produced for all three tubes investigated using the experimental results presented in the previous sections. The main target was to produce mathematical expressions where all the useful part of the information contained in the experimental data would be included, permitting easier handling and interpretation of the results obtained. This offered the possibility of solving the equations for sets of input variables which have not been directly observed, thus limiting the large number of experiments required for a fact-finding exploration to just a few necessary to confirm the validity of any hypothesis made. In fact more data can be generated using the produced equations than has been used for the development of the models.

All models were developed using results from welds fully penetrated (for the melt-in mode) or welds for which stable keyhole conditions were obtained throughout the circumference (for the keyhole mode), regardless of whether or not the bead widths obtained were within the specification. Non fully penetrated welds or loss of the keyhole even for a fraction of the circumference, resulted in the exclusion of the specific trial from the modelling process.

The Excel 5.0 statistical software package was used for data analysis and estimation of the coefficients for the developed equations. Multiple linear regression analysis techniques using the "least squares" method were employed. The welding parameters were chosen as the independent variables while the inner and outer bead widths along with the undercut type in keyhole welding as the dependent variables. The intermediate structure model was adopted again for all the developed models (see section 2.6.2.2) while a 95% significance level was used for the estimation of all the regression coefficients. It must be noted that such a model structure implies linearity between the parameters finally included in the equation and the output characteristic investigated. Although for a complex process like plasma welding this can be

considered a simplification, it can be assumed that this is valid for the parameter range utilised.

Although different models were considered, preference was given to the simplest general form that could offer the best representation for all the welding positions along with an easier interpretation (section 6.4.2 discusses this point to a greater extent). In order for the linear regression models employed to account for any non-linear process characteristics various interacting and power terms were originally considered for inclusion in the models. Only the significant interaction between welding current and welding speed which is a way of expressing heat input was finally introduced (see also section 6.4.2 for discussion of this point). Some of the independent values (mainly ESB) proved to have little or no influence on the dependant variables exhibiting mixed behaviour (both positive and negative regression coefficients). However they were included in the model equation due to their significance as major process characteristics.

Subsequently, all the developed equations were integrated in a single spreadsheet and the influence of the input parameter variations over the length of the weld was evaluated. Widths for intermediate bead positions were calculated by linear interpolation. Despite the rotor problem encountered towards the final phase of the weld (see section 5.3.1) this combination provided a relatively accurate representation of the weld bead characteristics in all three cases which was one of the main targets of this research work. In addition, the effect of the input variables on the fusion zone area as well as on the inner/outer bead width ratio was also evaluated. The assumption was made that the fusion zone area for all three tubes can be estimated by the following equation which gives the trapezium area:

$$FusionZoneArea(mm^2) = \frac{OuterBeadWidth(mm) + InnerBeadWidth(mm)}{2} * TubeThickness(mm)$$

It must be noted that due to the wine glass shape of the fusion zone in keyhole welding, the estimated fusion zone area results can only be used qualitatively.

It was generally observed that welding current and welding speed were the two predominant factors (along with PGFR in melt-in mode welding of 316L tubes).

However, a detailed description on the influence of the welding parameters on the bead characteristics will be made in section 5.5 for each input parameter individually.

5.3.3 Melt-in Welding of Ti-3Al-2.5V

The following expression was finally used for the outer and inner bead widths:

$$\text{OBW}(i) \text{ [or IBW}(i)\text{]}: b_{0,i} + b_{1,i}\text{WI} + b_{2,i}\text{WS} + b_{3,i}\text{PGFR} + b_{4,i}\text{ESB} + b_{5,i}(\text{HIS}) + b_{6,i}(\text{HI}_1/\text{WS})$$

where $i=3, 8, 13, 18, 23, 28$

Tables 25a and 26a show the multiple regression coefficients obtained for each outer bead width position while tables 25b and 26b for each inner bead width position for the 0.56mm and 0.79mm OD respectively. Tables 25c and 26c present the ranges of input parameters utilised for the development of the models for the 0.56mm and 0.79mm orifice diameters respectively. It can be observed that some of the experimental combinations included in the linear regression process were left outside the operational range. These were associated with:

- very low plasma gas flow rates ($<0.3\text{l/min}$) and,
- very low delay time-average starting current products during the starting segment ($<20\text{sec}\cdot\text{A}$).

These were excluded for practical purposes since poor process stability was observed for these two experimental conditions and as a result the obtained results did not exhibit the required repeatability.

It must also be noted that the estimated coefficient values along with their statistical indexes (P-values and t-values) acquired during the regression analysis procedure both indicated that the influence of PGFR and ESB was insignificant. The same criteria also indicated that the total heat input during the first segment exerted significant influence only on the inner and outer bead widths at position 3.

5.3.3.2 Melt-in Welding of 316L Stainless Steel

Outer and inner bead widths were expressed as follows:

$$\text{OBW}(i) \text{ [or IBW}(i)\text{]}: c_{0,i} + c_{1,i}\text{WI} + c_{2,i}\text{WS} + c_{3,i}\text{PGFR} + c_{4,i}\text{ESB} + c_{5,i}(\text{HI}_1/\text{WS})$$

where $i=3, 8, 13, 18, 23, 28, 33$

Table 27a and 27b show the multiple regression coefficients obtained for the outer and inner bead width positions. Table 27c presents the range of input parameters utilised for the development of the models. Again ESB had insignificant influence on weld bead characteristics while PGFR was proved both statistically and physically to exert significant influence on the geometric characteristics investigated (details about the PGFR influence on weld bead characteristics are discussed in section 6.3.2).

5.3.3.3 Keyhole Welding of 316L Stainless Steel

The same expression was again adopted for all the welding positions and for both output characteristics investigated, outer and inner weld bead width and undercut index for the outer bead. This is the following:

$$\text{OBW}(i) \text{ [or IBW}(i)\text{]}: d_{0,i} + d_{1,i}\text{WI} + d_{2,i}\text{WS} + d_{3,i}\text{PGFR} + d_{4,i}\text{ESB} + d_{5,i}(\text{HI}_1/\text{WS})$$

where $i=3, 8, 13, 18, 23, 28, 33$ and

$$\text{Ind[UND]}: e_{0,i} + e_{1,i}\text{WI} + e_{2,i}\text{WS} + e_{3,i}\text{PGFR} + e_{4,i}\text{ESB} + e_{5,i}(\text{HI}_1/\text{WS})$$

where $i=8, 18, 28$

Tables 28a and 28b show the multiple regression coefficients obtained for each outer and inner bead width position respectively.

It must be noted that a number of current/welding speed combinations for which stable keyhole conditions were achieved were excluded from the modelling procedure due to the significant influence of minor plasma gas flow rate and/or electrode set back variations upon them which could even lead to catastrophic failure of the joint (i.e. cutting). As expected, these trials were associated with welding

current/welding speed combinations close to the "stable keyhole" boundaries of the operational envelope due to the combine effect of electromagnetic forces and gas flow effects on keyhole formation and stability (see also sections 2.5.2A, 6.4.3, 6.5). The parameter range utilised in the modelling procedure is presented in Table 28c. However, Table 28c still includes some parametric combinations that were prone to cutting due to the shape of the operational envelope. These are the following:

1. $HI_1 > 19A$ and $WS < 2mm/sec$.
2. $HI_1 > 20.5A$ and $WS < 2.3mm/sec$.
3. $HI_1 > 21.5A$ and $WS < 2.7mm/sec$.

An initial evaluation on the effect of the input variables on the four quality outputs (Outer bead width, Inner bead width, Fusion Zone area, Inner/Outer bead width ratio) indicated that current and welding speed were the two most influential factors, while the influence of ESB and PGFR proved to be insignificant and no consistent trend was found.

Probably the major problem observed in the welds produced was the occurrence of undercut. The great complexity of the phenomenon made the development of a quantitative assessment on the influence of the process variables on undercutting difficult. It must be noted that this difficulty is further enhanced in orbital welding due to the continuous alteration of some of the forces (particularly the gravitational force) that influence the weld pool shape along with the influence of heat build-up. Furthermore, one of the main factors restricting the development of quantitative models for both undercut depth and undercut area, was the very small thickness of the examined tubes. The latter made the quantitative assessment of undercut depth very difficult. Techniques originally employed for measurement of undercut area, such as measurement of the imprint area of the weld, produced by plasticine and further magnified several times using a projector, proved to be inaccurate.

This investigation focused on a qualitative assessment of the influence of independent variables on undercut formation and also an appraisal of the undercut risk associated with the large number of parameter combinations employed. The end result was the development of models for this vague and imprecise phenomenon using regression analysis techniques, based on fuzzy functions that could provide a more

flexible indication of undercut than conventional logic. It must be emphasised that the developed models are a measure of risk of undercut formation and therefore must only be treated as a "possibility". The rules applied were based on personal practical experience and on observations made of the weld profile in association with the parameter combinations utilised. The coding presented at Table 29a was constructed for practical purposes, based on the type and seriousness of the undercut produced. The five labels utilised were expected to give a reasonable resolution in the resultant fuzzy regression equations. Classification of welding areas into different categories was again made according to subjective judgement and based on the criteria illustrated in Table 29a. It is presented in Table 24 for positions 8, 18 and 28.

Cutting was also included, which, together with label 0.5, was associated with excessive heat input. The latter, combined with excessive arc pressures primarily produced with high current values, resulted in melting through. Label -0.5 was primarily associated with lower heat inputs and therefore faster solidification rates. The latter resulted in the "tramline" effect, illustrated in Table 29a, and also in the formation of a sharp recess on the sides of the fusion zone. This was also related to a "high arc pressure and low heat input" combination produced with high current, high welding speed combinations. Label -1 refers to the same types of undercut but more pronounced in appearance.

Table 29b shows the multiple regression coefficients obtained for the three outer bead width positions investigated while table 29c presents the parameter range over which the developed undercut models are valid.

It must be noted that there are a number of other parameters that significantly affect undercut formation such as plasma gas flow rate, stand-off distance, orifice diameter and welding position (see sections 2.4.3.5, 2.5.2A). It is the author's opinion that heat input, which is mainly associated with welding current which in turn controls the arc pressure, and welding speed played the most significant part in undercut formation for the parameter range utilised and the materials employed during this investigation. Furthermore, these parameters are more easily controllable. It must also be emphasised that the continuous alteration of gravitational forces and the heat build-up also exerted a significant influence on the weld bead formation in orbital welding, but their influence was very difficult to assess directly.

It was subsequently determined, through correlation of the specimens with the output of the developed models and diagrams plotted for predicted versus actual values (see section 5.4.3.3), that for each label the following membership function identifies properly the range of input values that correspond best to it:

TYPE 1: $-0.10 \cdot \text{Ind(UND)} \times +0.10$

TYPE 1-2: $-0.20 \cdot \text{Ind(UND)} \times -0.10$

TYPE 2: $-0.60 \cdot \text{Ind(UND)} \times -0.20$

TYPE 2-3: $-0.80 \cdot \text{Ind(UND)} \times -0.60$

TYPE 3: $\text{Ind(UND)} \times -0.80$

TYPE 1-4: $0.10 \cdot \text{Ind(UND)} \times 0.20$

TYPE 4: $0.20 \cdot \text{Ind(UND)} \times 0.60$

TYPE 4-5: $0.60 \cdot \text{Ind(UND)} \times 0.80$

TYPE 5: $0.80 \cdot \text{Ind(UND)}$

It can be observed that the label regions do not define boundaries where each label applies fully on one side of a cut-off and not at all on the other. There is a region where values gradually change from being fully applicable to completely inapplicable, a fact which was also indicated from comparison of the predicted and obtained values (see section 5.4.3.3). However, due to the fact that coding was based on personal observation, the extent of these areas - and thus the shape of the membership functions for each label - is somewhat subjective.

5.4.3 Model Testing

Several considerations were used in order to examine the adequacy of the models developed. R^2 , Radjusted, Standard Error, F-ratio and P values were calculated for all developed models. Very high Radjusted values (greater than 0.80 in most cases) and very low F values were obtained (less than 0.00000). These indicated that good model fits were achieved and that a linear relationship between the responses and the input variables included in the models existed for the parameters range investigated. Furthermore, predicted versus obtained values and residuals versus predicted values were also plotted. The latter is used in order to examine whether a uniform distribution of residuals along the zero value is obtained and whether the residuals can be contained in a horizontal band which also reveals obvious model defects. These indicated that all the developed models were adequate, exhibiting good fit. Nevertheless, a new series of trials using "fresh" parameter combinations was conducted for each tube, in order to confirm the adequacy of the developed group of models. The majority of the results lie within the range involving the predicted value

plus or minus the standard error of the corresponding regression equation. The prediction error (ϵ) defined as :

$$\epsilon = \text{Actual Value} - \text{Predicted Value}$$

was also estimated. It was thought that the above way of expressing prediction error is more useful from a practical perspective compared with the percentile error expression:

$$\epsilon = [(\text{Actual Value} - \text{Predicted Value}) * 100] / \text{Actual Value}$$

5.3.4.1 Melt-in Model for Ti-3Al-2.5V

R^2 , Radjusted, Standard Error, F-ratio and P values for models developed for both orifice diameters are presented in Tables 25a, 25b and 26a, 26b. Sample plots of predicted versus measured values and residuals versus predicted values are also presented in figures 86a and 86b for the 0.56mm and 0.79mm orifice diameters respectively.

Ten more trials were made, five for each orifice diameter for validation purposes. Parameters used and results obtained are shown in Tables 30a and b respectively for the two orifice diameters used.

It can be seen that the models could accurately predict the bead width characteristics of the welds. The maximum absolute prediction error was 0.14mm for both outer and inner bead widths when the 0.56mm orifice diameter was utilised (see Table 30a) and 0.19mm when the 0.79mm orifice diameter was used (see Table 30b). Moreover, in most cases the prediction error was less than 0.1mm.

5.3.4.2 Melt-in Model for 316L Stainless Steel

Tables 27a and b present the statistical values utilised for model adequacy checking. It can be observed that the accuracy of all models (particularly for the outer bead widths) is lower (although still satisfactory) compared to values obtained on Ti-3Al-2.5V tube welding. Furthermore, sample plots of the residual against fitted

values and predicted versus measured values (presented in figure 87) also indicated that good model fits were obtained.

Trials made using fresh data showed a maximum absolute prediction error of 0.28mm (position 3) for the outer bead width and 0.14mm (position 23) for the inner bead width (see figure 31). However the absolute prediction error in the vast majority of the predictions was less than 0.1mm.

5.3.4.3 Keyhole Model for 316L Stainless Steel

R^2 , Radjusted, Standard Error, F-ratio and P values, calculated again for all the developed models (see Tables 28 a and b), along with the graphs plotted for predicted versus measured and residual versus predicted values (see sample plots in figure 88) reveal a reasonably good fit. As expected, these values were lower for the undercut models (see Table 29b). Also they were relatively low (although satisfactory) for positions 3 and 28. For the former this was due to the fact that formation of the keyhole could happen any time within the first 2 sec period of the delay time. A relatively delayed opening resulted in a wider outer and inner bead width. By contrast, an immediate formation resulted in a bead width with almost similar bead width dimensions to those of position 8. However, for the vast majority of the trials delayed keyhole opening occurred. Smaller statistical values for position 23 were attributed to the change of the stand-off distance at this position due to the rotor problem described in section 5.3.1. The shape of the bead produced at that position could lead to a large spread in the results if the position from which the measurement was taken was not accurately assessed.

Predicted versus measured values diagrams for all three undercut models (see figure 89) reveal overlapping regions between the membership functions which once more indicates that values gradually change from being fully applicable to completely inapplicable.

A number of new trials were also produced in order to examine further the adequacy of the models within their experimental range (parameters used and results obtained are presented in Table 32). The results indicate the accuracy of the models. The maximum absolute error observed was 0.28mm for the outer bead with (position 3) and 0.17mm for the inner bead width (position 3) while it was again less than 0.1mm

for most predictions. Furthermore, the undercut models gave a satisfactory prediction of the type of undercut expected; this could subsequently be evaluated for remedial action if necessary.

5.3.5 Optimal Selection of Welding Procedure

Following the integration of the developed models, the final system has been used for optimum procedure prediction based on the objectives identified in section 3.5. For optimum parameter selection the following were taken under consideration so that a systematic approach could be developed:

- Although a specification has been produced, the system offers the flexibility of seeking input parameters that can meet any specification irrespective of its stringency. However, generally it is more important to ensure full penetration than to meet arbitrary bead width specification limits. Therefore, welding conditions were always chosen with a view to satisfying this requirement.
- Probably the major problem that had to be tackled apart from developing stable, tolerant procedures was the non-uniformity of the bead width due to the progressive heating of the weld area. The following values related to the phenomenon were estimated for both outer and inner bead widths and were used as quality objectives for statistical control of weld bead uniformity:

- i. standard deviation of the bead width which is a useful descriptor of the dispersion or spread of the measured bead widths, is denoted by σ and is given by the following expression:

$$\sigma = (\sigma^2)^{1/2}$$

$$\text{where: } \sigma^2 = \sum_{i=1}^N (x_i - \mu)^2 / N$$

and:

N is the population size (number of predictions along the weld bead),

μ is an unbiased estimate of the population mean which for a finite

population is defined by: $\mu = \sum_{i=1}^N x_i / N$,

x_i is the i estimate (prediction) of the population

- ii. the dispersion of the bead width is also expressed as a percentage of the average bead width value, using the following expression (coefficient of variation):

$$D=100*\sigma/\text{average bead width}$$

- iii. the difference between the maximum and minimum bead width values obtained along the weld,
 - iv. the difference between the maximum and minimum bead width for the first 18mm of the bead width, which could be very useful when a three segment procedure was utilised.
- In addition to the standard deviation, coefficient of variation and bead range factors estimated for the whole weld and for specific sections, two undercut indices were also estimated in order to have a single indicative value of the undercut condition on the outer weld bead which could be more easily handled for control of undercut formation on the outer weld bead in keyhole welding of 316L stainless steel. These were:

The "Average Undercut Indication" factor estimated for each set of input parameters employed, which is given by the following equation:

$$G(UND)=[\text{Ind}(UND)_8+\text{Ind}(UND)_{18}+\text{Ind}(UND)_{28}]/2.5$$

The number 2.5 was used instead of 3 for "safety" purposes, to amplify the phenomenon and provide a way of incorporating the influence of heat build up on the estimated undercut index.

The "Maximum Absolute Undercut Factor" which is the maximum absolute undercut indication index between the three predicted undercut indices, defined as:

$$\text{MAX} [\text{ABS}(\text{Ind}(UND)_8), \text{ABS}(\text{Ind}(UND)_{18}), \text{ABS}(\text{Ind}(UND)_{28})]$$

5.3.5.1 Material and Mode Considerations

The following, related to the unique characteristics of each material used and the different mode utilised, were also taken under consideration so that an optimum welding procedure covering the most important aspects of each case could be developed:

- In arc welding of titanium alloys high solidification rates increase the possibility of gas bubbles, usually formed at the edge of the joint zone and being entrapped there. Therefore, welding conditions are usually selected to ensure the optimum duration of existence of the molten pool required for evolution and dissipation of the gas bubbles.
- Autogenous welding of austenitic stainless steels may be subject to variable penetration (weld variability problems). The use of the keyhole mode eliminates this danger. However, the surface active elements which are responsible for this problem can still influence the behaviour of the weld pool and give unexpected weld bead sizes and shapes. This danger must be taken into consideration during the selection of the bead geometry specification that will be used and/ or during the selection of the parametric constraints in both modes utilised, to allow for greater tolerances and to select parameters remote from the boundaries of the tolerance boxes (see figure 84 for melt-in mode and figure 85 for keyhole mode).
- One of the most important factors for the weld quality is the keyhole stability which depends on a large number of factors. Any instability can result in a variety of defects (e.g. incomplete penetration, melting through, undercut). For this reason the aim during the parameter selection procedure was to select the most tolerant parametric combinations that could provide a stable keyhole and a stable weld pool. Subsequently, keyhole initiation and closure were examined (see section 5.5.7).

5.3.5.2 Optimisation Technique

Constrained Optimisation of the indices developed for weld bead uniformity and undercut, based on values obtained from the models, was used for procedural optimisation for all three tubes examined.

The following constraints were utilised which were all expressed as inequalities (one upper-limit and one lower-limit constraint):

1. **Parametric Constraints** (pre determined input parameter range).
2. **Dimensional Constraints** (requirements for inner and outer bead width range).
3. **Quality Constraints** (related to weld bead uniformity or undercut formation).

An extra constraint, related to the value of the predicted inner/outer bead width (I/O) bead width ratio, was also introduced for the optimisation of keyhole welding procedures. It was observed that the risk of cutting increases as the I/O ratio increases. The phenomenon was noticeable for the medium and higher current values employed. It was attributed to the fact that as the I/O ratio increases, the weight of the fusion zone increases and surface tension forces can no longer sustain the weld pool. As a consequence the weld pool collapses.

A ratio of 1.2 was usually utilised for safety. Cutting risk was continuously assessed based on this for all welding positions. However it was observed that the last three positions exhibit a higher risk because of the heat build-up which, as expected, particularly influences the end of the weld producing greater fusion areas (see section 5.5). Such high inner/outer bead width ratios can be attributed to the influence of the purging gas flow rate on weld bead formation. In particular it seemed to significantly influence:

- the size and shape of the inner bead width (in all modes utilised) and,
- the whole operational envelope through its effect on the areas where cutting was obtained.

The above requirements made the selection of the purging gas flow rate critical, and special care was taken to ensure that it remained unaltered throughout the experimental work. Furthermore, it was observed that substitution of the plastic cups sealing the tube with others that had different shapes also influenced the output characteristics since the internal pressure was affected in this way.

It must be emphasised that the selection of the appropriate minimum and maximum values for the constraints defined above provides a convenient "framework" for constructive thought about each problem's requirements and also

allows the user to influence the end result by providing his/her own input to optimisation of the procedure since the decision variables must satisfy the constraints upper and lower limits at any solution (if there is one).

The optimisation was achieved through minimisation of the developed indices (objective functions) related to the two major quality problems encountered in orbital plasma welding:

- 1. Heat build-up** (outer and inner weld bead uniformity).
- 2. Undercut** (probability of undercut formation on the outer weld bead in keyhole welding).

The objective functions depend indirectly (through their connection with the developed models) on the input plasma parameters (welding current, welding speed, plasma gas flow rate, electrode set back distance and heat input during the first segment for titanium tubes) which comprise the decision variables (changing or adjustable variables) of the optimisation process. The mathematical relationships between the decision variables and the objective function and constraints - created by the formulae in the models - determine whether a solution can be found.

The following objective functions have been developed and applied for process optimisation:

- 1. Standard Deviation for the outer bead width along the outer weld bead (G1).**
- 2. Standard Deviation for the inner bead width along the inner weld bead (G2).**
- 3. Coefficient of variation for the outer bead width along the weld bead (G3).**
- 4. Coefficient of variation for the inner bead along the weld bead (G4).**
- 5. Width range between the maximum and minimum value for the outer bead width along the weld bead (G5).**
- 6. Width range between the maximum and minimum value for the inner bead width along the weld bead (G6).**

7. Width range between the maximum and minimum value for the outer bead width for the first half of the weld (up to position 18) (G7).
8. Width range between the maximum and minimum value for the inner bead width for the first half of the weld (up to position 18) (G8).
9. Undercut Indication index (G9).
10. Maximum Absolute Undercut Factor (G10).

The optimisation problem is solved using a variant of Lasdon & Waren's GRG2 (Generalised Reduced Gradient) code called as a subroutine in the Excel Solver operation. "GRG2 uses an implementation of the generalised reduced gradient (GRG) algorithm. It seeks a feasible solution first (if one is not provided) and then retains feasibility as the objective is improved. It uses a robust implementation of the BFGS quasi-Newton algorithm as its default choice for determining a search direction" [241]. In general, it uses iterative numerical methods that involve "plugging in" trial values for the adjustable cells and observing the results calculated by the constraint cells and the optimum cell. Each trial is called an iteration. Because a pure "trial and error" approach would require an extremely long time (especially for problems involving many adjustable cells and constraints), an extensive analysis of the observed outputs and their rates of change as the inputs are varied is performed, to guide the selection of new trial values [242].

A weakness of this method has been identified when a problem has many local minimum points. When started at a given set of adjustable values, the method tends to converge on a single optimum point close to the starting point without having a sure way of testing whether there is another one, some distance away. The application of external knowledge of the problem is the best way to find the global optimum. The selection of the general region where the global optimum lies can be achieved either through common sense reasoning about the problem or through experimentation. Subsequently the optimisation procedure must start using adjustable values that are within that region. Alternatively, the method must start from several different, widely separated points and see which solution is best. Both techniques have been used during this investigation.

Figure 90 illustrates diagrammatically the procedure utilised for optimisation of the process.

5.3.5.3 Testing the Optimisation Model

A number of procedures have been developed using the technique described in the previous section in order to determine the optimum set of input parameters based on the defined criteria and requirements for all three tubes investigated. As already mentioned, the main target was to control weld bead uniformity for the melt-in mode welds and both weld bead uniformity and undercut formation for the keyhole welds. Procedures developed were subsequently verified experimentally. It was decided that in order to increase the weld bead uniformity, the best approach would be to modify the parameters half-way through, to counter problems with the rotor concentricity in the last part of the weld joint (see section 5.3.1). A sample of the procedures developed for each tube is described below:

a) Melt-in Mode Welding of Ti-3Al-2.5V

A number of procedures were generated using the objective functions G3, G4, G5, G6, G8 (see section 5.3.4.3 for definitions) and two different groups of constraints. Figures 91 and 92 present the estimated parameters along with the predicted results for the 0.56mm orifice diameter while figures 93 and 94 show results for the 0.79mm orifice diameter. The aim of the second group of constraints was to reduce the solidification rate by increasing the heat input. It was notable from the proposed parameters that higher welding speeds and lower current and plasma gas flow rate values were usually suggested in order to enhance weld bead uniformity. Furthermore, maximum ESB distances and low $DT \cdot I_{st}$ (HIS) products were utilised in most cases.

Since current was the governing factor, it was decided to alter only the current value employed during the first segment in a two segment procedure, reducing it by approximately 10%. This significantly improved results, and only minor adjustments were required in order to achieve the main target of a uniform bead width. Figures 95 and 96 illustrate the parameters utilised along with the results for the three segment procedures performed with the 0.56mm and 0.79mm orifice diameters respectively.

b) Melt-in Mode Welding of 316L Stainless Steels

Two and three segments procedures developed are presented in figures 97 and 98 respectively. As with the Ti-3Al-2.5V, the (G3, G4, G5, G6, G8) objective functions were employed while again an approximately 1A current reduction was utilised for the third segment. Results obtained indicate that considerable weld bead uniformity for both inner and outer weld beads was again achieved.

c) Keyhole Welding of 316L Stainless Steels

A number of objective functions were used in order to optimise the developed procedures based on the defined criteria (G3, G4, G5, G6, G9, G10). Figures 99 and 100 illustrate the group of constraints employed along with the suggested input parameters for each objective function and the predicted results.

Although, considerable weld bead uniformity and undercut minimisation could be obtained with the use of these parameters for the whole circumference (particularly with the constraints and objective functions suggested in figure 100), it was considered that a 1A current reduction during the second half of the weld could further enhance weld bead uniformity and undercut minimisation. Three trials were made, which experimentally verified these considerations (see figure 101).

5.4 The Influence of Welding Parameters on Weld Bead Characteristics.

The large number of parameters involved makes the investigation of their influence on the weld bead characteristics difficult. The nature of the equations obtained however, where all plasma parameters examined were included irrespective of their significance, makes the determination of some correlations possible. It must be noted that the small influence of electrode set back and plasma gas flow rate on weld bead characteristics (with the exception of 316L melt-in mode), made their exact influence unclear (see sections 5.4.3 and 6.5 for further investigation and discussion of this point). Therefore, these parameters do not always appear with the same sign in the developed mathematical expressions. The following four outputs were examined:

1. outer bead width,

2. inner bead width,
3. inner/outer bead width ratio,
4. weld area,
5. undercut probability (in keyhole welding).

The following inputs were investigated:

1. Heat Input During the Starting Segment (only for the Ti-3Al-2.5V tubes).
2. Orifice Diameter (only for the Ti-3Al-2.5V tubes).
3. Plasma Gas Flow Rate (PGFR).
4. Electrode Set Back (ESB).
5. Shielding Gas Composition (only for the keyhole welding of 316L tubes).
6. Welding Current (I_1).
7. Welding Speed (WS).

It must be emphasised that contamination free inner and outer weld beads were produced while all metallographic analyses revealed porosity free welds for all three tubes investigated, as illustrated in section 5.8. It must also be noted that slight undercut was observed for some parameter combinations (usually associated with the higher PGFR and current values) in melt-in mode welding of 316L tubes. Nevertheless, the phenomenon was not intense and could easily be eliminated with a cosmetic pass.

5.4.1 Heat Input During the Starting Segment (HIS)

Contrary to expectations, HIS proved to exert significant influence only in the first position (3) while its influence on all other welding positions was very small (less than 10% of the original values with a 100% increase of the HIS) as can be seen in the results illustrated in figure 102. It must be noted however that the use of a relatively long delay time proved to be beneficial for the following reasons:

- It allowed better stabilisation of the arc to be achieved after ignition
- It assured full penetration, particularly during the first stages of the weld, where the tube had not been sufficiently heated.

5.4.2 The Influence of Orifice Diameter

For the small orifice diameters employed it was found that similar bead width characteristics were obtained for both orifice diameters (0.56mm and 0.79mm) utilised (see figure 103). However, it can be seen that slightly higher Inner/Outer weld bead ratios were obtained with the 0.56mm orifice diameter as a result of the higher inner bead widths obtained.

A more depressed weld bead surface was observed when the 0.56mm OD was utilised. The chance also of producing fully penetrating welds at high welding speeds and low currents was enhanced with the use of the small orifice which increased plasma constriction (at the expense of arc stability).

The use of the smaller orifice was restricted by the maximum permissible current (15A), above which the orifice shape was damaged. Prolonged use of this nozzle for current values close to its upper limit could also result in orifice damage. The latter was avoided with the use of the 0.79mm OD for the same current values due to its wider current range (30A maximum current value). Similar results obtained with both orifices along with the lower risk of damage with the 0.79mm OD makes the use of the 0.79mm OD advantageous.

5.4.3 The Influence of Plasma Gas Flow Rate (PGFR)

The influence of PGFR on the examined output bead characteristics was studied for a wide range of gas flow settings in all three tubes (see figures 104a and b).

Contrary to expectations its influence is of no account when welding with the 0.56mm Orifice Diameter (OD) the Ti-3Al-2.5V tubes (see figure 104.a). Its influence is more pronounced when welding with the 0.79mm OD. A small but systematic decrease is generally observed as PGFR increases in all output characteristics which is more pronounced on the inner bead widths (4% to 14%). Furthermore, the latter resulted also in lower I/O ratios giving welds of a more orthogonal shape (see figure 104b). Nevertheless, this influence was relatively small for the range of PGFR employed, to justify the use of this parameter as a control variable in welds made in such small thicknesses. Finally, it must be noted that the use of high plasma gas flow rates could enhance the risk of gas entrapment in the weld. It must also be emphasised that in a

limited number of trials when welding with the 0.56mm OD, double arcing along with damage of the orifice shape occurred for gas flow rates less than 0.3l/min which was particularly pronounced when combined with high current values.

The influence of PGFR on all output characteristics was significant during melt-in mode welding the 316L tubes. All output characteristics increase as PGFR increases (see figure 104b). The influence is particularly important for the inner bead width (approximately 40% increase for the inner bead and 20% for the outer). Higher I/O ratios obtained resulted in welds of a more orthogonal shape. Furthermore, it was observed that higher heat inputs combined with higher PGFR increased the risk for hole formation (see figure 84).

In keyhole welding of 316L tubes, PGFR had almost no influence on all output characteristics investigated (see figure 104b). Nevertheless, it was noticed that PGFR played a very important part in the process stability. Unexpected PGFR variations due to system inconsistency could result in the disruption of the weld pool. This in turn could lead either to loss of the keyhole or, even worse, to tube cutting.

5.4.4 Influence of Electrode Set Back (ESB)

The influence of ESB on the output characteristics for the range of values examined was insignificant (see figures 105a and b). These figures indicate that only very small variations were observed. The latter combined with the fact that positive and negative variations were obtained for the various welding positions as ESB distance increases, made the determination of any general conclusion concerning the effect of the ESB on the bead width impractical, since these effects may lie within the bands of experimental scatter.

5.4.5 The Influence of Shielding Gas Composition

One of the most influential factors in weld pool formation, particularly when operating in the keyhole mode, is the shielding gas composition. To examine its influence on bead geometry, a number of trials were made using two shielding gas compositions, **Ar+10%H₂** and **Ar+5%H₂**, both gases widely employed for keyhole welding in stainless steel.

1. Ar+10%H₂

An investigation was initially made in order to identify the parameter combinations offering sufficiently acceptable outputs and therefore the position of the operational envelope. Based on experience acquired during the previous investigation a relatively small number of trials were required. Only the following three input parameters were examined:

1. **welding current,**
2. **welding speed,**
3. **plasma gas flow rate.**

These were expected to exert the greatest influence on the output characteristics:

a) outer and inner bead widths, b) inner/outer bead width ratio, c) fusion zone area and d) undercut.

Parameters utilised and results obtained are presented in Table 33 while the experimental envelope is illustrated in figure 106. Three distinct areas were identified which include parametric combinations for which:

- stable keyhole conditions producing keyhole welds with variable undercut degree were achieved,
- cutting was obtained from the start or at a subsequent stage and
- a humping bead was produced.

The following four general observations were made:

1. Humping was usually associated with high welding speeds and arc pressures but was not observed when argon was used as the shielding gas due to the maximum welding speed limit of the head. The shift of the operational envelope with H₂ addition to lower welding currents and speeds allowed this phenomenon to be observed.

2. Welding currents required to achieve stable keyhole conditions were considerably lower than currents utilised with pure argon.
3. A much cleaner outer and inner bead surface was produced as a result of the use of this shielding gas composition.
4. Much more uniform outer and inner beads were produced which, for most parameter combinations, indicated that the use of a three segment procedure was not necessary in order to obtain a uniform bead width.

A comparison was also made between results produced using the models for pure argon and results obtained from the experimental trials made with a 10% hydrogen addition in the shielding gas. Since the two operational envelopes had only a small common overlap the number of welding current/welding speed combinations compared were limited (see figure 107). Nevertheless, results indicated that a more uniform weld bead along with a less pronounced wine glass shape weld zone was obtained when Ar+10% H_2 was utilised.

2. Ar+5% H_2

A limited number of trials were also made using Ar+5% H_2 as shielding gas (see Table 34 for parameter combinations and results) which did not allow the construction of the operational envelope for this shielding gas. However it could be seen that most of the remarks made for Ar+10% H_2 were also valid for Ar+5% H_2 (i.e. less heat input necessary for stable keyhole operations, clean outer and inner bead surfaces). Nevertheless the uniformity of the outer and inner bead width was significantly lower than that obtained with the Ar+10% H_2 mixture. The latter was clearly observed when results from trials made with similar parameter combinations were compared (see figure 108). The use of Ar+10% H_2 resulted not only in a more uniform outer and inner bead width but also in a more orthogonal shape of the fusion zone, as a result of the more constricted arc produced with the greater hydrogen content. However, reduced inner and outer bead widths observed with the use of Ar+10% H_2 compared to Ar+5% H_2 for similar parameter combinations indicate that a large amount of heat is lost through the keyhole efflux (see also figure 108).

5.4.6 The Influence of Welding Speed (WS)

As expected, welding speed exerts a significant influence on weld bead formation and weld bead characteristics (see figures 109a, b, c and d). Its influence is more important on the inner bead width than the outer as the variation in the values obtained indicated. A 50% increase in welding speed in Ti-3Al-2.5V tube welding resulted in an approximately 40% decrease of the inner bead width and a 20% decrease of the outer bead width in all welding positions examined (see figure 109.a). The variation was slightly greater for the 0.79mm orifice diameter. The same welding speed increase in melt-in mode welding of 316L tubes resulted in an approximately 55% and 30% decrease of the inner and outer bead widths respectively (see figure 109b). In keyhole welding of 316L tubes, a 40% increase in welding speed resulted in an approximately 30% and 15% decrease of the outer and inner bead widths respectively. As expected, variations are not the same for all welding positions due to heat build up.

Speed significantly affected the type of undercut which occurred, with higher welding speed increasing the risk for undercut types related to fast solidification rates (negative values of the general undercut index were observed, see figure 109d). On the contrary, lower welding speed increased the Inner/Outer bead width ratio which in turn increased the risk of collapse of the weld pool.

Finally, heat build-up is more notable, as expected, with lower welding speeds. Low welding speeds resulted in alleviation of the problem related to bead widths and fusion area reduction after position 3. The latter is particularly notable for low welding current values and high welding speeds. However, high welding speeds enhance weld bead uniformity as the RW index [range between the maximum and the minimum value of the outer (inner) bead width] indicates although positive results cannot be obtained with the use of the COV index [coefficient of variation for the outer (inner) bead width] for weld bead uniformity (see figures 109c and d).

5.4.7 The Influence of Welding Current (HI_1) and Pulse Frequency

Welding current plays the most important part in determining the size and shape of the weld bead. Current increase resulted in significant increase of all the examined output bead characteristics in all three tubes investigated (see figures 110a,

b, c and d). In common with the welding speed, current exerted a greater influence on the inner bead width compared to the outer bead width. The maximum possible current variation for a typical parameter combination was utilised in order to examine current influence in all three cases. A 40% increase in welding current in Ti-3Al-2.5V tube welding resulted in an approximately 55% and 110% increase in outer and inner bead widths respectively (see figure 110a). The same current increase in 316L melt-in mode welding resulted in an approximately 50% and 130% outer and inner bead width increase respectively (see figure 110b). Finally, a 25% welding current increase in 316L keyhole welding resulted in an approximately 20% and 55% increase in inner and outer bead widths respectively (figure 110b). In the same figure it can be seen that higher current values increased the risk of undercut types related to excessive heat input and increased arc pressures. The influence of welding current on weld bead uniformity is illustrated in figures 110c and 110d based on the RW and COV indices estimated for the outer and inner bead width. A mixed influence was observed for the parameter combinations employed which makes it difficult to draw any conclusion related to the independent influence of welding current on weld bead uniformity.

Figure 110d also indicates that as welding current increases the possibility of undercut types related to high heat input and excessive arc pressure also increases. However, the influence of current on undercut is better examined along with that of the welding speed, since the resultant behaviour is closely related to both factors. Examination of undercut possibility based on a number of welding current-welding speed combinations (see figure 110e) reveals that there is a band of minimum undercut possibility. It indicates an approximately linear dependence between welding current - and welding speed for minimum undercut results. Above this band negative general undercut indices indicate the need for lower solidification rates and/or lower arc pressures, while under this line positive general undercut indices suggest that excess heat input or arc pressures might have occurred.

As a result of the heat build up the bead widths and the fusion area increases from position 8 to 23. The faster rise rate of the IBW in comparison with the OBW also results in an increase of the I/O ratio (see figures 110a and b). The influence of heat build-up becomes more pronounced with the use of high current values where

the reduction in the output characteristics observed after position 3 can again be avoided.

A number of trials were made with the use of Ar+5%H₂ as a shielding gas in order to examine the effect of varying pulse frequency on weld bead characteristics, keeping all the other variables constant. Two different parameter combinations were investigated. The input variables utilised are presented in Table 35.

It was clearly observed that the welding current pulse frequency exerted a significant influence on the undercut characteristics of the weld bead, which, for specific frequencies was almost completely eliminated. Furthermore, some of the frequencies also offered a very smooth outer and internal surface, almost ideally continuous with the inner and outer tube surfaces. However, the optimum frequency was different in each group of trials (5Hz, 6.7Hz and continuous current for 14A welding average welding current and 2.66mm/sec welding speed while 10Hz for 12.5A average welding current and 3.32mm/sec welding speed), thus indicating that frequency is closely related to the other welding parameters utilised and particularly the magnitude of the current and the welding speed.

The outer and inner bead width measurements that were performed indicated that both outer and inner bead width increase when lower welding frequencies were employed. However, after a certain frequency which again depended on the other parameter combinations utilised, an unacceptable bead profile was obtained consisting of distinct, overlapped spots. Subsequently hole formation was obtained with lower frequencies. Results are presented in Table 35 along with a general description of the weld bead appearance for each frequency.

Finally, it could also be seen that lower thermal pulsing frequencies increase the risk of cutting as a result of the different period over which the peak current value and thus the maximum arc pressure influences the weld pool.

The automatic sloping down of the welding current and plasma gas flow rate, along with the use of a number of segments that could provide sloping down of welding speed made closure of the keyhole relatively easy. With appropriate parameter combinations a smooth transition from the keyhole to melt-in-mode was

obtained after a full revolution in the keyhole mode. Subsequently, a smooth extinction of the arc was achieved. It was also found that sloping up of the current was sufficient to provide a smooth keyhole formation without expulsion of the molten metal. However, it must be noted that a steep slope down of the plasma gas flow rate must be avoided, otherwise the keyhole imprint could remain on the joint. Usually a two second sloping down period was necessary, however, when high welding speeds were utilised, this could result in a significant overlap of the already welded area. A typical welding cycle is illustrated in figure 111.

5.5 Butt Joints

A number of trials indicated that the results obtained using bead-on-plate experiments could successfully be transferred to butt joints. However this could only be achieved under optimum preparation, fit-up and fixturing conditions, described in sections 3.4.1 and 3.4.2. An intimate contact was critical and failure to achieve it, always lead to severe burn-through. Joint fit-up was equally important and there was very little tolerance to joint mis-match. Therefore, successful and careful tack welding was vital for the subsequent weld. However, it was observed that for a number of trials, tack welds led to keyhole disruption which usually resulted in catastrophic failures (i.e. cutting).

The final problem was related to the positioning of the joint with respect to the orifice position. Very small variations in the positioning resulted in completely different results. When the orifice was positioned exactly at the middle of the joint no significant problems were encountered. Even a very small displacement (approximately greater than 0.5mm) resulted in cutting for most trials.

Overall, the process proved to be particularly sensitive in any procedural errors. Nevertheless, if the defined procedures were carefully followed satisfactory results were obtained.

The use of a cosmetic pass was employed when deep undercut was obtained. It was noticed that a smooth outer bead surface could be obtained with a low current (approximately 20A) GTAW arc. A plasma arc can also be used, however more than one cosmetic pass is typically required when a small orifice diameter is utilised.

5.6 Excel Spreadsheet

The whole optimisation procedure described above has been developed using a Microsoft Excel 5.0 spreadsheet. Initially, all models were integrated into a single spreadsheet. Scrolling bars linked to input variables were used in order to obtain simultaneous variation of all model output values and, therefore, a better representation of the inner and outer bead width profiles. Alarms have been positioned above the input parameter selection menu, indicating whether parametric combinations utilised are within the operational envelope. All the objective functions described in section 5.3.2.3 were incorporated into "macro" command, which were used to automate the Excel commands and operations related to minimisation of these values (using Excel's Solver tool). The solver's problem for each macro function was saved in a different worksheet. Furthermore, the constraints added to each problem could automatically be altered through the dialogue box included in the worksheet.

The above technique allowed the simultaneous handling of a large number of formulae, which were copied into different cells on the spreadsheet. The latter made it easier to track down and correct possible errors of the optimisation model. It also provided a better understanding of the major problems encountered in orbital tube welding. Furthermore, all the statistical tools incorporated in the software could easily be used to minimise the time required to develop an optimisation model in comparison with writing a program. Moreover, possible alterations to the original model will also require alteration to the original program. The latter is handled automatically by Excel.

A typical optimisation sheet developed for the keyhole welding of the 316L tubes is illustrated in figure 112.

5.7 Metallographic Examination

A macro and micro metallurgical examination was performed in several welds for all three tubes investigated. Microscopic examination carried out at high magnifications in the weld zone (and HAZ for the Ti-3Al-2.5V tubes) revealed a sound microstructure. Porosity was not observed in any of the sectioned samples.

Figures 113-115 present a number of metallographic photographs for the Ti-3Al-2.5V tube. Clean inner and outer bead surfaces can be observed as a result of the complete shielding from the atmospheric gases in the welding chamber and the appropriate precleaning procedure adopted. These also resulted in elimination of porosity that can be produced during welding. Figure 114 shows the bead geometry obtained with an unprotected inner bead. It can be seen that severe oxidation had taken place. Figure 115 presents typical weld and heat affected zone microstructures where serrated α (outlined), acicular α (light) and an amount of β (dark) phases can be identified.

Figures 116-117 refer to 316L tubes (12.7mm X 0.7mm). Figure 116 shows a number of outer and inner bead widths produced where different degrees of weld bead uniformity have been obtained depending on the parameter combination utilised. It can be seen that high current-high plasma gas flow rates increase the risk of hole formation, particularly towards the end of the weld where heat build-up and increased fusion zone areas also support the phenomenon. Figure 117 shows a number of typical weld microstructures obtained for different parameter combinations. The initial grain growth occurs epitaxially starting from the surface of the base metal giving a cellular-dendritic microstructure. The orientation of the welding crystals indicates the steepest temperature gradient. The equiaxed zone observed at the centre of the weld zone is an indication of much nucleation and high grain growth. The significant size of this zone is also an indication of fast cooling rates.

Figures 118-124 present macro and microphotographs from the 316L keyhole welds produced with all three shielding gases utilised. A selection of typical undercut types obtained with different parameter combinations is also presented. Figures 118 to 120 show the influence of current pulsation on weld bead geometry and reveals that different thermal pulsing is required in order to obtain an optimum weld bead geometry for a given parameter combination. Figure 121 illustrates various undercut types obtained when pure argon is used as shielding gas. Figures 122 to 125 present a selection of microstructures and weld bead geometries for various parameter combinations and for all three shielding gases utilised. It can be observed that the average undercut indication index estimated offers an excellent representation of the weld bead geometry obtained in all cases. Finally, it can be seen that the microstructure obtained is similar to that of the melt-in mode welding of 316L tubes.

5.8 Summary

This chapter presented the concepts utilised and the procedures developed for optimisation of the dimensional and quality characteristics of three different tubes using the prototype orbital plasma torch developed. The experimental work demonstrated that the development of an orbital plasma welding head for small bore tubes is possible and that the general characteristics of the plasma torch modification resemble those of a conventional plasma torch despite their significant differences and the design limitations of the prototype system. The application of the system for orbital plasma welding of small bore Ti-3Al-2.5V and 316L tubes revealed the benefits that the technique can offer in a number of situations where problems have been encountered in the past with the GTAW process. It also indicated that statistical analysis can provide a useful tool for the analysis and modelling of orbital plasma welding.

Although parameter optimisation for the orbital plasma welding of small bore tubes is a complicated phenomenon due to the large number of interrelated input parameter and output characteristics, a novel method has also been developed for optimisation of the multivariable orbital welding procedures. The same simple and robust technique can be used for any tube diameter, thickness and material composition. It provides an empirical way of analysing the phenomena minimising at the same time the number of the experiments required. The user can influence the selection of the optimisation procedure through a number of parameter, dimensional and quality constraints, depending on the objectives required. This approach should be applicable to most thin, small bore tubes.

6. General Discussion

6. GENERAL DISCUSSION

6.1 Introduction

One of the most important tasks of the welding engineer is the selection of optimum arc welding parameters. This selection is based in a number of objectives which are always closely associated with the special features of each situation and with the quality and production requirements of each fabricator. This work was motivated by the industrial need for off-line control of a number of problems mainly associated with GTA welding of titanium and austenitic stainless steel tubes. These are:

1. **Pore creation and entrapment in the weld zone when GTA welding small bore titanium tubes.**
2. **Weld variability problems when welding austenitic stainless steel tubes.**

Research work conducted in the past had established that automated plasma arc welding in a controlled atmosphere could offer a reliable solution to these problems. Nevertheless, consideration for application of this technique had several repercussions elsewhere in terms of:

1. The need to develop prototype equipment and investigate its characteristics.
2. The need to evaluate the behaviour of the system and the effect of the main welding parameters when applied to the specific situations investigated.

The latter will give an improved understanding of the function of the process control parameters, make the process more predictable and will make the transfer of optimum parameters to non-identical equipment easier. This is currently very difficult as many researchers have already identified [e.g. 6, 194]. Furthermore, it will allow solutions to two specific problems, associated with orbital welding of small bore tubes and plasma welding in general:

- a) bead width variation due to heat build-up. The increase in weld width which particularly affects the final section of the weld, also causes superheating of the metal and impairs its structure, thus increasing cracking susceptibility [192].

- b) undercut formation due to the characteristics of the plasma arc (mainly high arc pressures).

The final aim was to develop a structured approach which could lead to defect prevention rather than defect detection and which could subsequently be used for a number of different conditions. Therefore, the strategy developed was based on the need to gain a better understanding of both the specific problems tackled and the characteristics of orbital plasma welding in a totally enclosed head. A flowchart illustrating the approach adopted is presented in figure 55.

The main aims of this chapter are:

1. to evaluate the performance of the orbital welding system developed for low current applications, not only against the criteria set out in the design study (see section 4.2) but also against the results obtained from the utilisation of the developed system in a number of applications.
2. to evaluate the effectiveness of the mathematical modelling process in order to obtain empirical statistical models relating the major welding parameters (input variables) and weld bead characteristics (output variables) for orbital plasma welding of small bore tubing.
3. to evaluate the empirical models constructed for several applications along with the optimisation strategy developed with their support, as an aid for predicting optimum weld bead characteristics within the range of parametric settings investigated.
4. to highlight the physical mechanisms governing the weld bead formation and examine the influence of the major plasma parameters to the resultant output characteristics.

The discussion of the results is split into two parts, the first one is related to the development of the system and the second one deals with the modelling procedure. The merging of these two parts in certain areas of the discussion is however unavoidable due to the fact that the characteristics of the torch in plasma welding have a strong influence on the characteristics of the welds produced.

6.2 General Evaluation of the Developed System

Totally enclosed orbital welding heads have been used for some time for butt welding in a wide range of tubes involving different materials and sizes. However, the compact design of these heads makes GTAW the only process suitable for implementation. One of the primary targets of this research project was to examine the feasibility of modifying an already existing GTAW head for low current plasma welding applications for reasons already presented in section 1.2.

Although a number of restrictions had been imposed on the GTAW orbital welding head modification, which did not allow the best design options to be utilised in the originally developed modification, the final system proved to be very effective, offering a reliable solution to the problems associated with the materials under investigation. Furthermore, the simplicity of the modification made the shift from GTAW to PAW easy and fast since no major alteration had been made to the GTAW head.

Visual observation of the plasma column indicated a similar behaviour to that of a normal water cooled plasma torch for the parameter combinations utilised. The plasma column remained virtually unaltered even when long arcing times were utilised. The small gradual reduction of the copper mass temperature rise rate close to the orifice (see section 5.2.1.3), where maximum temperatures are expected to be reached along with the relatively low temperatures in the same area, indicated that for the parameter range under investigation, the heat dissipation provided by the copper mass was gradually falling, although it was still sufficient to provide stable plasma arc operations. The latter, combined with the fact that a) double arcing conditions were found only when very low PGFR (less than 0.3l/min) and higher current values were used for prolonged periods and b) no orifice damage was observed for a large number of trials even when the smaller orifices were employed (i.e. 0.56mm and 0.79mm), also indicates that the relatively cool non-conductive gas at the nozzle walls still provided the necessary protection of the nozzle from the high arc temperatures. It also indicates that the flow pattern of the plasma gas in the nozzle which is governed by the geometry of the torch is satisfactory, and excessive gas turbulence in the nozzle which may lead to nozzle failure is avoided.

Nevertheless, the gradual fall of the arc voltage values recorded indicates that the width of the cool non-conductive layer becomes gradually smaller allowing a larger cross sectional area for the current to flow which subsequently results in an arc voltage fall due to the reduced energy required as a result of the lower resistance of the arc column. Therefore the use of the current pulsing for relatively high current applications is not feasible since this would result in double arcing conditions very quickly. Moreover, the author considers that the voltage fall is also a significant disadvantage for the developed modification, since it effectively results in an uncontrollable alteration of the arc characteristics. This fall is less than 1.0V for a 60sec arcing time under the most adverse conditions for the torch body temperature (observed when Ar+5% H_2 was used as a shielding gas) and for the parameter range investigated (see section 5.2.2.1) and becomes even smaller during the short welding periods required for the small bore tubes examined. However, special care was taken in order to perform all the welding trials with the same start torch body temperature and hence to reduce these undesirable effect.

Another significant disadvantage was that cooling of the torch after the extinction of the arc was very slow and the only way that this could be accelerated with the present design was to use of an increased post-purge period allowing very high gas flow rates (e.g. 5l/min) to flow through the orifice. However, very small improvements obtained with such high flows combined with the uneconomical gas consumption indicated that water cooling channels or heat pipes are the best solutions for effective cooling and therefore higher production rates. Furthermore, the latter will increase the reliability of the equipment for higher current welding applications which will ensure an increase in the acceptance of the equipment.

It must be emphasised that the developed plasma welding system for orbital welding operations in a totally enclosed head has two other unique characteristics compared to the wide range of plasma torches available. The first one is that there is only one stream of gas supplied to the torch (i.e. the plasma gas) since shielding gas is supplied through a number of holes situated all around the head rotor, filling the chamber with gas uniformly. Hence, the arc characteristics were affected since the way that the shielding gas penetrates into the plasma stream is significantly different than it is in a normal plasma torch. The second difference is the absence of a pilot arc. This did not affect the consistency of arc ignition indicating the significance of the

proper shielding atmosphere developed in the chamber, which requires lower ionisation potentials than air for a reliable arc ignition and a stable arc operation. Moreover, orifice and electrode life were both significantly extended. For the latter, the use of argon as a plasma gas provides the lowest rate of erosion (see section 2.5.2.4)

Finally, another area which was found to cause a number of problems and requires further development of the torch design was the adjustment of the torch stand-off distance. Although the use of a large number of Tufnol layers could provide the appropriate adjustment, continuous variation of a parameter found to exert significant influence on the weld bead geometry results obtained during the feasibility studies was not possible. Furthermore, the need to replace the Tufnol layer every time that the stand-off distance needed to be changed proved to be time consuming, since it required the re-assembly of the plasma torch, new tapes to be placed for avoidance of gas leakage and the electrode to be re-centralised.

6.3 Influence of Major Welding Parameters on Arc Voltage Characteristics

The unique characteristics of the developed system and in particular of the developed plasma torch provoked the investigation of the influence of the major welding variables on arc voltage, since the product of arc voltage with welding current provides a useful approximate estimation of the thermal capacity of the welding arc and highlights the physical mechanisms which dictates the observed arc behaviour.

6.3.1 The Effect of Orifice Diameter

Results indicated a significant increase in arc voltage as orifice diameter decreases (see section 5.2.2.2). Since the anode and cathode voltages are not affected by the orifice diameter the latter is attributed to the effect of the constricting nozzle on the flow conditions of the plasma gas and its influence on the arc column component. The reduction of the available area through which the current can flow results in an increase of current density which is necessary to maintain the current. The latter produces a higher column resistance, therefore for a given current to pass through this high resistance extra energy is required for its conduction which appears

as higher voltage and power dissipation, and consequently increases the arc temperature [4]. Furthermore, higher gas velocities are produced with decreased orifice diameters for a given gas flow rate as a result of the law for the conservation of mass. This is associated with an increase of the plasma gas kinetic energy and therefore increase of the overall resistance which also explains why increased voltage values are observed with increasing plasma gas flow rates. At the same time, convective, conductive and radiation losses also increase due to the rise in arc column temperature.

This description is consistent with the similar results obtained for the melt-in-mode plasma welding of Ti-3Al-2.5V tubes with both orifice diameters and indicates why higher torch body temperatures were recorded when the smaller orifice diameter was utilised.

6.3.2 The Effect of Plasma Gas Flow Rate

The very small but systematic increase in arc voltage with increasing plasma gas flow rate, which is evidence of increasing thermal power of the arc for the range of plasma gas flow examined was expected. The phenomenon can be explained in two different ways. The first, suggested by Demin et al [129] argues that the increased thermal power is due to an increase in the thickness of the cold insulating layer of gas which protects the walls of the torch and reduces the extent of heat losses from the arc column to the nozzle causing an increase in the intensity of the arc column electric field necessary to maintain the current passing through the reduced available area.

The second explanation suggests that with higher plasma gas flow rates extra energy is required to heat the extra gas mass forced into the arc column to sufficient temperature to maintain the conduction of a given current due to the increased particle collision frequency. This also results in an increase in arc voltage.

The author is of the opinion that both explanations are valid and that both phenomena described take place at the same time.

6.3.3 The Effect of Electrode Set Back

The nature of the experimental set-up employed during this investigation gave rise to an increase in the total arc length along with any increase of the electrode set back distance. However, it can be assumed that the increased arc voltage values recorded (see section 5.2.2.3) can solely be attributed to the effect of altering the electrode set back distance and, therefore, the total arc length since the free arc length remained unaltered.

As already described in section 5.2.2.3, electrode set back influences the gas flow pattern of the plasma gas. However, the author considers that for the electrode set back distances and orifices employed along with the torch geometry utilised, changes in gas flow patterns do not contribute significantly to the voltage variations observed.

6.3.4 The Effect of Electrode Vertex Angle

The small increase in arc voltage with increase of the electrode vertex angle may be attributed to the effect of electrode angle on arc structure. With the electrode set back distances utilised, which place the electrode away from the orifice throat area, the electrode angle did not have any effect on the actual constricting diameter of the orifice, mathematically described by Richardson (see section 2.4.2.6), which will result in higher gas velocities and therefore increased arc voltage values. The increase in arc voltage observed with smaller angles may be attributed to the increased plasma jet velocity due to higher current density at the electrode tip [151].

6.3.5 The Effect of Welding Current

As mentioned in section 5.2.2.5 the voltage-current curve had a form similar to that of a free burning arc. It can be described by an empirical expression described by Nottingham which has the following form:

$$V=A+BI+CI^{-n}$$

where A: constant associated electrode fall effects,

B: constant associated with ohmic heating

while C and n represent modified electrode fall voltage behaviour.

The negative slope arm of the curve at very low currents investigated by a number of researchers was qualitatively explained in terms of arc energy loss mechanism and forces dictating the phenomenon [1, 37]. It was found that energy transport at low currents is dominated by buoyancy forces. The positive slope arm of the curve is associated with an energy mechanism driven by electromagnetic forces. The almost linear curve indicates the ohmic nature of the arc for this current range, which like any other normal ohmic conductor possesses a constant resistance and has a straight line V-I characteristic curve with a specific slope.

Another significant advantage revealed by the V-I curves is that the negative slope obtained for current values approximately less than 20A is smaller than that obtained with a TIG arc, which further contributes to arc stability. The reason is that buoyancy forces dominating the outer regions of low current TIG arcs causing lack of stability and directionality are suppressed in the outer regions of a plasma arc by the enforced gas flow. Furthermore, according to Richardson [37] "the arc finds it energetically more favourable to maintain the enthalpy flow (generated by the movement of hot gas away from the cathode region) parallel to the applied gas flow than to take the shortest distance from the cathode to the anode which minimises the arc length but increasing the energy loss due to convection".

6.3.6 The effect of Shielding Gas Flow Rate and Shielding Gas Composition

One of the most substantial differences between the developed orbital plasma welding system and conventional plasma torches is the introduction of the shielding gas from a number of holes situated around the rotor and not through a shielding cup positioned around the orifice. This was expected to significantly affect the arc structure since the shielding gas is surrounding and not penetrating the plasma column. Nevertheless, results recorded indicated that the effect of the shielding gas flow rate was insignificant. Therefore, it can be assumed that changes in the shield gas flow did not have any effect on the arc gas flow since the arc voltage was not affected.

Ionisation of gas surrounding the plasma arc resulted in a less constricted arc, particularly when argon was used, due to the ionisation of argon molecules. The same phenomenon was also observed with Ar+5% H_2 as a shielding gas, however the hydrogen additions resulted in a hotter and more constricted arc [33], as indicated by the results obtained during the keyhole welding of austenitic stainless steels (lower current and plasma gas flow rate values required for stable keyhole operations). Furthermore, the observed increase in arc voltage values with the 5% hydrogen addition in the shielding gas is attributed to the extra energy required to ionise the diatomic hydrogen molecules (higher ionisation potential than argon) which creates a barrier around the plasma arc (see section 24.2.4). However, apart from the arc voltage rise no other change in the general V-I characteristics was observed.

6.3.7 General Evaluation of the Arc Voltage Values

The unique characteristics of the orbital torch modification do not allow any direct comparison of the arc voltage values recorded with results obtained with other plasma torches. However it must be stressed that maximum arc voltage values recorded were not excessive and, therefore, consistent with stable operation. All arc voltage values recorded were significantly lower than the maximum open circuit voltage of the BDH 320 power source (80V).

6.4 Modelling of Orbital Plasma Welding Procedures

The results of the current work indicated the difficulties encountered along with the advantages obtained from the application of orbital plasma welding techniques in small bore tubes using the prototype system. Quality welds were produced and critical defects investigated (i.e. porosity and weld variability) were eliminated using the experimental strategy developed in section 3.5. A deeper understanding of the general process behaviour and characteristics was also achieved. The simplicity of the developed empirical models along with the precise representation of the weld outcome can provide the basis for a system that could emulate a welders control actions for a future on-line control strategy. More importantly it gives the opportunity to predetermine optimum welding parameters which can make the procedure tolerant to unexpected parameter variations. Furthermore, it provides the flexibility for re-evaluation of the procedures utilised if

this is considered necessary, offering information on the impact of the major welding parameters on the resultant weld. It must be noted that the final system allows the engineer to have a personal influence on the determination of the most suitable welding parameters suggested, through a number of parameter and quality constraints also incorporated. Therefore, experience and empirical information which are very difficult to record in any system which tries to emulate a process, are also indirectly incorporated.

Information related to a number of bead characteristics (inner/outer bead width ratio, fusion zone area, graphical representation of the inner and outer bead width profiles) can be used as criteria for evaluation of the risk of certain geometrical defects (primarily risk of undercut based on I/O ratio). *Therefore the final system could be better described as an information-calculation system for optimising welding procedures based on models built using regression analysis techniques.*

Identification of suitable operational envelopes for full penetrated welds along with off-line modelling of the following output characteristics have been used as the basis for the developed system:

- I. outer bead width,**
- II. inner bead width,**
- III. undercut type and significance (where necessary).**

The very small thickness of the examined tubes made it both impracticable and unnecessary to investigate the influence of the major plasma welding parameters on penetration characteristics since the range of penetration depths obtained is very small and welds are usually classified either as "fully penetrated" or "incompletely penetrated". At the same time plasma gas flow rates employed during the identification of the operational envelopes were kept within reasonable limits, particularly when the melt-in-mode was used, since the use of excessive flow rates in order to achieve full penetration could result in an increased risk of porosity, while at the same time, penetration will be vulnerable to (sometimes unavoidable) plasma gas flow rate fluctuations.

It must be stressed that the large number of parameters associated with plasma welding makes it possible that more than one "suitable" operational envelope exists for the same tube. Nevertheless, before starting the experimentation for data collection, emphasis was given to the avoidance of using excessive input parameter levels, such as high plasma gas flow rates, large electrode set back distances, even smaller orifice diameters than already used, or very low current values combined with very low welding speeds since all these could affect other aspects of the welding procedure (e.g. unstable operation or reduced productivity).

6.4.1 Assessment of the Experimental Techniques

Considering the very large number of parameters associated with orbital plasma welding, the strategy followed for simultaneous development of the operational envelopes along with model building proved to be very successful. It provided all the necessary information required for the development of the empirical models, which in turn represent the data they have been derived from. Furthermore, the number of trials required was minimised, since the number of experiments conducted outside the full penetration area was kept to a minimum. The quick establishment of the envelope boundaries allowed for a more detailed investigation within the envelopes and in particular in the more promising areas. However, the most important advantage of this experimental technique was the fact that it allowed for experience gained during each previous stage of the experimentation, related to process performance and effect of input parameters, to be used in the subsequent stages. Moreover, better experimental blocking was also achieved, making for example a large number of experiments using the same electrode set back distance, thus providing more homogeneous experimental groups, and reducing the number of abnormal points that could distort the analysis of the data. The latter also eliminated the problems associated with inconsistent and incorrect electrode centralisation which could be faced if continuous alteration of the ESB distance was required. Another example of the benefits gained through the experimental blocking utilised is the investigation of the influence of welding speed, keeping all other input parameters constant. The experience gained in this way provided useful information for the next "welding speed" trial series indicating areas where further experimentation was of little practical value and, therefore, allowing more useful information to be extracted.

The selection of the input variables to be examined for use during the model building phase of the project was very significant, due to its influence on the developed models. The selection was based on:

- experience gained during the feasibility studies conducted at a preliminary stage of the project,
- the special characteristics of the developed prototype system and,
- the available resources.

In addition, it was very soon established that the predominant factors affecting the weld bead characteristics were welding current and welding speed. Therefore, a larger increment and less experimentation was used for the investigation of the other input variables, thus reducing the number of experiments required to an acceptable level.

6.4.2 Assessment of the Model Development Techniques

The initial stage of the modelling strategy adopted involved the use of multiple regression analysis techniques (least square method) in order to obtain good fit mathematical equations for a number of specified welding positions along the weld circumference. The equations produced provided the models relating the major input variables with the quality objectives which were either quantitative (inner and outer bead widths) or qualitative (undercut for keyhole welding). The techniques used to obtain these equations have already been described in chapter 5 for each different condition along with the basic concepts utilised during the model building phase in each case. The following two assumptions were made during this stage:

- a. The sample used for model development is representative of the large number of operating conditions (parameter combinations) that may be used so that inferences may be considered valid. This was partially assured by following the strategy described in the previous section (6.4.1) which also made sure that the sample obtained, "parallels" the population with respect to certain key characteristics which were thought to be important during this investigation.
- b. The effect of each predictor variable was assumed to be linear within the parameter range examined, although non-linear effects could also be

accommodated if necessary through the introduction of extra indicator variables based on a more qualitative analysis of the results, from the welding technology point of view and from results obtained during correlation analysis which reveal certain trends. However only the substantial correlation between the average welding current and welding speed (HI_1/WS) which provides an indication of the heat input was introduced as a regressor in all the developed models. This was the only function found to significantly increase the explanatory power of the developed models.

It must be stressed that during the regression analysis process the derivation of models that produced "best fit" to the results was not the only criterion applied. Effort was focused on developing models that will comply with the following criteria:

1. Include all those independent variables that have a significant effect on the overall process performance and stability (i.e. HI_1 , WS , $PGFR$, ESB , HIS) and not just those that are statistically significant (HI_1 , WS and $PGFR$ with HIS in some cases). This means that all the parameters originally selected during the experimental design stage were finally included in the model structure.
2. Use of the same model structure for all the conditions and positions investigated provided that it offers a satisfactory fit to the results. It was observed that further introduction of regressors into the finally proposed equation did not give any significant improvement in the accuracy of the models, while at the same time adding complication to the physical interpretation of the estimated coefficients. In general the aim of this research work was to provide simple model structures based on factors that will give them physical substantiation. The latter will offer the possibility of using the same structure for pipes of different diameter and thickness or different materials, altering only the value of the estimated coefficients.

Investigation of the residuals conducted for all the developed models related to bead width also indicated that the multivariate model structure adopted provided unbiased linear regression models. Nevertheless, the same model structure was also used for the development of fuzzy models for undercut and for which analysis of residuals was not performed since the deviations between the observed values and the estimated values are assumed to depend on the indefiniteness of the system. Moreover,

these deviations are regarded as the fuzziness of the parameters of the system which are reflected in the linear functions with fuzzy parameters developed (see section 5.3.3.2).

The lower fitting values of the models obtained for the melt-in mode welding of the 316L tubes (although still acceptable-see table 27a) can be attributed to the quality of the welded material and the influence of surface active elements on the fluid flow in the weld pool (weld variability problems). Nevertheless, the technique not only offered more tolerant procedures but also significantly reduced the influence of material variations on the resultant weld as a result of the hot and stiff arc produced. The consistency of the results obtained and the process performance in keyhole welding of the thicker 316L tubes is an indication that this technique is not affected by minor variations in the chemical composition.

Taking all the above into consideration it can be seen that there is a close connection between the experimental design, the regressors selected and the final form of the models. Although a number of model structures might be suitable for the available data, the selection of those regressors that will be included in the equation is rather subjective and strongly influences the practical value of the predictions made since a complicated or an incorrect model structure could lead to wrong conclusions.

During this investigation, a primary target was to provide simple equations that could provide a high degree of confidence in predicting the required weld bead output characteristics and can also indicate the influence upon them of the major input parameters. Furthermore, the development of equations for a number of positions along the weld bead profile provided an accurate representation of geometric characteristics throughout the weld bead. This allowed a better evaluation of heat build-up and undercut in the orbital welding of small bore tubes, to be obtained for any parameter combination utilised within the experimental range used for the development of the models. The latter illustrates that each model has very little practical value unless combined with all others developed for each position. This combination leads to the development of a very useful tool for optimisation of the process, which will be analysed in section 6.4.3. In addition, the influence of all major parameters on the characteristics of the whole weld can also be evaluated. This model combination was achieved in a user friendly form by using an EXCEL 5.0 spreadsheet, which offered a number of significant advantages as already described in section 5.6.

It must be emphasised, that following the validation of the models, these can be used for data generation which is very important considering that one of the biggest problems for the exploitation of the plasma process is the large number of parameter combinations that exist. The latter allows the end user to assess the outcome of parameter combinations for which experiments have not been made. Therefore, a simple validation of the suggested results is required which again reduces the number of experiments that must be made in order to achieve a desirable outcome. This reduces the cost of process development through the minimisation of time and materials required.

It is considered that similar spreadsheets can be developed for any case using just a limited number of experiments, provided that the experimental design employed will capture all the useful information required so that the models do not to give misleading results.

The different characteristics of the materials employed (e.g. composition, thermal coefficient, thickness, diameter of the tube) along with the unique characteristics of the plasma mode utilised for each material, not only prompted a separate detailed investigation but also lead to an individual assessment of the influence of major welding parameters on the weld bead geometry which is presented below.

6.4.3 Optimum Parameter Selection - Criteria and Constraints

As already described in section 2.5.2 one of the major problems encountered in orbital welding of small diameter tubes is the difficulty in ensuring a stable weld width and in particular, a stable inner bead width along the entire length of the joint because the temperature field does not reach the quasi-steady state in the zone of formation throughout the entire welding process. This weld width increase - which is more pronounced for certain geometrical dimensions (i.e. very small diameters) and certain material thermophysical properties (i.e. high thermal conductivity) - can be a major drawback for the application of plasma welding, particularly in the keyhole mode, since it enhances the danger of weld pool collapse. In addition, increase of the weld width might impair the structure of the metal for certain parameter combinations increasing cracking susceptibility while it might be beneficial for other

combinations by reducing for example the solidification rate and therefore decrease the risk for porosity (e.g. titanium and titanium alloys).

Heat build-up was found to be related to a number of input parameters, although results indicated that welding current and welding speed, the two input parameters primarily associated with the total heat input in the anode, were exerting the most significance influence on the progressive heating of the weld area. Although direct comparison is not possible for the three tubes investigated, its influence on weld bead variation appeared to be significantly lower in keyhole welding mainly because of heat losses through the keyhole efflux (the purging gas is carrying away the heat) and the different weld pool formation mechanism (see sections 2.2.3.1 and 2.2.3.2). Weld bead variation in this case, and particularly with the use of Ar+10% H_2 , was found to be mainly due to problems related to the equipment (see section 5.3.1) and with the special characteristics of keyhole formation in the starting position.

Another output characteristic found to be significantly affected during this investigation by the progressive heating of the weld area was undercut, mainly observed in keyhole welding. Undercut significance and type were both found to vary along the weld bead profile for certain parameter combinations. Although undercut formation is a very complex phenomenon related to a very large number of parameters (see section 2.4.3.5), results obtained may be explained in terms of high arc forces and more specifically high arc pressures [151, 170, 181, 182]. The latter is again associated with a number of parameters. It is believed that the very small orifice diameter and the very small stand-off distance originally employed made it difficult to eliminate undercut which was found in most of the welds. However, these parameters remained constant throughout the experimentation therefore changes in the undercut characteristics of the weld bead profile were attributed to:

- **welding speed:** high welding speeds increase the cooling rate of the molten metal and reduce the weld pool size, which promotes undercut formation since it increases the probability of crystallisation of the edges of the weld pool before it is filled. Heat build-up on the other hand decreases the cooling rate of the molten metal and increases the weld pool size, therefore a gradual decrease in the intensity of types of undercut associated with fast cooling rates was observed along the weld progression (see figure 109b). By contrast, heat build up had a

negative effect when parameter combinations providing undercut-free conditions were originally employed, leading to types of undercut associated with weld pool depression for a given arc pressure, due to an increase of the weld pool volume.

Previous research work [58] had established that welding speed did not have any effect on arc pressure and arc pressure distribution and, therefore, this could not be one of the reasons for higher probability of undercut formation with increase in welding speed.

- **welding current:** welding current seems to have a substantial influence on undercut formation, which appears to be complex and difficult to evaluate in tube welding, mainly because current has a simultaneous influence on the following two areas:
 - the heat build-up, because heat input increases linearly with average current and, therefore, heat accumulation also increases and,
 - the arc pressure which is a combination of electromagnetic forces and gas flow effects. This has been shown to increase approximately in proportion to the square of current [22].

The use of low welding currents for example increases the weld pool cooling rate which promotes undercut, but at the same time significantly reduces arc force which diminishes undercut and in addition enhances in most cases weld bead uniformity by reducing the problems related to heat build-up.

On the contrary, the use of high currents decreases the weld pool cooling rate which reduces the risk of undercut but at the same time increases arc force significantly which may cause weld pool depression and additionally increases the risk of significant weld bead variation.

Therefore, it is considered that in general when a lower heat input is required for undercut elimination, current reduction is the most appropriate remedial action, while the use of welding speed as a control parameter is recommended when higher heat input is required. Arc pressure, when necessary, can only be significantly affected by current variation. Furthermore, experimental results indicated that PGFR and ESB,

which can also influence the arc pressure and can be used as an alternative, have an insignificant influence on undercut characteristics for the parameter range utilised.

Arc current pulse frequency and shielding gas composition were also found to exert a significant influence on undercut characteristics (see section 6.5).

The complexity of the plasma process, further enhanced by the difficulties described above, makes the optimisation of procedures problematic. The interrelated welding parameters utilised along with the relatively large number of models required to describe the weld bead must all be treated simultaneously. Therefore, the methodology used becomes critical for the success of the optimisation. Several criteria and constraints must simultaneously be considered in order to evaluate the optimum set of input parameters for a specific application. To ensure the quality, reliability and strength of a weldment, a wide inspection programme is generally required which greatly depends upon the intended service of the product. Nevertheless, the quality of the weld that will be acceptable for one welding application may not meet the needs of another. The latter indicates that the selection of the "optimum set of input parameters" is a rather subjective decision, which is mainly based on the requirements of an application (as these are illustrated in the specification of the product) and which is also influenced by the approach of the welding engineer to the problem. This is due to the fact that there may be several approaches to an optimisation procedure, taking into consideration factors that cannot be included in a specification, such as the tolerance of the procedure to unexpected parameter variations, the solidification rate required to avoid porosity or whether high or low arc pressure is beneficial to avoid weld variability problems.

The optimisation strategy developed during this investigation was designed as a system that could incorporate a large amount of information related to the bead characteristics of the weld and which incorporates the operating characteristics of the torch design to combine a number of parameter and quality constraints which will allow the user to influence the selection of the optimum parameters. By doing this, the developed models are not only capable of providing the user with the best answer to the problem, which as already mentioned is subjective to a certain extent, but also offers a convenient framework for understanding the problem. The latter is also assisted by the simplicity of the developed models which realistically represent the situation and which also allow data to be easily collected and conclusions to be drawn

from the experimental results. Different "optimum" parameter combinations found as a result of varying parameter and quality constraints, also indicate the practical value of the models.

This work has shown that there are a number of ways of expressing uniformity of the weld bead. Undercut type and intensity are more difficult to express in numerical terms due to the characteristics of the defect which makes it difficult to identify a unique quantifiable characteristic. Nevertheless several indices were constructed and used as objective functions. The RW index (width range between the maximum and minimum bead width) was generally found to be the one offering the best results, since the two other statistical indexes constructed, the COV index (coefficient of variation of the bead width) and the STDEV index (standard deviation of the bead width), were found to be influenced to a certain extent by the values of the bead widths (high or low).

Welding current and welding speed were found to be the most influential input variables and, therefore, the optimisation of the bead characteristics was mainly based on their control. The product of the delay time and average starting current employed during the modelling of titanium tube weld bead characteristics proved to exert significance influence only at the beginning of the weld (see section 5.4.1). It was particularly important when lower welding currents or high welding speeds are utilised since it provides a means for ensuring full penetration. This problem is attributed to the relatively low tube temperatures next to the starting position and therefore to the consumption of the heat for the parent metal to reach melting temperatures.

All the procedures derived gave very satisfactory results. Targeted defects were prevented which is particularly advantageous from an economic point of view, although this requires some commitment to careful following of the pre-weld procedures, particularly in keyhole welding due to the very small thickness of the tubes.

6.5 Individual Effect of the Input Variables

Before proceeding to the following part it must be stressed that all the prime variables investigated are interrelated in their effect on the quality characteristics. Therefore, the individual effect of each parameter is complex and only the following

generalisations can be made using the experimental results, which are only valid for the parameter ranges examined.

Influence of the Orifice Diameter (OD)

Contrary to expectations, orifice diameter was not found to play an important role in the weld bead characteristics of Ti-3Al-2.5V tubes (see section 5.4.2). Although the total arc power increases due to the increased arc constriction, similar weld bead characteristics were obtained with both orifice diameters utilised. It has been estimated (see Appendix E) that approximately the same percentage of the generated heat is dissipated in the torch body for both orifice diameters. Furthermore, similar fusion areas were obtained under the same welding conditions. Therefore, it can be assumed that the extra power generated with the smaller orifice diameter (0.56mm OD) is lost in the surrounding environment, without making any significant contribution to increasing the fusion zone area. However, it must be emphasised that the above observation does not imply that the influence of orifice diameter on weld bead characteristics is not important across the range of orifice diameters.

The more depressed weld bead surface generally observed with the smaller orifice is attributed to the higher arc force achieved with the smaller orifice diameter for a constant plasma gas flow velocity. Although this increases the possibility for full penetration when low current and high welding speeds are employed, it also increases the possibility of burning through the metal, particularly in the final welding positions as a result of the fusion area increase due to heat build-up.

In addition, reduced arc stability and the increased probability of double arcing and subsequent electrode damage were also observed with the smaller orifice diameter indicate that the optimum orifice diameter for the specific application and with the present experimental set-up is the 0.79mm OD. Its use also permitted a marginal increase in fusion area.

Influence of the Preheating Effect at the Start of the Welding (HIS)

In general, it has been shown that for the tube diameter utilised that the temperature distribution and therefore the weld bead characteristics in the Ti-3Al-2.5V tube are only slightly influenced by the preheating effect at the start of the welding. Only the first position investigated (position 3) just after the initiation of

heads rotation is significantly affected with a variation greater than 10% in all output characteristics examined. However, it was observed that even this small influence can become particularly significant for very low current applications, since, as already noted, there is always the danger of incomplete penetration at the beginning of welding due to the low tube temperature. Furthermore, the use of high heat input during the starting segment reduces the cooling rate at the preliminary stages of the weld where fast cooling rates can result in gas entrapment and pore formation.

By contrast, the relatively low thermal conductivity of the 316L tubes, combined with heat input during the starting segment could lead to weld pool collapse in melt-in mode welding and for such small thicknesses due to the significant heat accumulation at the starting area. Therefore, preheat is not considered necessary in this occasion and is better avoided (see section 5.3.2.2).

Influence of the Plasma Gas Flow Rate (PGFR)

Plasma Gas Flow Rate has a multifunctional role in orbital tube plasma welding and in plasma welding in general.

PGFR was found to exert only a very small influence on weld bead characteristics in melt-in mode welding of Ti-3Al-2.5V and in keyhole welding of 316L tubes. However, it must be emphasised that results obtained with Ti-3Al-2.5V tubes surprisingly indicated a small but systematic decrease in the inner bead width and correspondingly in the fusion area as PGFR increased (see section 5.4.3). This experimental observation, seems to indicate that the larger stream of cooler non-ionised gas that impinges on the weld edges with higher PGFR decreases the penetrating power of the arc rather than increases it. This trend was not observed in the melt-in mode welding of 316L tubes where PGFR increase resulted in a significant increase of all bead measurements. This may be understood in terms of increased arc pressure and improved process efficiency with increased PGFR. The increase in process efficiency in melt-in mode welding can be partially accounted for by the fact that as the PGFR increases arc voltage increases and the resultant heat input increases as well. Also lower torch temperatures achieved with higher PGFR reduce the heat losses in the torch body. Increased arc pressure contributes to the increased Inner/Outer bead width ratio obtained with higher PGFR. However, different

experimental conditions (e.g. significantly different stand-off distance) do not allow direct comparison between experiments performed on the Ti-3Al-2.5V and 316L tubes.

By contrast, in keyhole welding of 316L tubes, PGFR increase results in a greater keyhole efflux and the percent of heat losses out of the bottom of the keyhole increases. Therefore, PGFR does not have any profound influence on weld bead characteristics. Contrary to expectations, it was also observed that PGFR did not play any significant part in undercut formation for the small flow rate range investigated. Nevertheless, it must be emphasised that in orbital welding PGFR has one of the most important roles in forming and sustaining the keyhole. This, together with the electromagnetic forces, which are strongly influenced by the current value utilised, comprise the two main forces continuously supporting keyhole opening (see section 2.5.2-Beam Pressure). Therefore, it was absolutely vital to control the value of the PGFR throughout the welding operation since any significant variation which could lead to keyhole instability and could also result in either loss of penetration or weld pool collapse. In addition, it was found that equilibrium of the keyhole cannot subsequently be reinstated with the original welding parameters. It appeared that there was a minimum PGFR (1.7l/min approximately) at which full penetration was consistently achieved in all welding positions and for all the parameter combinations employed (with pure argon as shielding gas). This value was further reduced with the hydrogen additions as a result of the higher arc pressure achieved. In all cases, the tolerance of the developed procedures to PGFR instabilities was sufficient to allow for small, sometimes unavoidable, PGFR variations although the equipment utilised provided a relatively accurate PGFR (± 0.14 l/min, see section 4.9.1).

Apart from being the medium for transportation of the thermal and kinetic energy of the arc to the base metal the plasma gas is also the medium that protects the orifice from high temperatures. In general, it was observed that a PGFR equal to or greater than 0.3l/min was adequate to provide this protection when argon was used, although this value also depends on both current and orifice diameter. In general, smaller orifice diameters and higher current values require higher plasma gas flow rates for protection of the nozzle walls since these conditions reduce the size of the insulating gas layer that protects the nozzle walls.

Influence of the Electrode Set Back Distance (ESB)

Electrode Set Back Distance was not found to exert any significant influence on the output characteristics investigated. The latter, combined with the slightly higher torch temperatures recorded with higher ESB shows that although higher arc voltages, i.e. higher arc powers, are attained with increased ESB, heat losses are also higher. The latter results in reduced process efficiency [also reported by Metzler (175)], therefore, the overall process performance seems to be unaffected by the ESB distance employed.

Influence of the Shielding Gas Composition (SGC)

The effect of Shielding Gas Composition on weld bead quality and characteristics in keyhole welding of 316L tubes was found to be very important. Benefits obtained can be attributed to the improved heat transfer, the hotter and more constricted arc obtained with hydrogen additions in the shielding gas (see section 2.4.2.4.B).

The increased arc constriction obtained with a 10% hydrogen addition particularly results in improved weld bead uniformity and reduces the effect of heat build-up on weld bead characteristics, permitting the use of only one set of input parameters for the whole circumference. Furthermore, the significantly improved heat input obtained (also indicated by the higher arc voltages) permits the use of higher welding speeds and lower current values in order to obtain weld bead geometries similar to those with a pure argon shielding gas. Heat losses in the plasma torch are higher than with argon, as torch temperature measurements indicate, but still, significantly improved results are observed with hydrogen additions.

On occasions, the hotter more constricted arc gave rise to humping which was observed even at low currents and high welding speeds. Undercut was also observed for most input parameter combinations utilised as a result of the increased concentration of the thermal flux.

Another important benefit acquired with hydrogen additions in the shielding gas is the significantly cleaner inner and outer bead surfaces obtained due to the reducing action of the gas, which assists in the removal of oxides.

Influence of the Welding Speed (WS)

The effect of welding speed on undercut formation in conjunction with Welding Current has already been analysed in section 6.2.4.2. Therefore this section is restricted to the influence of WS on the other weld bead output geometries.

It was observed throughout the investigation of the statistical models that for a suitable welding current there is a wide range of welding speeds that can produce acceptable welds. This becomes particularly important in keyhole welding where a tolerant procedure is required to minimise the possibility of keyhole disruption.

Another general observation in all situations investigated was that the outer bead width decreases as the travel speed is increased and the inner bead decreases at a faster rate than the outer bead as the welding speed is increased, as a result of the decreased heat input per unit volume. Increased speeds also result in a reduction in the heat build-up and therefore enhanced weld bead uniformity. Decrease of the fusion area and the Inner/Outer bead width ratio were also observed as a result of decreasing widths. The rate of decrease depends primarily on the welding current utilised. It must also be noted that particularly in keyhole welding, low welding speeds increase the length of time over which the arc acts on a given area of metal increasing the risk of weld pool collapse. Similar behaviour to conventional GTAW was also observed for a given degree of penetration, where an increase in welding speed requires an increase in welding current required. However, in practice, other welding parameters and primarily welding current determines the required welding speed.

Influence of the Welding Current (HI_1)

Current pulsation using high frequency thermal pulsing was used throughout the modelling investigation. The peak current level was always selected to be lower than the orifice rating. The lowest background level was always selected so that the largest pulsed current differential, which ensured penetration for all welding positions, could be used (equipment limitation: 5A), since a more forceful arc can thus be produced while gravitational forces can more easily be controlled for the wide range of welding speeds investigated. Furthermore, low background levels provided rapid cooling between pulses while constant plasma gas flow rate maintained the

keyhole. High frequency thermal pulsing also reduced the risk of weld pool collapse since excessive keyhole sizes were not formed. Large keyholes eventually lead to burn-through and cutting as illustrated in figure 121. In addition, excessive pulse times lead to greater energy losses through the keyhole efflux. Another disadvantage, particularly for the thinner materials, is the increased undercut (both tramline effect for low heat inputs and weld pool sinkage for high) observed with high peak current values and short pulse times and which can be attributed to the high arc pressures developed along with rapid cooling rates. Nevertheless, current pulsation provides the necessary enhanced tolerance in the procedures for all three tubes examined, and particularly for keyhole welding operations through the improved control of weld pool behaviour afforded by intermittent solidification. The small weld bead dimension increase, obtained with the lower frequencies, indicated a marginally improved heat transfer. Finally, it must be emphasised that improved weld bead uniformity obtained with current pulsation [as supported by a number of researchers (28, 29, 33, 186)], is particularly important in orbital welding due to the heat build-up problem encountered.

In general for all conditions investigated, an increased average welding current widens both the inner and outer weld beads, the former at a higher rate, as a result of the higher heat input. The faster increase rate of the inner bead width which results in increased Inner/Outer bead width ratios with increased welding currents can primarily be attributed to the increased arc pressures obtained (arc pressure is directly proportional to the square of welding current). This is consistent with similar observations for increased plasma gas flow rates and decreased welding speeds.

6.5 Industrial Applications and Limitations.

As already stated in section 6.1, the industrial need for solutions to specific problems provided the motivation for this project. The plasma torch modification combined with the process optimisation technique developed can provide a reliable solution to a large number of applications, extending the use of plasma welding in both melt-in and keyhole modes for the orbital welding of small diameter tubes. The flexibility and simplicity of the software are also some of the significant benefits of this work, despite the problems encountered with the prototype equipment. The software places emphasis on different aspects of weld quality providing the opportunity to control simultaneously (off-line) a large number of quality problems

and particularly heat build-up and undercut. The latter, as the literature survey indicated, is a very complex phenomenon which is difficult to be controlled particularly in plasma keyhole welding and normal technique in industry is the use of a second melt run or the use of a filler wire addition. In addition uniform weld beads can be achieved despite the heat build-up and equipment problems which contribute to weld bead non-uniformity.

Demonstration software which illustrates the use of the developed optimisation algorithm for defect prevention through optimum parameter generation along with the simulation of the weld bead characteristics has been written for all three tubes examined. The demonstration disk along with instructions for use are available with this thesis.

It is considered that the major limitation of this work (apart from the constraints related to the development of the equipment, which can all be eliminated with further modifications) is the fact that it depends on experimentation and calculation of statistical results for particular materials and thicknesses. However, the three situations investigated indicate that the concept utilised for process optimisation, the model structure selected and the statistical techniques employed can potentially be used in many other situations.

In summary this study has resulted in:

1. A prototype system for low current orbital plasma welding (in both melt-in and keyhole mode) of small bore tubes in a totally enclosed head and,
2. A systematic methodology for the prediction and optimisation of welding procedures based on predetermined criteria.

7. Conclusions

7. CONCLUSIONS

The detailed account of the torch modification for orbital plasma welding, the parameter optimisation technique and the influence of the major factors upon them have been reported and discussed in the preceding sections. The work conducted indicated that plasma welding is one of the most promising techniques for the quick and economical quality orbital welding of small bore tubes. Progress was achieved in gaining a deeper understanding of how the parameter combinations affect the weld quality characteristics, and the weld bead characteristics are now quite controllable. A summary of the most important points arising from the different subject areas of this investigation will be given below.

A: TORCH MODIFICATION FOR PLASMA WELDING

1. The appropriate extraction of the generated heat from the torch body is important for the functionality of the system in order to avoid continuous alteration of the arc properties and torch damage. Inappropriate extraction of the heat also results in low duty cycles and very small production rates. The use of a big copper mass can successfully support low current applications.
2. The welding current is the dominant factor affecting the torch temperature, while a minimum plasma gas flow rate is required for nozzle protection.
3. Volt-Ampere characteristics produced with the "copper" cooled plasma torch and with the introduction of the gas through holes situated around the rotor of the head are similar with those of a conventional plasma torch.
4. The proper atmosphere developed in the chamber eliminates the need for a pilot arc when low ionisation potential gases are employed. The latter also improved electrode life increasing significantly the number of runs before re-grinding was required.

B: MODEL DEVELOPMENT FOR ORBITAL PLASMA WELDING

1. It has been established that statistical analysis techniques can successfully be utilised for the development of empirical models describing the weld bead geometry characteristics (outer and inner bead widths and undercut) in the orbital plasma welding of small bore tubes.

2. As a result of problems related to heat build-up which particularly affects small bore tubes, a number of models are required for the various welding positions. These have been combined in order to obtain an accurate representation of the weld bead characteristics along the joint .
3. Weld bead uniformity and undercut elimination can be controlled through the selection of the appropriate parameter combinations.
4. Off-line programming based on a procedure generator system not only provides defect prevention but also allows the user to take into consideration different materials and mode aspects.

C: INFLUENCE OF MAJOR FACTORS AFFECTING WELD BEAD CHARACTERISTICS

1. It has been established that significant weld bead uniformity can be achieved using only one set of input parameters for the whole circumference despite the problems encountered with the progressive heating of the tubes (heat build-up). Use of more than one segment will further enhance the outer and inner bead uniformity.
2. Welding current and welding speed are the two most influential factors on weld bead formation. Plasma gas flow rate significantly affected the output characteristics only in melt-in mode welding of 316L tubes. Nevertheless it was established that PGFR plays a very significant role in the stability of the plasma process.
3. Stable and tolerant melt-in mode conditions have been developed for Ti-3Al-2.5V and 316L tubes. Analysis indicated that porosity did not occur in the titanium tubes and no significant problems were encountered with weld variability in austenitic stainless steel tubes.
4. Stable keyhole conditions have been developed for small diameter (12.7mm), thin (1.25mm) 316L tubes. The allowable range of variation for the major welding parameters (welding current, welding speed, plasma gas flow rate) was sufficient to provide a tolerant procedure.
5. Undercut formation is the major problem encountered in keyhole welding. The number of parameter combinations offering undercut-free welds is small and in close association with the other conditions employed (primarily shielding gas composition, frequency of the current pulsation). However, average welding current and welding speed are the two dominant factors controlling the formation of weld defects.

6. The use of hydrogen additions in the shielding gas significantly improves the results obtained in the keyhole welding of 316L steels, reducing the current required to achieve a given bead geometry.
7. The outer bead width of the welds increases as the welding current increases and decreases as the welding speed decreases. The inner bead width increases at a faster rate than the outer bead as the current is increased and decreases at a faster rate than the outer bead as the speed is decreased.
8. The small thickness of the examined tubes makes the procedures intolerant to any gap or misalignment during butt welding.

8. Recommendations for Future Work

8. RECOMMENDATIONS FOR FURTHER WORK

Despite the problems encountered in this study, it is clear that the orbital microplasma welding (in both keyhole and melt-in modes) does offer a reasonable alternative to GTAW for the applications under consideration. The majority of the problems encountered were related to equipment limitations with the present prototype weld head. Given the close nature of the interaction between parametric envelopes and welding torch design, it is proposed that further modification and improvement of the head design must be carried out with particular emphasis in the areas of:

- **effective cooling of the torch,**
- **flexible adaptation of the stand-off distance.**

The modelling technique utilised must be further developed to include the effect of changes in the type of material, thickness and composition, shielding gas, stand-off distance and current pulsing frequency in the statistical models developed for the weld bead characteristics. The final models could subsequently be used for on-line quality control of the process based on the measurement of suitable transient signals which can possibly be arc voltage, arc sound or back pressure. However, the latter needs extensive experimentation to establish the relationships between the transient signal and the output weld bead quality characteristics, which will form the basis of a closed-loop control system along with the models already developed relating the major plasma welding parameters with the quality characteristics.

The welding head and the control system integration will finally provide a totally integrated-intelligent materials processing system for plasma welding operations, flexible enough to adopt to a range of material compositions and thicknesses and to any new equipment, thus making the process independent of the unique characteristics of each system.

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Appendices

APPENDIX A

Chemical composition of the materials under investigation.

1) Ti-3Al-2.5V

Specification: AECMATi-P69

Designation: prEN3120

Size: 10mm X 0.6mm

Al	C	Fe	H	N	O	V	OT	Other
2.5-3.5	0.05 max.	0.3 max.	0.015 max.	0.02 max.	0.12 max.	2.5-3.5	0.4 max.	Y 0.005 max. O E0.1 max. bal. Ti

2) 316 Austenitic Stainless Steel

Type: Seamless, Cold Drawn

Manufacturer: Sumikin SS Tube Co., Japan

Size: 12.7mm X 0.71mm

C	Si	Mn	P	S	Cr	Mo	Ni
0.070	0.33	1.34	0.023	0.001	16.25	2.04	11.19

3) 316L Austenitic Stainless Steel

Type: Seamless

Manufacturer: Schoeller Bleckmann, Germany

Size: 12.7mm X 1.25mm

C	Si	Mn	P	S	Cr	Mo	Ni
0.025	0.30	1.43	0.027	0.006	17.11	2.11	12.12

4) 316L Austenitic Stainless Steel

Type: Seamless

Manufacturer: Unknown

Size: 12.7mm X 1.21mm

Chemical composition not provided

Table B1: Average Recorded Temperature Measurements at 10sec Intervals for Various Parameter Combinations (SGC: Pure Argon).

Time(sec)	HT1(°C)	HT2(°C)	HT3(°C)	HT4(°C)	HT5(°C)	HT6(°C)	HT7(°C)	HT8(°C)
0	20	20	20	20	20	20	20	20
10	42	0	39	48	38	48	39	40
20	58	76	53	69	50	69	50	56
30	70	94	63	85	61	83	62	67
40	79	112	73	99	69	96	73	76
50	89	127	81	112	78	109	82	83
60	101	141	89	122	89	120	93	91
70	96	138	85	116	84	116	88	87
80	92	133	82	111	79	110	84	83
90	91	129	81	108	77	108	81	81
100	89	125	80	106	76	106	79	80
110	87	123	78	104	74	104	78	79
120	86	120	76	101	73	101	76	77
130	84	118	74	100	72	99	75	76
140	84	118	74	98	71	99	74	75
150	82	116	73	97	71	97	74	75
160	82	114	72	96	70	96	73	74
170	81	113	72	95	69	95	72	74
180	80	111	71	94	68	93	71	73
190	80	110	70	93	67	92	70	72
200	79	109	69	91	66	91	70	72
210	78	108	68	91	65	90	69	71
220	77	106	68	89	65	89	68	71
230	76	105	67	88	64	88	68	70
240	76	105	66	87	64	87	67	69

Experimental Conditions:

HT1: HI₁: 10A, OD: 0.56mm, PGFR: 1l/min, SGFR: 15l/min, ESB: 1.4mm, SDT: 2.15mm

HT2: HI₁: 15A, OD: 0.56mm, PGFR: 1l/min, SGFR: 10l/min, ESB: 1.1mm, SDT: 2.15mm

HT3: HI₁: 10A, OD: 0.56mm, PGFR: 2l/min, SGFR: 10l/min, ESB: 1.4mm, SDT: 2.15mm

HT4: HI₁: 15A, OD: 0.56mm, PGFR: 2l/min, SGFR: 15l/min, ESB: 1.1mm, SDT: 2.15mm

HT5: HI₁: 10A, OD: 0.79mm, PGFR: 1l/min, SGFR: 15l/min, ESB: 1.1mm, SDT: 2.20mm

HT6: HI₁: 15A, OD: 0.79mm, PGFR: 1l/min, SGFR: 10l/min, ESB: 1.4mm, SDT: 2.20mm

HT7: HI₁: 10A, OD: 0.79mm, PGFR: 2l/min, SGFR: 15l/min, ESB: 1.1mm, SDT: 2.20mm

HT8: HI₁: 15A, OD: 0.79mm, PGFR: 2l/min, SGFR: 15l/min, ESB: 1.4mm, SDT: 2.20mm

Table B2: Average Recorded Temperature Measurements at 5sec Intervals for Various Parameter Combinations (SGC: Ar+5%H₂).

Time(sec)	TEMP1 (°C)	TEMP2 (°C)
0	20	20
5	36	38
10	47	51
15	67	72
20	82	89
25	94	106
30	108	126
35	120	138
40	132	149
45	143	163
50	154	176
55	165	197
60	177	214
65	171	204
70	163	196
75	159	192
80	157	190
85	156	188
90	155	186
95	153	184
100	152	181
105	151	180
110	150	178
115	149	177
120	147	175
125	146	174
130	145	172

Experimental Conditions:

TEMP1: HI₁: 22A, OD: 0.79mm, PGFR: 1.1l/min, SGFR: 10l/min, ESB: 1.8mm, SDT: 2.20mm

TEMP2: HI₁: 28A, OD: 79mm, PGFR: 1.1l/min, SGFR: 10l/min, ESB: 1.8mm, SDT: 2.20mm

Table C1: Influence of Torch Heating Up on Arc Voltage (AV)

Time (sec)	Pure Argon, O.D: 0.56mm		Pure Argon, O.D: 0.79mm		Ar+5%H ₂ OD: 0.79mm	
	Temperature	AV	Temperatu	AV	Temperatur	AV
0	20		20		20	
2		23.4		19.53		25.36
4	32	22.99	30	19.28	34	25.19
6		22.84		19.17		25.12
8		22.77		19.16		25.05
10	47	22.71	43	19.22	49	25
12		22.67		19.15		24.94
14	55	22.64	50	19.07	65	24.89
16		22.62		18.94		24.8
18		22.61		18.9		24.73
20	71	22.6	63	18.83	89	24.7
22		22.58		18.81		24.68
24	75	22.53	66	18.75	103	24.63
26		22.55		18.71		24.55
28		22.52		18.69		24.9
30	82	22.51	72	18.66	126	24.42

Experimental Conditions:

SGC: Pure argon, OD: 56mm, HI_i: 15A, PGFR: 1.0l/min, SGFR: 10l/min, ESB: 2.0mm, SDT: 2.15mm.

SGC: Pure argon, OD: 79mm, HI_i: 15A, PGFR: 1.0l/min, SGFR: 10l/min, ESB: 2.0mm, SDT: 2.20mm.

SGC: Ar+5%H₂, OD: 79mm, HI_i: 28A, PGFR: 1.1l/min, SGFR: 10l/min, ESB: 1.8mm, SDT: 2.20mm.

Table D1: Influence of Orifice Diameter (OD) on Arc Voltage for Three Different Plasma Gas Flow Rates (PGFR)

OD(mm)	0.5l/min	0.7l/min	0.9l/min
0.56	23.85V	24.08V	24.25V
0.79	19.2V	19.71V	20.18V
1.17	14.18V	14.55V	14.78V
1.63	15.55V	15.77V	15.9V

Experimental Conditions:

OD: 0.56mm, HI₁: 15A, ESB: 1.45mm, SDT: 2.15mm, EA: 20°

OD: 0.79mm, HI₁: 15A, ESB: 1.40mm, SDT: 2.20mm, EA: 20°

OD: 1.17mm, HI₁: 15A, ESB: 0.55mm, SDT: 3.05mm, EA: 20°

OD: 1.63mm, HI₁: 15A, ESB: 1.30mm, SDT: 2.30mm, EA: 20°

Table D2: Influence of ESB on Arc Voltage for Three Different Plasma Gas Flow Rates and Two Orifice Diameters

OD(mm)	ESB(mm)	0.3l/min	0.7l/min	1.1l/min
0.79	1	18.61V	18.77V	18.85V
0.79	1.4	19.94V	20.04V	20.09V
0.79	1.8	20.74V	21.08V	21.14V
1.63	0.9	13.02V	13.13V	13.56V
1.63	1.3	14.54V	14.84V	15.03V
1.63	1.7	15.49V	15.73V	16.19V

Experimental Conditions:

OD: 0.79mm, HI₁: 30A, SDT: 2.20mm, EA: 20°

OD: 1.63mm, HI₁: 30A, SDT: 2.30mm, EA: 20°

Table D3: Influence of EA on Arc Voltage for Three Different Plasma Gas Flow Rates and Two Orifice Diameters

OD(mm)	EA(°)	0.3l/min	0.7l/min	1.1l/min
0.79	20	19.74V	20.05V	20.16V
0.79	40	19.21V	19.24V	19.48V
1.63	20	14.68V	14.76V	14.91V
1.63	40	14.02V	14.17V	14.48V

Experimental Conditions:

OD: 0.79mm, HI₁: 30A, ESB: 1.40mm, SDT: 2.20mm

OD: 1.63mm, HI₁: 30A, ESB: 1.30mm, SDT: 2.30mm

Table D4: Influence of Welding Current on Arc Voltage for Two Different Shielding Gases and Various Orifice Diameters

CUR(A)	OD:0.79mm pure Ar	OD:1.63mm pure Ar	OD:0.56mm Ar+5%H ₂	OD:0.79mm Ar+5%H ₂
5	20.57V	16.41V		25.2V
7			28.65V	
10	19.2V	15.71V	28.29V	24.7V
13			29.7V	
15	18.83V	15.4V		24.27V
20	18.6V	15.17V		24.09V
25	19.21V	15.39V		23.91V
28				24.76V
30	19.47V	15.55V		
35		15.74V		
40		15.79V		
45		15.96V		

Experimental Conditions:

OD: 0.79mm, SGC: pure Ar, PGFR: 0.7l/min, ESB: 1.1mm, SDT: 2.20mm, EA: 20°

OD: 1.63mm, SGC: pure Ar, PGFR: 0.7l/min, ESB: 1.3mm, SDT: 2.30mm, EA: 20°

OD: 0.79mm, SGC: Ar+5%H₂, PGFR: 0.7l/min, ESB: 1.1mm, SDT: 2.20mm, EA: 20°

OD: 56mm, SGC: Ar+5%H₂, PGFR: 0.6l/min, ESB: 1.9mm, SDT: 2.15mm, EA: 20°

Table D5: Influence of PGFR on Arc Voltage for Four Different Orifice Diameters

PGFR(l/min)	OD:0.56mm	OD:0.79mm	OD:1.17mm	OD:1.63mm
0.3	22.43V	18.67V	14.1V	15.12V
0.7	22.79V	18.97V	14.59V	15.5V
1.1	23.12V	19.2V	15.06V	15.61V
1.5	23.4V	19.5V	15.45V	16.03V

Experiimental Conditions:

OD: 0.56mm, HI₁: 30A, ESB: 1.45mm, SDT: 2.15mm, EA: 20o
OD: 0.79mm, HI₁: 30A, ESB: 1.40mm, SDT: 2.20mm, EA: 20o
OD: 1.17mm, HI₁: 30A, ESB: 0.55mm, SDT: 3.05mm, EA: 20o
OD: 1.63mm, HI₁: 30A, ESB: 1.30mm, SDT: 2.30mm, EA: 20o

Table D6: Influence of SGFR on Arc Voltage for Two Different Shielding Gases and for Various Welding Currents

HI ₁ (A)	SGFR:7l/min OD:0.79mm Ar+5%H ₂	SGFR:14l/min OD:0.79mm Ar+5%H ₂	SGFR:7l/min OD:0.56mm Ar+5%H ₂	SGFR:14l/min OD:0.56mm Ar+5%H ₂	SGFR:10l/min OD:1.63mm pure Ar	SGFR:15l/min OD:1.63mm pure Ar	SGFR:10l/min OD:0.79mm pure Ar	SGFR:15l/min OD:0.79mm pure Ar
5A	25.5V	25.2V			16.41V	16.35V	20.57V	20.48V
7A			29.81V	28.65V				
10A	24.53V	24.7V	29.5V	28.29V	15.71V	15.78V	19.2V	19.3V
13A			30.95V	29.7V				
15A	24.05V	24.27V			15.4V	15.2V	18.83V	18.74V
20A	24.4V	24.62V			15.17V	15.1V	18.6V	18.33V
25A	24.1V	23.91V			15.39V	15.49V	19.21V	18.98V
28A	24.92V	24.76V						
30A					15.55V	15.7V	19.47V	19.45V
35A					15.74V	15.78V		
40A					15.79V	15.84V		
45A					15.96V	15.93V		

Experimental Conditions:

SGC: Ar+5%H₂, OD: 0.79mm, PGFR: 0.7l/min, ESB: 1.4mm, SDT: 2.20mm, EA: 20°
SGC: Ar+5%H₂, OD: 0.56mm, PGFR: 1.1l/min, ESB: 1.9mm, SDT: 2.15mm, EA: 20°
SGC: pure argon, OD: 0.79mm, PGFR: 0.7l/min, ESB: 1.4mm, SDT: 2.20mm, EA: 20°
SGC: pure argon, OD: 1.63mm, PGFR: 0.7l/min, ESB: 1.1mm, SDT: 2.30mm, EA: 20°

APPENDIX E

The total heat input estimated based on arc voltage values measured for the 0.79mm OD and for the 0.56mm OD during the investigation of the characteristics of the system and for a typical 20sec arcing period is given by the following equation:

Total Heat Input = Average Current*Average Voltage*20sec
and was found to be

a: 7275J for the 0.56mm orifice diameter and b: 6054J for the 0.79mm orifice diameter for the following parameter combination:

Average Welding Current: 15A

Plasma Gas Flow Rate: 0.9l/min (pure argon)

Electrode Set Back: 1.45mm

Torch Stand Off Distance: 2.15mm

Shielding Gas Flow Rate: 10l/min (pure argon)

Estimated Arc Voltage Value for the 0.56mm orifice diameter: 24.25V

Estimated Arc Voltage Value for the 0.79mm orifice diameter: 20.18V

The amount of heat absorbed by the torch was estimated by the equation:

$$Q=m*c*\Delta\theta$$

assuming that the specific heat of the copper is not changing significantly with alteration of the copper body temperature and also that the whole copper torch body was reaching the same temperature throughout the duration of the arcing time.

Q was found to be:

a: 4304J for the 0.56mm orifice diameter and b: 3746J for the 0.79mm orifice diameter for similar parametric combinations where:

$\Delta\theta$ for the 0.56mm orifice diameter and for 20sec arcing time: 54K

$\Delta\theta$ for the 0.79mm orifice diameter and for 20sec arcing time: 47K

$\Delta\theta$ estimations were made using torch body temperatures derived from the temperature models.

The above simplified estimations indicate that approximately 59% and 62% of the heat generated by the arc is absorbed by the torch for the 0.59mm and 0.79mm orifice diameters respectively. The latter reveals that similar heat losses take place for both orifice diameters investigated.

Tables

Table 1: Comparison of Control Parameters necessary for the Specification of Various Arc Welding Processes (from [7])

General – all processes				
Welding Current	Arc Voltage			
Polarity	Welding Speed	Welding Position	Workpiece Geometry	
Workpiece Composition	Torch-workpiece Geometry	Welding Direction		
Gas shielded processes				
Shielding gas composition	Shielding gas flow rate	Shielding gas nozzle diameter (at exit)		
Non Consumable Processes		Continuous Wire Processes		
Electrode composition	Electrode Geometry	Contact tube size	Contact tube position	
Electrode diameter	Arc length	Torch stand off	(extension/set back)	
Filler wire – weld pool geometry	Filler wire addition rate	Wire feed rate	Wire diameter	
	Filler wire composition			
Plasma	GTAW	GMAW	FCAW	SMAW
Electrode set back	Electrode extension	Wire Manufacturer and Composition	Manufacturer (and wire/flux composition)	Electrode diameter
Plasma gas composition			Wire classification	Manufacturer
Plasma gas flow rate				(and core/flux composition)
Constriction nozzle diameter				Electrode Classification
Constriction nozzle geometry				
Plenum chamber geometry				
Throat length				
Pilot arc current				
Pilot arc voltage				

Table 2: Classification of Weld Joint Discontinuities (from [125])

Welding Process or Procedure Related	
A. Geometric	
Misalignment	
Undercut	
Concavity or convexity	
Excessive reinforcement	
Improper reinforcement	
Overlap	
Burn-through	
Backing left on	
Incomplete penetration	
Lack of fusion	
Shrinkage	
Surface irregularity	
B. Other	
Arc strikes	
Slag inclusions	
Tungsten inclusions	
Oxide films	
Spatter	
Arc craters	
Metallurgical	
A. Cracks or fissures	
Hot	
Cold or delayed	
Reheat, stress-relief, or strain-age	
Lamellar tearing	
B. Porosity	
Spherical	
Elongated	
Worm-hole	
C. Heat-affected zone, microstructure alteration	
D. Weld metal and heat-affected zone segregation	
E. Base plate laminations	
Design Related	
A. Changes in section and other stress concentrations	
B. Weld joint type	

Table 3: Typical Plasma and Shielding Gas Combinations for Plasma Welding of Different Materials (from [169])

Material	Plasma gas	Shielding gas
Mild steel	Argon	Argon Argon/2.5% Hydrogen*
Low alloy steels	Argon	Argon
Austenitic stainless steels	Argon	Argon/2.5% Hydrogen Helium*
Nickel & nickel alloys	Argon	Argon Argon/2.5% Hydrogen*
Titanium	Argon	Argon 75% Helium/25% Argon*
Copper & copper alloys	Argon	Argon 75% Helium/25% Argon*

Note: * signifies a gas or mixture that is also used.

Table 4 Common causes and remedies for incorrect bead size and appearance

Defects	Causes	Remedies
• Poor bead appearance	<ul style="list-style-type: none"> ♦ Poor shielding gas flow ♦ Entrapment of air or moisture in the gas ♦ High temperature oxidation of the inner bead ♦ dirty workpieces 	<ul style="list-style-type: none"> ⇒ Adjust gas flow rate ⇒ Check the installation ⇒ Modify the under bead protection ⇒ clean workpieces
• Misalignment of weld bead	<ul style="list-style-type: none"> ♦ Poor torch inclination ♦ Magnetic arc blow (with DC) ♦ poor joint preparation 	<ul style="list-style-type: none"> ⇒ Change inclination ⇒ Revise earth connections ⇒ Modify
• Excessive reinforcement and/or root convexity	<ul style="list-style-type: none"> ♦ Incorrect welding parameter selection ♦ Incorrect consumable selection (e.g. shielding gas) ♦ poor operating technique 	<ul style="list-style-type: none"> ⇒ Modify welding parameters ⇒ Modify ⇒ better control of welding parameters and automation
• Root concavity	<ul style="list-style-type: none"> ♦ Incorrect welding parameter selection (especially high currents and slow travel speeds) ♦ poor operating technique 	<ul style="list-style-type: none"> ⇒ Modify welding parameters ⇒ better control of welding parameters and automation
• Distortion	<ul style="list-style-type: none"> ♦ Error in prediction of distortion 	<ul style="list-style-type: none"> ⇒ Revise clamping methods and/or clamping equipment and/or welding parameters and/or modify predistortions

Table 5. Common causes and remedies for burn-through and overpenetration		
Defects	Causes	Remedies
<ul style="list-style-type: none"> • Overpenetration and/or Burn-through 	<ul style="list-style-type: none"> ♦ Current too high ♦ Welding speed too slow ♦ Insufficient root face ♦ Too great gap ♦ torch-joint misalignment ♦ plasma gas flow rate too high ♦ poor joint preparation 	<ul style="list-style-type: none"> ⇒ reduce current ⇒ reduce welding speed ⇒ modify the procedure or use a slight weave ⇒ reduce gap ⇒ modify and/or add an automatic tracking device ⇒ adjust plasma gas flow rate ⇒ modify preparation and/or welding procedure

Table 6: Common causes and remedies for inadequate penetration and lack of fusion		
Defects	Causes	Remedies
<ul style="list-style-type: none"> • Inadequate penetration and/or lack of fusion 	<ul style="list-style-type: none"> ♦ welding speed too high ♦ current too low ♦ insufficient weld pool at the start ♦ improper joint design ♦ incorrect electrode position ♦ incorrect torch inclination ♦ welding speed too slow resulting in weld metal running ahead of the arc ♦ plasma gas flow rate too low ♦ too large orifice diameter 	<ul style="list-style-type: none"> ⇒ reduce welding speed ⇒ increase current ⇒ increase "pre-fusion" time ⇒ modify design and/or welding procedure ⇒ adjust electrode position ⇒ modify inclination ⇒ increase welding speed and/or lower current ⇒ increase plasma gas flow rate and/or revise procedure ⇒ decrease orifice diameter and/or revise procedure

Table 7 Common causes and remedies of porosity or gas pockets		
Defect	Causes	Remedies
• Porosity or gas pockets	<ul style="list-style-type: none"> ♦ Insufficient flow of shielding gas ♦ Air entrapment in the welding atmosphere ♦ High solidification rate ♦ Rusty, greasy or moist base metal ♦ Excessive moisture on joint surfaces or in electrode covering ♦ Dirty filler wire ♦ Air and moisture ingress to gas lines ♦ High content of sulphur, carbon and phosphorus in base metal 	<ul style="list-style-type: none"> ⇒ Increase flow rate ⇒ Use screens ⇒ Increase heat input or preheat the materials ⇒ Clean base metal ⇒ Bake and store electrodes according to specifications ⇒ Use of appropriate quality assurance for consumable handling ⇒ Regular check of the connections ⇒ adjust the composition of the filler wire ⇒ Change base metal ⇒ Preheat the base metal

Table 8. Common causes and remedies for undercut formation		
Defect	Causes	Remedies
• Undercut	<ul style="list-style-type: none"> ♦ welding speed too high ♦ high current ♦ torch joint misalignment ♦ poor torch inclination ♦ presence of gap ♦ high voltage ♦ high plasma gas flow rate for a given orifice diameter ♦ low heat input ♦ small orifice diameter used with high energy plasma 	<ul style="list-style-type: none"> ⇒ reduce welding speed and/or revise welding procedure ⇒ reduce current ⇒ modify and/or add an automatic tracking device ⇒ change inclination ⇒ reduce gap ⇒ reduce voltage ⇒ reduce plasma gas flow rate and/or modify procedure ⇒ increase heat input ⇒ increase orifice diameter and/or modify procedure

Table 9: Typical Orbital Welding Heads and their Manufacturers (from 191).

A - Tubes up to 250 mm external diameter using a specific welding head

[illegible]

B - Tube/pipe welding using a crawler or track type unit

Manufacturer	Country origin	Model	Range of diameters (mm)	Method of		Orientation		Beam tracking (yes/no)	Method of welding				Wire feeder inbuilt or separate	Type of filler wire
				fixing to pipe	travel around pipe	fixed (yes/no)	method		Uphill	Downhill	300°	2 x 180°		
Arg Machines Inc (An Oerlikon Co.)	USA	118	25-1000	Guide ring	Roll and pivot on head/guide ring	Yes	Mechanical	Yes (opt.)	Yes	Yes	Yes	Yes	Inbuilt	Conventional materials
Dinvernia	USA	Gold Trade II Orbitas	12-1830	Track mounted clamps	Friction drive nylon rolls	Yes	Electronic	No	No	Yes	Yes	Yes	Inbuilt	For all dc applications
Robert Bros Inc.	USA	-	12-1000	Split clamping and guide ring	Head clamps to guide ring and travel round pipe	Yes	Electric drive with remote control of frequency and amplitude	Weld controlling remotely variable	Unit welds continuously around pipe				Inbuilt with 100 mm speed	Depends on pipe
Huntingdon Fusion Techniques Ltd	USA	-	50-1300 (larger on request)	Guide ring	Orbital carriage with direct positive drive	Yes	Cross-beam with dwell	Cross beam adjustable	Information N/A at present				Built in	Depends on pipe
Messer Griesheim Ltd	France	-	200 yards	Chain	Motor driven on 4-wheel hinged carriage	Yes	Sinusoidal/ rectangular	Position of welding head controls weld size on conver- sion of beam	No	No	Yes	No	In built	Depends on pipe
		-	250-1000	Track	4 wheel clamps to metal track 2 motor drive	Yes	Sinusoidal/ rectangular		No	No	Yes	No	In built	Depends on pipe
NEI Weldcontrol	UK	Low profile	50 mm -	Guide ring	Gear ring recessed into guide ring	Yes	Electro-mech. 20 mm travel variable speed/ dwell Electro mech.	Not standard	A full 300° rotation may be achieved, back winding after 3-4 revolutions				In built	102 mm sp
		Fixed head	50 mm -	Latch type rotator	Tube rotates	Yes		Not standard	Continuous multipass welding				Separate	102 mm sp
RTA SRL	Italy	Modular expandable system	-	Clamping ring, hydraulic	Roll with whisk rotation motors mesh	Yes	Variable	Yes	-	-	Yes	-	In built	TIG Coated wire

Table 10: Technical Specification of the BDH 320 Power Source

Power source	BDH 320
Mains voltage <ul style="list-style-type: none"> - standard version - version with change-over switch 	3x400 V $\pm 10\%$ 3x230 V $\pm 10\%$ 3x400/440/500 V $\pm 10\%$
Fuse	According to typeplate on the machine
Consumption max.	12,1 kVA
Efficiency	0.85
No-load effect	100 W
Permitted load: <ul style="list-style-type: none"> - 40% duty cycle - 60% duty cycle - 100% duty cycle 	320 A 260 A/30.8 V
Open circuit voltage MMA,MIG/MAG,TIG	80 V
Current range	5 - 320 A
Internal wire feed unit (Compact/Combi)	as KT14
Water module: <ul style="list-style-type: none"> - Cooling effect - Cooling capacity 	850 W 7 l
Application class	S
Protection class	IP 21
Norm	EN60974 EN50199
Dimensions without wire feed unit	67x46x80 cm
Weight incl. water module	110 kg
Wire feed unit, type	KT12/KT14
Operating supply voltage	24 Vac
Effect, 1-2 pcs.	105 W
Wire dimension	0.8 - 3.2 mm
Wire reel capacity	5 - 15 kg
Wire speed	1 - 24 m/min.
Dimensions	70x40x21 cm
Weight	22 kg

Table 11: Gas Combinations Utilised During the Experimental Study			
(PGFR, SGFR)	Argon, Argon	Argon, Argon+5%H ₂	Argon, Argon+10%H ₂
TUBES			
Ti-3Al-2.5V	•		
316L (Melt-in Mode)	•		
316L (Keyhole Mode)	•	•	•

Table 12: Weld Colour Significance and Suggested Remedy Actions in Titanium Welding (from [81])			
Color of Titanium	Significance	Shielding	Remedy
Silver	Generally a good weld	Good	
Straw to very light blue	Acceptable weld	Fair	Discoloration should be removed with stainless steel brush before next pass.
Blue or purple	Poor weld	Poor	Remove weld bead and adjacent metal completely; improve shielding before welding.
Gray or yellow	Very poor weld	Extremely poor	Remove weld bead and heat-affected zone completely. Examine shielding equipment for leaks, gas supply, etc. Make test welds before rewelding.

Table 13: Summary of Potentially Significant Input Variables for Orbital Plasma Welding

1. Welding Current
2. Welding Current Modulation
 - Current waveform
 - Peak Current
 - Peak Current Time
 - Background Current
 - Background Current Time
3. Welding or Travel Speed
4. Plasma Gas Flow Rate
5. Plasma Gas Composition
6. Shielding Gas Flow Rate
7. Shielding Gas Composition
8. Purging Gas Flow Rate
9. Purging Gas Composition
10. Electrode Set Back Distance
11. Electrode Stand-off Distance
12. Electrode Diameter and Type
13. Plasma Torch position
14. Plasma Torch Inclination
15. Orifice Diameter
16. Orifice Geometry
17. Plasma Chamber Geometry
18. Throat Length
19. Welding Position
20. Welding Sequence and Number of Segments utilised
21. Welding mode employed (Melt-in or Keyhole)
22. Material Composition
23. Material Thickness
24. Edge and Plate Preparation
25. Equipment Type
26. Pilot Arc Current (where applicable)

Table 14a: Classification of Parameters into Categories

Variables

Preset or Background

1. Electrode Stand-off Distance
2. Electrode Diameter and Type
3. Plasma Torch position
4. Plasma Torch Inclination
5. Orifice Geometry
6. Plasma Chamber Geometry
7. Throat Length
8. Welding Position
9. Welding mode employed (Melt-in or Keyhole)
10. Material Composition
11. Material Thickness
12. Edge and Plate Preparation
13. Equipment Type
14. Pilot Arc Current (where applicable)

Explanatory Variables

1. Welding Current
2. Welding Current Modulation
 - Current waveform
 - Peak Current
 - Peak Current Time
 - Background Current
 - Background Current Time
3. Welding or Travel Speed
4. Plasma Gas Flow Rate
5. Plasma Gas Composition
6. Shielding Gas Flow Rate
7. Shielding Gas Composition
8. Purging Gas Flow Rate
9. Purging Gas Composition
10. Orifice Diameter
11. Electrode Set Back Distance
12. Welding Sequence and Number of Segments utilised

Table 14b: Classification of Explanatory Variables into Categories

A1: Directly Controllable

1. Welding Current
2. Welding or Travel Speed
3. Plasma Gas Flow Rate
4. Shielding Gas Flow Rate
5. Purging Gas Flow Rate

A2: Observable

1. Welding Current
Modulation
2. Plasma Gas Composition
3. Shielding Gas
Composition
4. Purging Gas
Composition
5. Orifice Diameter
6. Electrode Set Back
Distance
7. Weld. Sequence &
Number of Segments
utilised

B1: Primary

1. Welding Current
2. Welding or Travel Speed
3. Plasma Gas Flow Rate
4. Welding Current
Modulation
5. Weld. Sequence and
Number of Segments
utilised

B2: Secondary

1. Plasma Gas Composition
2. Shielding Gas
Composition
3. Purging Gas
Composition
4. Shielding Gas Flow Rate
5. Purging Gas Flow Rate
6. Orifice Diameter
7. Electrode Set Back
Distance

Table 15: Technical Specification of the Tufnol Layer Utilised for the Development of the Torch Modification

Technical specification	
Cross breaking strength	130MPa
Impact strength, notched, charpg	11.5kJ/m ²
Compressive strength, flatwise	310MPa
Compressive strength, edgewise	200MPa
Shear strength flatwise	90MPa
Relative density	1.36
Insulation resistance after immersion in water	1x10 ⁹ ohms
Max. working temp:	
continuous	120°C
intermittent	130°C
Thermal conductivity through laminae	0.32W(mk)
Thermal expansion in plane of laminae	2.2x10 ⁻⁵ /K
Specific heat	1.5kJ/(kgK)

Table 16: Experimental Planning Matrix 2 ⁵⁻² for the Torch Temperature Investigation					
Independent Variables	WI (A)	OD (mm)	PGFR (l/min)	SGFR (l/min)	ESB (mm)
Basic level	12.5	-----	1.5	12.5	1.3
Range of Variation	2.5	-----	0.5	2.5	0.2
Upper level	15	0.79	2	15	1.5
Lower level	10	0.56	1	10	1.1

Table 17: Welding Conditions and Experimental Sequence						
Trial No.	Experim. Sequence	WI (A)	OD (mm)	PGFR (l/min)	SGFR (l/min)	ESB (mm)
HT1	1st and 9th	10	0.56	1	15	1.4
HT2	2nd and 13th	15	0.56	1	10	1.1
HT3	5th and 10th	10	0.56	2	10	1.4
HT4	7th and 16th	15	0.56	2	15	1.1
HT5	4th and 12th	10	0.79	1	15	1.1
HT6	3rd and 15th	15	0.79	1	10	1.4
HT7	8th and 11th	10	0.79	2	10	1.1
HT8	6th and 13th	15	0.79	2	15	1.4

Table 18: Correlation Analysis Results Based on Estimated Average Temperature Measurements													
CORRELATION ANALYSIS RESULTS													
	WI	O.D	SGFR	PGFR	ESB	10SEC	20 SEC	30SEC	60 SEC	90SEC	120SEC	180SEC	240SEC
WI	1												
O.D	0	1											
SGFR	0	0	1										
PGFR	0	0	0	1									
ESB	0	0	0	0	1								
10SEC	0.75	-0.41	-0.26	-0.36	-0.22	1.00							
20 SEC.	0.80	-0.42	-0.20	-0.34	-0.12	0.99	1.00						
30SEC	0.78	-0.42	-0.20	-0.33	-0.20	1.00	1.00	1.00					
60 SEC	0.70	-0.41	-0.27	-0.38	-0.30	0.99	0.97	0.99	1.00				
90SEC	0.69	-0.45	-0.30	-0.39	-0.24	1.00	0.98	0.99	1.00	1.00			
120SEC	0.70	-0.44	-0.28	-0.40	-0.24	1.00	0.98	0.99	1.00	1.00	1.00		
180SEC	0.71	-0.45	-0.27	-0.38	-0.24	1.00	0.98	0.99	1.00	1.00	1.00	1.00	
240SEC	0.70	-0.44	-0.27	-0.40	-0.23	0.99	0.98	0.98	0.99	1.00	1.00	1.00	1.00

Table 19: Torch Temperature Regression Analysis Coefficients and Models Adequacy Checking								
	10	20	30	60(max)	90	120	180	240
a_0	58.35	74.12	99.41	177.86	161.91	147.34	133.04	125.53
a_1	1.55	2.95	3.65	5.10	4.80	4.40	4.05	3.75
a_2	18.48	33.70	42.39	65.22	67.39	60.87	55.43	51.09
a_3	3.75	6.25	7.75	14.00	13.50	12.50	10.75	10.75
a_4	0.55	0.75	0.95	2.00	2.10	1.80	1.55	1.45
a_5	7.50	7.50	15.83	36.67	28.33	25.00	22.50	20.83
R^2	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.97
Radj.	0.89	0.92	0.91	0.88	0.92	0.90	0.92	0.90
SE	1.77	2.76	3.76	6.67	5.39	4.92	4.372	4.60
F-ratio	13.42	17.62	15.10	11.62	16.29	16.06	16.60	13.19
Sign. F (P value)	0.07	0.05	0.06	0.08	0.06	0.06	0.06	0.07

Table 20: Parameters Utilised for Temperature Measurements Validation Trials						
Trial No.	Experim. Sequence	WI (A)	OD (mm)	PGFR (l/min)	SGFR (l/min)	ESB (mm)
VALT1	1st	11	0.56	1.8	14	1.3
VALT2	2nd	13	0.56	1.5	9	1.1
VALT3	3rd	14	0.79	1.3	12	1.4

Table 21 (contd):Parameter Combinations Utilised and Responses Obtained Using the 0.56mm O.D

No	POSITION-OBW						POSITION-IBW					
	3	8	13	18	23	28	3	8	13	18	23	28
1	2.4	2.1	2.1	2.3	2.5	2.7	1.9	1.6	1.5	1.7	2.1	2.3
2	2.1	1.8	1.9	2.0	2.2	2.3	1.4	0.8	1.2	1.3	1.6	1.7
3	2.0	1.9	1.9	2.1	2.3	2.4	1.4	1.0	1.3	1.4	1.8	2.0
4	2.1	2.0	2.1	2.2	2.4	2.5	1.4	1.3	1.5	1.7	1.9	2.1
5	2.2	1.9	1.9	2.1	2.4	2.5	1.4	1.3	1.1	1.4	1.8	1.9
6	2.1	2.0	2.1	2.2	2.4	2.5	1.3	1.1	1.4	1.7	1.9	2.0
7	1.8	1.7	1.9	1.9	2.1	2.3	1.0	1.0	1.1	1.5	1.7	1.8
8	2.4	2.0	2.0	2.2	2.3	2.5	1.8	1.3	1.4	1.5	1.7	2.0
9	1.9	1.7	1.9	2.0	2.2	2.3	1.2	1.0	1.1	1.4	1.5	1.6
10	2.5	2.5	2.5	2.7	2.9	3.0	2.0	2.0	2.0	2.2	2.5	2.6
11	1.9	1.7	1.8	1.9	2.0	2.0	1.0	0.8	0.7	0.9	1.1	1.2
12	2.1	2.0	2.0	2.1	2.3	2.5	1.4	1.3	1.3	1.2	1.6	1.8
13	2.1	2.1	2.3	2.4	2.7	2.7	1.6	1.5	1.7	1.8	2.2	2.2
14	2.0	2.0	2.1	2.2	2.4	2.5	1.3	1.3	1.3	1.5	1.8	1.8
15	2.3	2.3	2.4	2.5	2.8	2.8	1.5	1.7	1.8	2.0	2.4	2.5
16	1.9	1.7	1.8	1.9	2.0	2.0	0.9	0.7	0.7	1.0	1.2	1.3
17	2.5	2.7	2.9	3.1	3.2	3.3	2.0	2.2	2.5	2.7	3.1	3.2
18	2.2	2.2	2.4	2.4	2.5	2.6	1.4	1.5	1.6	1.7	2.0	2.1
19	2.4	2.4	2.5	2.7	2.9	2.9	1.7	1.9	2.0	2.2	2.4	2.5
20	1.9	1.9	2.0	2.1	2.2	2.3	1.0	1.2	1.2	1.4	1.6	1.6
21	2.8	3.1	3.2	3.4	3.8	3.8	2.4	2.6	2.7	3.2	3.6	3.7
22	3.0	3.3	3.4	3.8	4.1	4.2	2.5	2.9	3.2	3.6	4.0	4.1
23	3.0	2.9	2.9	3.1	3.4	3.5	2.5	2.5	2.6	2.9	3.3	3.4
24	2.5	2.4	2.4	2.6	2.9	2.9	2.0	2.0	1.9	2.2	2.6	2.6
25	2.2	1.9	1.9	2.0	2.3	2.3	1.5	1.3	1.2	1.4	1.7	1.8
26	2.8	2.8	2.9	2.9	3.2	3.2	2.4	2.5	2.5	2.5	2.9	2.9
27	2.5	2.6	2.6	2.7	2.9	2.9	2.0	2.0	2.0	2.1	2.5	2.5
28	2.9	2.6	2.5	2.9	3.1	3.2	2.3	2.1	2.0	2.4	2.7	2.8
29	2.1	2.4	2.4	2.5	2.7	2.7	1.5	1.8	1.9	2.0	2.4	2.4
30	1.9	1.7	1.8	2.0	2.1	2.1	1.0	0.8	0.9	1.1	1.3	1.3
31	2.5	2.4	2.6	2.7	3.0	3.0	2.1	2.0	2.1	2.3	2.6	2.7
32	2.6	2.4	2.6	2.7	3.0	3.0	2.0	1.9	2.0	2.3	2.7	2.7
33	2.5	2.4	2.5	2.6	2.9	3.0	1.9	1.8	2.0	2.2	2.6	2.6
34	2.6	2.5	2.5	2.7	3.0	3.0	2.1	2.0	2.1	2.4	2.6	2.7
35	2.0	2.0	2.1	2.2	2.4	2.4	1.1	1.1	1.2	1.4	1.7	1.7
36	2.0	2.1	2.1	2.2	2.4	2.4	1.1	1.2	1.2	1.6	1.7	1.7
37	2.1	2.0	2.1	2.2	2.4	2.4	1.1	1.2	1.2	1.6	1.7	1.7
38	2.6	2.6	2.7	2.7	2.9	3.0	2.2	2.1	2.3	2.4	2.6	2.7
39	2.1	2.1	2.2	2.2	2.4	2.5	1.4	1.1	1.4	1.5	1.7	1.8
40	2.8	2.6	2.8	2.8	3.1	3.2	2.3	2.2	2.4	2.6	2.9	3.0
41	1.8	1.9	2.0	2.0	2.2	2.2	0.9	0.9	1.2	1.4	1.6	1.7
42	2.2	2.1	2.1	2.1	2.3	2.4	1.5	1.3	1.2	1.6	1.7	1.8
43	1.8	1.9	2.0	2.0	2.3	2.3	0.8	0.9	1.2	1.4	1.6	1.7
44	1.8	1.7	1.8	2.0	2.3	2.3	0.9	0.9	1.0	1.2	1.5	1.7
45	2.1	2.0	2.1	2.3	2.6	2.7	1.3	1.2	1.4	1.5	2.0	2.1
46	2.7	2.6	2.5	2.5	2.8	2.9	2.1	2.0	2.1	2.1	2.4	2.7
47	1.9	1.9	2.1	2.2	2.3	2.3	0.9	1.0	1.2	1.3	1.5	1.7
48	INCOMPLETE PENETRATION											
49	INCOMPLETE PENETRATION											
50	INCOMPLETE PENETRATION											
51	INCOMPLETE PENETRATION											
52	INCOMPLETE PENETRATION											
53	INCOMPLETE PENETRATION											
54	INCOMPLETE PENETRATION											

where: OBW: Outer Bead Width (in mm)
IBW: Inner Bead Width (in mm)

Table 22:Parameter Combinations Utilised and Responses Obtained Using the 0.79mm O.D

1st SEGMENT								2nd SEGMENT								ESB	SDT
No	I _{st}	I _p	t _p	I _b	t _b	PGFR	DT	HI ₁	I _p	t _p	I _b	t _b	WS	PGFR			
1	10.7	14	70	5	40	0.7	3	10.7	14	70	5	40	2.88	0.7	1.65	2.2	
2	8.8	11	70	5	40	0.3	3	8.8	11	70	5	40	2.09	0.3	1.65	2.2	
3	10.8	30	20	6	80	0.3	3	10.8	30	20	6	80	2.88	0.3	1.65	2.2	
4	10.8	30	20	6	80	0.3	4	10.8	30	20	6	80	2.88	0.3	1.65	2.2	
5	8.8	11	70	5	40	0.1	3	8.8	11	70	5	40	2.09	0.1	2.20	2.2	
6	10.7	14	70	5	40	0.7	3	10.7	14	70	5	40	2.88	0.7	2.20	2.2	
7	10.8	30	20	6	80	0.3	3	10.8	30	20	6	80	2.88	0.3	2.20	2.2	
8	10.8	30	20	6	80	0.3	3	10.8	30	20	6	80	2.88	0.3	2.20	2.2	
9	10	15	50	5	50	0.3	3	12	19	50	5	50	2.62	0.3	1.95	2.2	
10	10	15	50	5	50	0.7	3	12	19	50	5	50	2.62	0.7	1.95	2.2	
11	10	15	50	5	50	0.7	3	12	19	50	5	50	2.62	0.7	1.35	2.2	
12	10	15	50	5	50	0.3	3	12	19	50	5	50	2.62	0.3	1.35	2.2	
13	10	15	50	5	50	0.3	3	12	19	50	5	50	2.62	0.3	1.35	2.2	
14	10	15	50	5	50	0.3	3	12	19	50	5	50	2.62	0.3	2.45	2.2	
15	10	15	50	5	50	0.7	3	12	19	50	5	50	2.62	0.7	2.45	2.2	
16	10	15	50	5	50	0.1	3	11	17	50	5	50	2.62	0.1	1.95	2.2	
17	10	15	50	5	50	0.5	3	11	17	50	5	50	2.62	0.5	1.95	2.2	
18	10	15	50	5	50	0.9	3	11	17	50	5	50	2.62	0.9	1.95	2.2	
19	10	15	50	5	50	0.1	3	13	21	50	5	50	2.62	0.1	1.95	2.2	
20	10	15	50	5	50	0.5	3	13	21	50	5	50	2.62	0.5	1.95	2.2	
21	10	15	50	5	50	0.9	3	13	21	50	5	50	2.62	0.9	1.95	2.2	
22	10	15	50	5	50	0.1	3	11	17	50	5	50	2.62	0.1	1.95	2.2	
23	10	15	50	5	50	0.3	0	12	19	50	5	50	3.14	0.3	1.95	2.2	
24	10	15	50	5	50	0.3	1	12	19	50	5	50	3.14	0.3	1.95	2.2	
25	10	15	50	5	50	0.3	2	12	19	50	5	50	3.14	0.3	1.95	2.2	
26	10	15	50	5	50	0.3	3	12	19	50	5	50	3.14	0.3	1.95	2.2	
27	10	15	50	5	50	0.3	4	12	19	50	5	50	3.14	0.3	1.95	2.2	
28	10	15	50	5	50	0.3	2	12	19	50	5	50	3.14	0.3	1.95	2.2	
29	10	15	50	5	50	0.3	2	9	13	50	5	50	2.09	0.3	1.95	2.2	
30	10	15	50	5	50	0.3	2	12	19	50	5	50	2.09	0.3	1.95	2.2	
31	10	15	50	5	50	0.3	2	10	15	50	5	50	2.09	0.3	1.95	2.2	
32	10	15	50	5	50	0.3	2	14	23	50	5	50	2.09	0.3	1.95	2.2	
33	10	15	50	5	50	0.3	2	8	11	50	5	50	1.57	0.3	1.95	2.2	
34	10	15	50	5	50	0.3	2	13	21	50	5	50	3.14	0.3	1.95	2.2	
35	10	15	50	5	50	0.3	2	14	23	50	5	50	3.14	0.3	1.95	2.2	
36	10	15	50	5	50	0.3	2	15	25	50	5	50	2.62	0.3	1.95	2.2	
37	10	15	50	5	50	0.3	1	9	13	50	5	50	2.09	0.3	2.05	2.2	
38	10	15	50	5	50	0.3	3	9	31	50	5	50	2.09	0.3	2.05	2.2	
39	10	15	50	5	50	0.5	1	14	23	50	5	50	3.14	0.5	2.05	2.2	
40	10	15	50	5	50	0.5	3	14	23	50	5	50	3.14	0.5	2.05	2.2	
41	8.8	11	70	5	40	0.3	3	8.8	11	70	5	40	2.62	0.3	1.65	2.2	
42	10.8	30	20	6	80	0.3	1	10.8	30	20	6	80	2.88	0.3	1.65	2.2	
43	10	15	50	5	50	0.3	2	8	15	50	5	50	2.09	0.3	1.95	2.2	
44	10	15	50	5	50	0.7	2	10	15	50	5	50	3.14	0.7	1.95	2.2	
45	10	15	50	5	50	0.5	2	8	11	50	5	50	2.36	0.5	1.95	2.2	
46	10	15	50	5	50	0.9	2	9	13	50	5	50	2.88	0.9	1.95	2.2	
47	10	15	50	5	50	0.9	2	7	9	50	5	50	1.83	0.9	2.05	2.2	
48	10	15	50	5	50	0.9	2	8	11	50	5	50	2.36	0.9	1.35	2.2	
49	10	15	50	5	50	0.3	2	9	13	50	5	50	2.88	0.3	1.35	2.2	
50	10	15	50	5	50	0.9	2	10	15	50	5	50	3.14	0.9	1.65	2.2	

where: I_{st}: Average Welding Current Before the Initiation of the Torch Rotation (in Amps)
HI₁: Average Welding Current During the Torch Rotation (in Amps)
I_p: Peak Welding Current (in Amps) t_p: Peak Current Time (in msec)
I_b: Background Welding Current (in Amps) t_b: Background Current Time (in msec)
WS: Welding Speed i(in mm/sec) PGFR : Plasma Gas Flow Rate (in l/min)
ESB: Electrode Set Back Distance (in mm) SDT (Stand Off Distance (in mm)
DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)

Table 22 (contd):Parameter Combinations Utilised and Responses Obtained Using the 0.79mm O.D

No	POSITION-OBW						POSITION-IBW					
	3	8	13	18	23	28	3	8	13	18	23	28
1	2.5	2.2	2.1	2.2	2.3	2.5	1.6	1.3	1.2	1.3	1.8	1.8
2	2.2	2.1	2.0	2.0	2.3	2.3	1.3	1.2	1.2	1.5	1.7	1.7
3	2.5	2.2	2.2	2.2	2.4	2.6	1.7	1.1	1.1	1.4	1.9	2.0
4	2.5	2.3	2.2	2.4	2.5	2.7	1.8	1.2	1.2	1.5	2.0	2.2
5	1.9	1.8	1.9	2.0	2.3	2.4	1.2	1.1	1.2	1.4	1.6	1.8
6	2.5	1.9	2.0	2.0	2.1	2.3	1.6	1.0	0.9	1.1	1.5	1.6
7	2.3	2.0	2.0	2.0	2.3	2.3	1.5	1.3	1.2	1.3	1.7	1.9
8	2.3	2.0	2.0	2.0	2.3	2.3	1.5	1.2	1.1	1.3	1.7	1.9
9	2.7	2.5	2.6	2.8	3.0	3.1	2.2	2.0	2.0	2.4	2.7	2.8
10	2.7	2.6	2.5	2.8	3.0	3.1	2.2	2.0	1.9	2.3	2.7	2.8
11	2.6	2.4	2.4	2.7	3.0	3.0	2.0	1.6	1.7	2.2	2.6	2.8
12	2.5	2.4	2.4	2.7	3.0	3.0	2.0	1.8	1.8	2.2	2.6	2.7
13	2.7	2.6	2.7	2.8	3.1	3.2	2.2	2.0	2.0	2.3	2.7	2.8
14	2.8	2.5	2.7	2.7	3.0	3.1	2.3	2.1	2.1	2.3	2.6	2.8
15	2.8	2.5	2.6	2.7	3.0	3.1	2.1	1.8	1.8	2.1	2.6	2.7
16	2.6	2.4	2.3	2.6	2.8	2.7	2.0	1.8	1.8	2.0	2.3	2.3
17	2.4	2.3	2.2	2.5	2.6	2.7	1.8	1.6	1.6	1.9	2.1	2.2
18	2.3	2.2	2.1	2.3	2.5	2.6	1.6	1.4	1.3	1.6	1.9	2.1
19	2.9	2.9	3.0	3.2	3.4	3.5	2.3	2.3	2.4	2.7	3.0	3.1
20	2.9	2.9	2.9	3.2	3.3	3.4	2.4	2.3	2.4	2.7	3.0	3.1
21	2.7	2.6	2.7	3.0	3.2	3.3	2.2	1.9	2.1	2.4	2.8	2.9
22	2.4	2.3	2.2	2.4	2.7	2.7	1.7	1.5	1.5	2.0	2.1	2.2
23	2.2	2.3	2.3	2.4	2.5	2.5	1.5	1.5	1.6	1.8	2.1	2.1
24	2.2	2.3	2.3	2.4	2.6	2.6	1.5	1.6	1.6	1.8	2.1	2.1
25	2.3	2.3	2.3	2.3	2.5	2.5	1.6	1.6	1.6	1.8	2.1	2.1
26	2.6	2.2	2.2	2.3	2.7	2.7	2.0	1.4	1.5	1.7	2.2	2.2
27	2.7	2.5	2.3	2.5	2.8	2.8	2.0	1.7	1.5	1.8	2.2	2.4
28	2.2	2.1	2.2	2.2	2.6	2.7	1.5	1.3	1.5	1.6	2.1	2.1
29	2.0	1.8	1.8	2.0	2.4	2.4	1.4	1.3	1.4	1.6	1.9	2.0
30	2.8	2.8	2.9	3.2	3.5	3.6	2.1	2.3	2.6	2.9	3.3	3.4
31	2.3	2.1	2.3	2.6	2.8	2.8	1.6	1.5	1.8	2.1	2.4	2.5
32	3.2	3.3	3.5	3.9	4.2	4.3	2.8	3.0	3.4	3.8	4.1	4.2
33	1.9	1.9	2.1	2.3	2.4	2.4	1.1	1.1	1.4	1.7	1.8	1.9
34	2.5	2.3	2.4	2.6	3.0	3.1	2.0	1.7	1.9	2.1	2.7	2.7
35	2.7	2.6	2.9	2.9	3.2	3.3	2.1	2.0	2.2	2.4	2.9	3.1
36	2.9	3.0	3.2	3.5	3.9	4.0	2.7	2.7	3.0	3.4	3.8	4.0
37	1.7	1.8	1.8	2.0	2.2	2.3	1.2	1.3	1.4	1.5	1.8	1.9
38	2.0	1.9	1.9	2.0	2.3	2.3	1.5	1.4	1.5	1.5	1.9	2.0
39	2.6	2.7	2.8	2.9	3.3	3.4	2.2	2.2	2.3	2.4	2.9	3.0
40	3.0	2.8	2.8	2.8	3.3	3.4	2.4	2.2	2.1	2.3	2.9	3.0
41	2.0	1.9	1.8	1.9	2.1	2.1	1.3	1.2	1.3	1.6	1.9	2.0
42	2.0	1.9	1.9	2.2	2.4	2.6	0.9	0.6	0.6	0.7	1.1	1.2
43	1.8	1.7	1.8	1.9	2.1	2.1	0.9	0.8	0.9	1.1	1.3	1.4

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INCOMPLETE PENETRATION
INCOMPLETE PENETRATION
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INCOMPLETE PENETRATION
INCOMPLETE PENETRATION
INCOMPLETE PENETRATION

where: OBW: Outer Bead Width (in mm)
 IBW: Inner Bead Width (in mm)

Table 23: Parameter Combinations Utilised and Results Obtained for Melt-In Mode Plasma Welding of the 316L Tubes

1st SEGMENT								2nd SEGMENT								
No	I _{st}	I _p	t _p	I _b	t _b	PGFR	DT	HI ₁	I _p	t _p	I _b	t _b	WS	PGFR	ESB	SDT
1	15	25	50	5	50	0.7	1	10.1	22	30	5	70	1.99	0.7	1.45	1.60
2	15	25	50	5	50	0.4	1	8.6	14	40	5	60	1.99	0.4	1.45	1.60
3	15	25	50	5	50	0.4	1	15.0	30	20	5	30	3.99	0.4	1.45	1.60
4	15	25	50	5	50	0.4	1	8.2	13	20	5	30	1.33	0.4	1.45	1.60
5	15	25	50	5	50	0.4	1	11.0	20	20	5	30	3.32	0.4	1.45	1.60
6	15	25	50	5	50	0.4	1	12.2	23	20	5	30	3.99	0.4	1.45	1.60
7	15	25	50	5	50	0.2	1	9.0	15	20	5	30	1.33	0.2	1.45	1.60
8	15	25	50	5	50	0.4	1	12.2	23	20	5	30	2.66	0.4	1.45	1.60
9	15	25	50	5	50	0.6	1	12.2	23	20	5	30	2.66	0.6	1.45	1.60
10	15	25	50	5	50	0.4	1	9.0	15	20	5	30	1.99	0.4	1.45	1.60
11	15	25	50	5	50	0.6	1	9.0	15	20	5	30	1.99	0.6	1.45	1.60
12	15	25	50	5	50	0.6	1	10.2	18	20	5	30	2.66	0.6	1.45	1.60
13	15	25	50	5	50	0.6	1	10.2	18	20	5	30	2.66	0.6	1.45	1.60
14	15	25	50	5	50	0.4	1	11.0	20	20	5	30	1.99	0.4	1.45	1.60
15	15	25	50	5	50	0.6	1	12.2	23	20	5	30	3.99	0.6	1.45	1.60
16	15	25	50	5	50	0.6	1	13.0	25	20	5	30	3.99	0.6	1.45	1.60
17	15	25	50	5	50	0.4	1	13.0	25	20	5	30	2.66	0.4	1.45	1.60
18	15	25	50	5	50	0.2	1	15.0	30	20	5	30	3.32	0.2	1.45	1.60
19	15	25	50	5	50	0.2	1	14.2	28	20	5	30	2.99	0.2	1.45	1.60
20	15	25	50	5	50	0.4	1	9.0	15	20	5	30	1.33	0.4	1.45	1.60
21	15	25	50	5	50	0.6	1	9.0	15	20	5	30	2.66	0.6	1.45	1.60
22	15	25	50	5	50	0.4	1	14.2	28	20	5	30	3.99	0.4	1.45	1.60
23	15	25	50	5	50	0.2	1	11.0	20	20	5	30	2.66	0.2	1.45	1.60
24	15	25	50	5	50	0.6	1	12.2	23	20	5	30	3.32	0.6	1.45	1.60
25	15	25	50	5	50	0.4	1	14.2	28	20	5	30	3.32	0.4	1.45	1.60
26	15	25	50	5	50	0.4	1	13.0	25	20	5	30	3.32	0.4	1.45	1.60
27	15	25	50	5	50	0.6	1	13.0	25	20	5	30	3.32	0.6	1.45	1.60
28	15	25	50	5	50	0.4	1	12.2	23	20	5	30	2.66	0.4	1.95	1.60
29	15	25	50	5	50	0.2	1	10.2	18	20	5	30	1.99	0.2	1.95	1.60
30	15	25	50	5	50	0.6	1	10.2	18	20	5	30	1.99	0.6	1.95	1.60
31	15	25	50	5	50	0.4	1	15.0	30	20	5	30	3.99	0.4	1.95	1.60
32	15	25	50	5	50	0.2	1	15.0	30	20	5	30	3.32	0.2	1.95	1.60
33	15	25	50	5	50	0.6	1	9.0	15	20	5	30	1.99	0.6	1.95	1.60
34	15	25	50	5	50	0.4	1	14.2	28	20	5	30	2.66	0.4	1.95	1.60
35	15	25	50	5	50	0.4	1	10.2	18	20	5	30	2.50	0.4	1.95	1.60
36	15	25	50	5	50	0.3	1	11.4	21	20	5	30	1.95	0.3	1.95	1.60
37	15	25	50	5	50	0.2	1	14.6	29	20	5	30	3.74	0.2	1.65	1.60
38	15	25	50	5	50	0.4	1	8.2	13	20	5	30	1.83	0.4	1.65	1.60
39	15	25	50	5	50	0.3	1	12.6	24	20	5	30	2.07	0.3	1.65	1.60
40	15	25	50	5	50	0.4	1	11.0	20	20	5	30	1.33	0.4	1.65	1.60
41	15	25	50	5	50	0.4	1	13.0	25	20	5	30	1.99	0.4	1.65	1.60
42	15	25	50	5	50	0.6	1	11.0	20	20	5	30	1.99	0.6	1.65	1.60
43	15	25	50	5	50	0.6	1	13.0	25	20	5	30	2.99	0.6	1.65	1.60
44	15	25	50	5	50	0.6	1	15.0	30	20	5	30	3.99	0.6	1.65	1.60
45	15	25	50	5	50	0.4	1	11	20	20	5	30	3.32	0.4	1.65	1.60
46	15	25	50	5	50	0.2	1	13.0	25	20	5	30	3.99	0.2	1.65	1.60
47	15	25	50	5	50	0.2	1	12.2	23	20	5	30	3.32	0.2	1.65	1.60
48	15	25	50	5	50	0.4	1	9.0	15	20	5	30	2.19	0.4	1.65	1.60
49	15	25	50	5	50	0.4	1	8.2	13	20	5	30	3.99	0.4	1.65	1.60
50	15	25	50	5	50	0.6	1	9.0	15	20	5	30	3.32	0.6	1.65	1.60

where:	I_{st} : Average Welding Current Before the Initiation of the Torch Rotation (in Amps)
	HI_1 : Average Welding Current During the Torch Rotation (in Amps)
	I_p : Peak Welding Current (in Amps)
	t_p : Peak Current Time (in msec)
	I_b : Background Welding Current (in Amps)
	t_b : Background Current Time (in msec)
	WS: Welding Speed (in mm/sec)
	PGFR: Plasma Gas Flow Rate (in l/min)
	ESB: Electrode Set Back Distance (in mm)
	SDT: Stand Off Distance (in mm)

Table 23 (contd): Parameter Combinations Utilised and Results Obtained for Melt-In Mode Plasma Welding of the 316L Tubes

POSITION-OBW								POSITION-IBW							
No	3	8	13	18	23	28	33	3	8	13	18	23	28	33	
1	2.5	2.4	2.5	2.6	2.7	2.9	2.8	1.9	1.8	1.9	2.0	2.3	2.7	2.6	
2	1.8	1.7	1.9	1.9	2.0	2.2	2.0	1.0	1.0	1.2	1.5	1.6	2.0	1.9	
3	2.4	2.2	2.2	2.2	2.1	2.6	2.5	1.6	1.2	1.2	1.3	1.4	1.8	1.8	
4	2.3	2.2	2.2	2.3	2.3	2.5	2.4	1.6	1.6	1.7	1.9	2.0	2.2	2.1	
5	1.7	1.6	1.6	1.6	1.6	1.8	1.7	0.9	0.8	0.6	0.7	0.9	1.1	1.2	
6	1.8	1.5	1.5	1.5	1.5	1.6	1.5	1.1	0.6	0.4	0.5	0.6	1.0	0.9	
7	2.1	2.0	2.0	2.3	2.3	2.5	2.4	1.4	1.3	1.5	1.7	2.0	2.2	2.2	
8	2.2	2.2	2.3	2.3	2.4	2.7	2.6	1.8	1.6	1.5	1.7	1.9	2.4	2.4	
9	2.6	2.5	2.5	2.6	2.7	2.9	2.9	2.1	2.1	2.2	2.2	2.2	2.6	2.5	
10	1.8	1.7	1.7	1.8	1.8	2.0	2.0	1.3	1.1	1.0	1.2	1.4	1.7	1.6	
11	2.1	2.0	2.1	2.1	2.1	2.3	2.2	1.6	1.5	1.7	1.8	1.8	2.0	1.9	
12	1.9	1.7	1.7	1.7	1.8	2.1	2.0	1.3	1.0	1.2	1.3	1.4	1.8	1.8	
13	2.0	1.8	1.9	1.9	2.0	2.2	2.1	1.5	1.0	1.2	1.3	1.4	1.7	1.6	
14	2.6	2.5	2.6	2.7	2.7	3.0	2.9	2.0	2.0	2.1	2.1	2.3	2.6	2.6	
15	1.8	1.7	1.8	1.7	1.8	2.1	1.8	1.1	0.6	0.6	0.7	0.9	1.2	1.1	
16	2.2	1.8	1.8	1.8	1.8	2.0	2.1	1.4	0.8	0.8	0.9	1.0	1.4	1.3	
17	2.6	2.2	2.3	2.3	2.4	2.6	2.5	2.1	2.0	2.0	2.0	2.1	2.3	2.3	
18	2.1	2.1	2.2	2.2	2.2	2.4	2.3	1.6	1.4	1.4	1.4	1.5	1.9	1.9	
19	2.2	2.0	2.1	2.1	2.1	2.4	2.4	1.8	1.6	1.6	1.6	1.8	2.2	2.3	
20	2.3	2.5	2.6	2.6	2.8	3.0	2.9	1.6	2.1	2.4	2.4	2.6	2.9	2.7	
21	2.0	1.9	2.0	2.0	2.0	2.2	2.1	0.9	0.4	0.5	0.8	1.3	1.5	1.2	
22	2.1	1.9	1.8	1.9	1.9	2.1	1.9	1.7	1.1	0.8	0.8	1.0	1.6	1.5	
23	1.8	1.8	1.8	1.9	1.9	2.0	1.9	1.0	0.8	0.6	0.6	0.8	1.3	1.1	
24	2.0	1.9	1.9	1.9	2.0	2.1	2.0	1.4	1.2	1.1	1.1	1.3	1.7	1.6	
25	2.3	2.1	2.1	2.2	2.2	2.5	2.4	1.9	1.8	1.6	1.6	1.6	2.1	2.0	
26	2.1	1.9	1.9	2.0	2.1	2.3	2.2	1.4	1.1	1.0	1.2	1.2	1.7	1.6	
27	2.2	2.0	2.0	2.0	2.2	2.4	2.2	1.8	1.5	1.4	1.5	1.6	2.3	2.2	
28	2.5	2.5	1.9	2.2	2.4	2.8	2.7	2.0	1.7	1.3	1.6	2.0	2.5	2.3	
29	1.7	1.8	1.9	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.4	1.6	1.8	1.7	
30	2.6	2.7	2.7	2.8	2.8	2.9	2.8	2.0	2.2	2.3	2.5	2.7	3.0	2.9	
31	2.4	2.2	2.0	1.8	2.4	2.5	2.3	2.0	1.2	0.9	1.1	1.3	2.0	1.5	
32	2.3	2.0	1.8	2.0	2.1	2.5	2.4	1.6	1.3	1.3	1.4	1.4	2.0	1.9	
33	2.2	2.1	2.1	2.1	2.3	2.4	2.3	1.5	1.3	1.7	2.0	2.2	2.5	2.4	
34	2.6	2.7	2.7	2.8	2.9	3.1	3.1	2.4	2.2	2.2	2.3	2.6	3.1	3.2	
35	1.9	1.8	1.9	2.0	2.0	2.2	2.1	1.1	1.1	1.2	1.4	1.4	2.0	1.8	
36	2.4	2.7	2.7	2.8	2.9	3.0	2.9	1.6	2.1	2.3	2.5	2.7	3.0	3.0	
37	1.8	1.8	1.7	1.8	1.9	1.8	1.8	1.5	1.3	1.0	1.1	1.4	1.5	1.6	
38	1.8	1.8	1.8	1.9	2.0	2.3	2.3	1.0	0.7	0.9	1.2	1.7	2.0	1.9	
39	2.7	2.8	2.9	2.9	3.0	3.2	3.2	2.3	2.0	2.3	2.4	2.6	2.8	2.8	

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where: OBW: Outer Bead Width (in mm)
 IBW: Inner Bead Width (in mm)

Table 24: Parameter Combinations Utilised and Results Obtained for Keyhole Plasma Welding of the 316L Tubes

1st SEGMENT								2nd SEGMENT										
No	L _{st}	L _p	L _p	L _b	t _b	PGFR	DT	HI ₁	L _p	L _p	L _b	t _b	WS	PGFR	ESB	SDT		
1	16.5	28	20	5	20	2.3	2	17.0	28	20	6	20	2.66	1.9	1.30	1.60		
2	16.5	28	20	5	20	2.3	2	20.0	28	20	12	20	2.99	1.9	1.30	1.60		
3	16.5	28	20	5	20	2.3	2	20.0	28	20	12	20	3.99	2.1	1.30	1.60		
4	16.5	28	20	5	20	2.3	2	22.0	28	20	16	20	3.66	2.1	1.30	1.60		
5	16.5	28	20	5	20	2.3	2	20.5	28	20	13	20	2.33	1.9	1.30	1.60		
6	16.5	28	20	5	20	2.3	2	15.5	26	20	5	20	1.66	2.3	1.30	1.60		
7	16.5	28	20	5	20	2.3	2	15.0	25	20	5	20	2.66	2.1	1.30	1.60		
8	16.5	28	20	5	20	2.3	2	16.5	28	20	5	20	2.00	1.9	1.30	1.60		
9	16.5	28	20	5	20	2.3	2	19.0	28	20	10	20	3.33	1.9	1.30	1.60		
10	16.5	28	20	5	20	2.3	2	21.5	28	20	15	20	3.99	2.1	1.30	1.60		
11	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	3.66	2.1	1.30	1.60		
12	16.5	28	20	5	20	2.3	2	21.5	28	20	15	20	3.33	1.7	1.30	1.60		
13	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	3.66	1.7	1.30	1.60		
14	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	3.66	1.5	1.30	1.60		
15	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	3.66	2.3	1.30	1.60		
16	16.5	28	20	5	20	2.3	2	17.0	28	20	6	20	3.66	1.7	1.30	1.60		
17	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	2.33	1.7	1.30	1.60		
18	16.5	28	20	5	20	2.3	2	21.0	28	20	14	20	3.66	2.3	1.30	1.60		
19	16.5	28	20	5	20	2.3	2	16.5	28	20	5	20	3.66	2.3	1.30	1.60		
20	16.5	28	20	5	20	2.3	2	18.0	28	20	8	20	2.99	1.7	1.30	1.60		
21	16.5	28	20	5	20	2.3	2	15.0	25	20	5	20	2.00	1.9	1.30	1.60		
22	16.5	28	20	5	20	2.3	2	15.5	26	20	5	20	3.99	2.3	1.30	1.60		
23	16.5	28	20	5	20	2.3	2	18.0	28	20	8	20	3.99	2.1	1.30	1.60		
24	16.5	28	20	5	20	2.3	2	17.5	28	20	7	20	2.00	2.3	2.00	1.60		
25	16.5	28	20	5	20	2.3	2	19.5	28	20	11	20	2.99	1.9	2.00	1.60		
26	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	3.66	2.3	2.00	1.60		
27	16.5	28	20	5	20	2.3	2	16.0	27	20	5	20	2.33	1.9	2.00	1.60		
28	16.5	28	20	5	20	2.3	2	15.0	25	20	5	20	2.33	2.3	2.00	1.60		
29	16.5	28	20	5	20	2.3	2	15.0	25	20	5	20	2.99	2.3	2.00	1.60		
30	16.5	28	20	5	20	2.3	2	15.5	26	20	5	20	2.00	1.9	2.00	1.60		
31	16.5	28	20	5	20	2.3	2	15.5	26	20	5	20	2.66	2.1	2.00	1.60		
32	16.5	28	20	5	20	2.3	2	18.5	28	20	9	20	2.66	2.1	2.00	1.60		
33	16.5	28	20	5	20	2.3	2	22.0	28	20	16	20	3.99	2.1	2.00	1.60		
34	16.5	28	20	5	20	2.1	2	20.0	28	20	12	20	2.66	1.9	2.00	1.60		
35	16.5	28	20	5	20	2.3	2	19.0	28	20	10	20	3.99	1.9	2.00	1.60		
36	16.5	28	20	5	20	2.3	2	20.0	28	20	12	20	3.99	1.9	2.00	1.60		
37	16.5	28	20	5	20	2.3	2	18.0	28	20	8	20	3.99	2.1	2.00	1.60		
38	16.5	28	20	5	20	2.3	2	17.5	28	20	7	20	2.66	1.9	2.00	1.60		
39	16.5	28	20	5	20	2.3	2	17.5	28	20	7	20	2.66	1.9	2.00	1.60		
40	16.5	28	20	5	20	2.3	2	17.5	28	20	7	20	3.33	1.9	2.00	1.60		
41	16.5	28	20	5	20	2.3	2	19.5	28	20	11	20	3.66	2.3	2.00	1.60		
42	16.5	28	20	5	20	2.3	2	19.5	28	20	11	20	3.66	1.9	2.00	1.60		
43	16.5	28	20	5	20	2.3	2	17.5	28	20	7	20	3.99	2.3	2.00	1.60		
44	16.5	28	20	5	20	2.3	2	18.0	28	20	8	20	2.99	2.3	2.00	1.60		
45	16.5	28	20	5	20	2.3	2	15.0	25	20	5	20	1.66	2.3	2.00	1.60		
46	16.5	28	20	5	20	2.3	2	19.0	28	20	10	20	2.66	2.3	2.00	1.60		
47	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	2.66	1.9	2.00	1.60		
48	16.5	28	20	5	20	2.3	2	16.5	28	20	5	20	2.33	2.1	2.00	1.60		
49	16.5	28	20	5	20	2.3	2	16.5	28	20	5	20	2.99	2.1	2.00	1.60		
50	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	2.99	1.9	2.00	1.60		
51	16.5	28	20	5	20	2.3	2	16.5	28	20	5	20	3.66	1.9	2.00	1.60		
52	16.5	28	20	5	20	2.1	2	18.0	28	20	8	20	2.99	1.9	2.00	1.60		
53	16.5	28	20	5	20	2.1	2	18.0	28	20	8	20	3.66	1.9	2.00	1.60		
54	16.5	28	20	5	20	2.1	2	18.0	28	20	8	20	2.33	1.9	2.00	1.60		
55	16.5	28	20	5	20	2.1	2	20.0	28	20	12	20	2.99	1.9	2.00	1.60		
56	16.5	28	20	5	20	2.5	2	20.0	28	20	12	20	3.66	2.3	2.00	1.60		
57	16.5	28	20	5	20	2.5	2	20.0	28	20	12	20	2.99	2.3	2.00	1.60		
58	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	2.33	1.9	2.00	1.60		
59	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	2.66	1.9	2.00	1.60		
60	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	2.99	1.9	2.00	1.60		
61	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	2.00	1.9	2.00	1.60		
62	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	3.33	1.9	2.00	1.60		
63	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	3.66	1.9	2.00	1.60		
64	16.5	28	20	5	20	2.1	2	16.5	28	20	5	20	3.99	1.9	2.00	1.60		
65	16.5	28	20	5	20	2.1	2	15.5	26	20	5	20	2.00	1.9	2.00	1.60		
66	16.5	28	20	5	20	2.1	2	15.0	25	20	5	20	2.00	1.9	2.00	1.60		
67	16.5	28	20	5	20	2.1	2	21.5	28	20	15	20	2.12	2.3	1.30	1.60		
68	16.5	28	20	5	20	2.1	2	18.0	28	20	8	20	1.93	2.3	1.30	1.60		
69	16.5	28	20	5	20	2.1	2	19.5	28	20	11	20	1.73	2.1	1.30	1.60		
70	16.5	28	20	5	20	2.1	2	19.5	28	20	11	20	2.12	2.1	1.30	1.60		
71	16.5	28	20	5	20	2.1	2	22.0	28	20	16	20	2.12	2.1	1.30	1.60		
72	16.5	28	20	5	20	2.1	2	19.0	28	20	10	20	2.32	2.1	1.30	1.60		
73	16.5	28	20	5	20	2.1	2	22.0	28	20	16	20	2.10	1.9	2.00	1.60		
74	16.5	28	20	5	20	2.1	2	22.0	28	20	16	20	2.10	2.3	2.00	1.60		
75	16.5	28	20	5	20	2.1	2	19.0	28	20	10	20	1.90	1.9	2.00	1.60		
76	16.5	28	20	5	20	2.1	2	19.0	28	20	10	20	2.10	2.1	2.00	1.60		
77	16.5	28	20	5	20	2.1	2	17.5	28	20	7	20	1.90	2.3	2.00	1.60		
78	16.5	28	20	5	20	2.1	2	19.5	28	20	11	20	2.30	2.3				

Table 24 (contd): Parameter Combinations Utilised and Results Obtained for Keyhole Plasma Welding of 316L Tubes

POSITION-OBW								POSITION-IBW								UND		
No	3	8	13	18	23	28	33	3	8	13	18	23	28	33	8	18	28	
1	2.0	2.0	2.0	2.1	2.1	2.3	2.2	1.5	1.4	1.5	1.6	1.6	1.8	1.7	-0.5	-0.5	-0.5	
2	2.4	2.2	2.3	2.2	2.2	2.3	NW	2.2	1.8	1.8	2.0	2.0	2.4	NW	0.0	0.0	0.5	
3	2.1	1.8	1.8	1.8	1.9	2.2	2.2	1.7	1.1	1.1	1.3	1.5	1.8	1.8	-0.5	-0.5	-0.5	
4	2.4	2.1	2.0	2.0	2.1	2.2	2.3	2.3	1.9	1.7	1.8	1.9	2.3	2.4	0.0	0.0	0.5	
5	2.7	2.4	2.4	2.4	2.7	2.7	NW	2.6	2.4	2.4	2.5	2.7	2.7	NW	0.5	0.5	0.5	
6	2.3	2.3	2.3	2.3	2.4	2.6	NW	1.6	1.6	1.8	2.0	2.2	2.4	NW	-0.5	-0.5	-0.5	
7	1.9	1.6	1.7	1.7	1.7	2.0	2.1	1.3	1.0	1.0	1.1	1.3	1.7	1.8	-1.0	-1.0	-1.0	
8	2.3	2.1	2.1	2.3	2.2	2.3	NW	1.8	1.8	1.9	2.0	2.0	2.1	NW	-0.5	-0.5	0.5	
9	2.3	1.8	1.9	1.9	1.8	2.2	1.9	1.8	1.3	1.4	1.4	1.5	1.9	1.9	-0.5	-0.5	-0.5	
10	2.4	1.9	1.8	1.9	1.9	2.2	2.2	2.0	1.4	1.6	1.7	1.8	2.0	2.6	-0.5	-0.5	-0.5	
11	2.2	1.7	1.7	1.7	1.9	2.2	2.0	1.8	1.1	1.1	1.1	1.3	1.7	1.7	-0.5	-0.5	-1.0	
12	2.8	2.3	2.3	2.2	2.1	2.4	2.3	2.3	1.8	2.0	2.0	1.9	2.3	2.2	0.0	0.5	1.0	
13	2.2	1.7	1.7	1.7	1.8	2.0	1.9	1.8	1.2	1.1	1.2	1.3	1.7	1.8	-1.0	-0.5	-1.0	
14	2.2	1.9	1.9	1.9	1.9	2.2	2.2	1.8	1.1	1.0	1.1	1.3	1.5	1.5	-0.5	-0.5	-0.5	
15	2.0	1.7	1.8	1.8	1.8	2.1	2.0	1.6	1.2	1.3	1.3	1.5	1.9	1.9	-0.5	-0.5	-0.5	
16	2.0	1.6	1.6	1.6	1.6	2.1	1.9	1.5	1.0	1.0	1.0	1.0	1.4	1.3	-1.0	-1.0	-1.0	
17	2.6	2.3	2.3	2.4	2.3	2.5	NW	2.0	2.1	2.1	2.1	2.2	2.3	NW	0.0	0.0	0.5	
18	2.4	2.1	2.0	2.0	2.0	2.4	2.3	2.3	1.6	1.6	1.8	1.9	2.2	2.2	-0.5	-0.5	0.5	
19	1.9	1.7	1.6	1.6	1.7	2.0	1.8	1.3	0.9	0.9	1.0	1.0	1.2	1.2	-1.0	-1.0	-1.0	
20	2.1	1.9	1.9	2.0	2.0	2.3	2.1	1.6	1.5	1.5	1.6	1.7	1.9	1.9	-0.5	-0.5	-0.5	
21	2.2	2.0	2.0	2.1	2.1	2.3	NW	1.7	1.6	1.6	1.6	1.8	2.1	NW	-0.5	-0.5	-0.5	
22	1.8	1.6	1.5	1.4	1.4	1.7	1.6	1.1	0.6	0.6	0.6	0.6	1.0	0.8	-1.0	-1.0	-1.0	
23	2.1	1.8	1.5	1.5	1.6	2.1	1.8	1.6	0.9	0.9	0.9	1.0	1.5	1.4	-0.5	-0.5	-0.5	
24	2.5	2.1	2.2	2.4	2.5	2.5	NW	1.9	1.7	2.0	2.0	2.1	2.4	NW	-0.5	-0.5	-0.5	
25	2.6	2.1	2.0	2.0	2.0	2.4	2.3	2.0	1.7	1.6	1.6	1.7	2.2	2.1	0.0	-0.5	-0.5	
26	2.3	1.8	1.8	1.8	1.8	2.1	1.9	1.8	1.1	1.1	1.1	1.2	1.6	1.5	-0.5	-0.5	-0.5	
27	2.4	2.1	2.1	2.1	2.2	2.5	2.4	1.7	1.5	1.4	1.5	1.7	1.9	1.9	-0.5	-0.5	-0.5	
28	2.1	1.9	1.9	1.9	2.1	2.4	2.2	1.4	1.1	1.1	1.3	1.6	2.0	1.9	-1.0	-1.0	-0.5	
29	2.1	1.6	1.6	1.7	1.7	1.9	1.8	1.1	0.8	0.7	1.0	1.1	1.3	1.2	-1.0	-1.0	-1.0	
30	2.3	2.1	2.2	2.3	2.2	2.4	NW	1.7	1.5	1.5	1.6	1.7	2.2	NW	-0.5	-0.5	-0.5	
31	2.3	1.9	1.9	1.8	1.8	2.2	2.1	1.3	0.9	0.9	1.0	1.3	1.7	1.7	-1.0	-1.0	-1.0	
32	2.8	2.2	2.2	2.1	2.1	2.3	2.3	2.1	1.8	1.8	1.9	2.1	2.3	2.3	0.0	-0.5	0.5	
33	2.7	2.1	2.1	1.9	1.9	2.1	2.1	2.3	1.5	1.4	1.5	1.6	1.9	2.1	0.0	0.0	0.5	
34	2.9	2.4	2.3	2.1	2.2	2.4	2.4	2.5	2.2	2.1	2.2	2.2	2.6	2.8	0.0	0.5	0.5	
35	2.4	1.7	1.8	1.8	1.8	2.0	1.8	1.8	1.0	0.9	1.1	1.2	1.5	1.5	-0.5	-0.5	-0.5	
36	2.6	1.8	1.8	1.9	2.0	2.2	1.9	2.0	1.0	1.1	1.2	1.4	1.6	1.6	-0.5	-0.5	-0.5	
37	2.2	1.8	1.6	1.6	1.7	2.0	1.8	1.5	0.8	0.6	0.7	1.0	1.4	1.3	-1.0	-1.0	-0.5	
38	2.4	1.9	1.8	1.9	1.9	2.2	1.8	1.6	1.2	1.2	1.4	1.5	1.8	1.5	-0.5	-0.5	-0.5	
39	2.7	2.1	2.1	2.1	2.1	NW	NW	1.9	1.6	1.5	1.5	1.7	NW	NW	0.0	0.0	0.0	
40	2.5	1.8	1.7	1.8	1.8	2.2	2.0	1.5	1.0	0.9	1.1	1.3	1.4	1.5	-0.5	-0.5	-0.5	
41	2.7	1.9	1.7	1.9	1.9	2.2	NW	1.9	1.1	1.2	1.2	1.5	1.8	NW	-0.5	-0.5	-0.5	
42	2.7	2.0	1.9	1.9	1.9	2.3	2.1	2.0	1.4	1.3	1.3	1.3	1.7	1.7	-0.5	-0.5	-0.5	
43	2.4	1.6	1.6	1.6	1.7	1.9	1.7	1.3	0.8	0.6	0.7	0.9	1.3	1.2	-1.0	-1.0	-1.0	
44	2.6	2.0	2.0	2.1	2.1	2.4	2.2	2.2	1.5	1.6	1.6	1.8	2.2	2.3	-0.5	-0.5	-0.5	
45	2.5	2.2	2.3	2.2	2.3	NW	NW	1.7	1.5	1.8	1.9	2.0	NW	NW	-0.5	-0.5	-0.5	
46	2.8	2.2	2.1	2.0	2.2	2.3	NW	2.3	1.8	1.9	1.9	1.9	2.3	NW	-0.5	-0.5	-0.5	
47	2.6	1.9	1.7	1.9	2.0	2.3	2.1	1.5	1.3	1.2	1.2	1.3	1.7	1.8	-0.5	-0.5	-0.5	
48	2.6	2.1	2.1	2.2	2.3	2.4	2.2	1.7	1.4	1.5	1.5	1.6	2.0	2.0	-0.5	-0.5	-0.5	
49	2.4	1.8	1.8	1.9	2.0	2.2	1.9	1.5	0.9	1.0	1.0	1.1	1.5	1.5	-1.0	-0.5	-0.5	
50	2.4	1.8	1.6	1.7	1.8	2.2	2.0	1.7	1.1	1.0	1.0	1.1	1.5	1.5	-1.0	-1.0	-1.0	
51	2.4	1.7	1.5	1.5	1.5	2.0	1.6	1.4	0.8	0.7	0.8	0.8	1.2	1.1	-1.0	-1.0	-1.0	
52	2.6	2.0	1.8	1.9	2.0	2.3	2.1	1.7	1.4	1.5	1.5	1.6	2.0	2.0	-0.5	-0.5	-0.5	
53	2.5	1.8	1.7	1.7	1.7	2.2	1.9	1.6	1.0	1.0	1.0	1.0	1.6	1.5	-0.5	-0.5	-0.5	
54	2.8	2.0	2.2	2.3	2.3	2.5	2.6	2.2	1.8	1.9	2.0	2.1	2.3	2.6	-0.5	-0.5	0.5	
55	2.8	2.0	2.0	2.0	2.1	2.3	2.4	2.3	1.8	1.8	1.8	2.0	2.4	2.6	0.0	0.0	0.5	
56	2.6	2.0	1.8	1.8	1.8	2.1	2.0	2.0	1.2	1.3	1.5	1.6	2.0	1.8	-0.5	-0.5	-0.5	
57	2.8	2.2	2.1	2.1	2.3	2.5	2.4	2.4	1.8	1.8	1.8	2.0	2.3	2.5	0.0	0.5	0.5	
58	2.3	2.0	2.0	2.1	2.1	2.3	2.2	1.7	1.3	1.3	1.5	1.5	1.9	2.0	-0.5	-0.5	-0.5	
59	2.2	1.8	1.9	1.9	2.0	2.3	2.0	1.4	1.1	1.2	1.3	1.3	1.8	1.7	-0.5	-0.5	-0.5	
60	2.2	1.7	1.7	1.7	1.7	2.1	1.9	1.4	1.0	1.0	1.0	1.0	1.6	1.3	-1.0	-1.0	-1.0	
61	2.6	2.1	2.1	2.2	2.2	2.3	2.2	1.8	1.8	1.8	2.0	2.0	2.3	2.3	0.0	0.5	0.5	
62	2.2	1.6	1.6	1.6	1.6	1.9	1.7	1.3	1.0	0.9	1.0	1.0	1.4	1.3	-1.0	-1.0	-1.0	
63	2.2	1.6	1.6	1.6	1.6	1.8	1.7	1.3	0.9	0.8	0.9	0.8	1.1	1.0	-1.0	-1.0	-1.0	
64	2.0	1.4	1.5	1.4	1.5	1.8	1.6	1.3	0.6	0.7	0.7	0.8	1.0	0.8	-1.0	-1.0	-1.0	
65	2.3	2.0	2.1	2.1	2.0	2.2	2.1	1.5	1.5	1.6	1.6	1.6	2.0	2.0	-0.5	-0.5	-0.5	
66	2.2	1.8	1.9	1.9	2.0	2.3	2.1	1.3	1.2	1.3	1.4	1.5	1.7	1.9	-0.5	-0.5	-0.5	
67 CUTTING	where: I_{st} : Average Welding Current Before the Initiation of the Torch Rotation (in Amps)														0.5	1.0	1.0	
68 CUTTING	H_1 : Average Welding Current During the Torch Rotation (in Amps)														0.5	0.5	1.0	
69 CUTTING	I_p : Peak Welding Current (in Amps) t_p : Peak Current Time (in msec)														0.5	0.5	1.0	
70 CUTTING	I_b : Background Welding Current (in Amps) t_b : Background Current Time (in msec)														0.5	0.5	1.0	
71 CUTTING	WS: Welding Speed (in mm/sec) PGFR: Plasma Gas Flow Rate (in l/min)														0.5	0.5	1.0	
72 CUTTING	ESB: Electrode Set Back Distance (in mm) SDT (Stand Off Distance) (in mm)														0.5	0.5	1.0	
73 CUTTING	DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)														0.0	0.5	1.0	
74 CUTTING	where: OBW: Outer Bead Width (in mm)														0.5	0.5	1.0	
75 CUTTING	IBW: Inner Bead Width (in mm)														0.0	0.5	1.0	
76 CUTTING	UND: Undercut Classification (Fuzzy)														0.5	0.5	1.0	
77 CUTTING	NW: Not Welded														0.5	0.5	1.0	
78 CUTTING															0.0	0.5	1.0	
79 CUTTING															0.0	0.5	1.0	
80 CUTTING															0.5	0.5	1.0	
81 CUTTING															0.0	-0.5	1.0	
84 UNSTABLE KEYHOLE - MELT-IN MODE																		
85 UNSTABLE KEYHOLE - MELT-IN MODE																		
86 UNSTABLE KEYHOLE - MELT-IN MODE																		
87 UNSTABLE KEYHOLE - MELT-IN MODE																		
88 UNSTABLE KEYHOLE - MELT-IN MODE																		

Table 25a: Regression coefficients for the Ti-3Al-2.5V models (0.56mm O.D)						
	OBW (3)	OBW(8)	OBW(13)	OBW(18)	OBW(23)	OBW(28)
b ₁	0.186436	0.234895	0.217047	0.241056	0.262741	0.279333
b ₂	-0.113867	-0.350633	-0.316516	-0.366922	-0.362715	-0.41477
b ₃	-0.053354	0.038363	0.01976	-0.011558	-0.000992	0.002647
b ₄	0.047462	0.096201	0.123026	-0.018433	-0.018707	0.01399
b ₅	0.008977	-0.000791	-0.001599	0.005391	0.003623	0.007439
b ₆	0.067026	0.084266	0.125216	0.141922	0.144227	0.114916
R ²	0.906067	0.934317	0.939085	0.943555	0.954135	0.959345
Radjusted	0.870222	0.901916	0.907267	0.912282	0.924151	0.929997
S.E	0.111866	0.105971	0.101003	0.105202	0.103382	0.097183
F ratio	65.91384	97.20116	105.3456	114.229	142.1532	161.2481
Sign. F (P value)	0.0000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 25b: Regression coefficients for the Ti-3Al-2.5V models (0.56mm O.D)						
	IBW (3)	IBW(8)	IBW(13)	IBW(18)	IBW(23)	IBW(28)
b ₀	-1.74517					
b ₁	0.273198	0.464968	0.498564	0.538327	0.541381	0.537035
b ₂	-0.134367	-1.050632	-1.203528	-1.37145	-1.252506	-1.225069
b ₃	-0.106169	-0.04576	0.057091	0.149291	0.052944	0.096021
b ₄	0.155729	0.039883	0.126831	0.198745	0.082525	0.026981
b ₅	0.011444	0.001619	0.001736	0.005489	0.004793	0.008037
b ₆	-0.064356	-0.212601	-0.235926	-0.252651	-0.199486	-0.188336
R ²	0.937067	0.943409	0.965092	0.967658	0.979546	0.980491
Radjusted	0.927628	0.912118	0.936445	0.939324	0.952661	0.953721
S.E	0.134782	0.13997	0.111851	0.111678	0.096417	0.093465
F ratio	99.26687	113.9167	188.9216	204.4527	327.2465	343.4285
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 25c: Input parameters range for 0.56mm OD		
Input parameter	Minimum Value	Maximum Value
WI (A)	8	14
WS (mm/sec)	1.57	3.14
PGFR (l/min)	0.3	1.3
ESB (mm)	1	2
HIS (DT*Ist in sec*A)	20	40

Table 26a: Regression coefficients for the Ti-3Al-2.5V models (0.79mm OD)						
	OBW (3)	OBW(8)	OBW(13)	OBW(18)	OBW(23)	OBW(28)
b_1	0.174994	0.18271	0.229495	0.22014	0.254355	0.267343
b_2	-0.121613	-0.139562	-0.322507	-0.318754	-0.364055	-0.382494
b_3	-0.003527	-0.104676	-0.166028	-0.102233	-0.237851	-0.129377
b_4	0.00626	-0.11397	-0.008746	-0.162548	-0.103755	-0.115476
b_5	0.016421	0.006656	0.003102	0.002884	0.003366	0.003823
b_6	0.080404	0.160693	0.136625	0.259034	0.238068	0.223972
R^2	0.903019	0.908833	0.941943	0.950608	0.975225	0.96771
Radjusted	0.862886	0.869486	0.907071	0.916906	0.94485	0.936319
S.E	0.115476	0.118001	0.104405	0.108534	0.081327	0.095701
F ratio	57.41968	61.475	100.0514	118.6838	242.7374	184.8082
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 26b: Regression coefficients for the Ti-3Al-2.5V models (0.79mm OD)						
	IBW (3)	IBW(8)	IBW(13)	IBW(18)	IBW(23)	IBW(28)
b_0	-0.52841					
b_1	0.323818	0.389638	0.387048	0.391116	0.419893	0.434575
b_2	-0.57494	-0.938191	-0.976522	-0.970872	-0.8993	-0.970925
b_3	-0.08948	-0.274245	-0.372452	-0.358596	-0.260011	-0.255878
b_4	0.039926	0.105657	0.0536	-0.102526	-0.138307	-0.08629
b_5	0.015841	0.002858	-0.003618	-0.000128	0.001503	0.004848
b_6	-0.06476	-0.115201	-0.001158	0.090396	0.052672	0.038394
R^2	0.944963	0.93264	0.964943	0.974551	0.973738	0.97624
Radjusted	0.93579	0.896511	0.933178	0.944085	0.943162	0.946002
S.E	0.114595	0.137876	0.111173	0.103068	0.107756	0.104077
F ratio	103.0175	85.38164	169.7351	236.1487	228.6491	253.373
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 26 c Input parameters range for 0.79mm OD		
Input parameter	Minimum Value	Maximum Value
WI (A)	8	14
WS (mm/sec)	1.57	3.14
PGFR (l/min)	0.3	0.9
ESB (mm)	1.35	2.2
HIS (DT*1st in sec*A)	20	40

Table 27a: Regression coefficients for the OBW Models (Melt-in Mode Welding of A.S.S)							
	OBW(3)	OBW(8)	OBW(13)	OBW(18)	OBW(23)	OBW(28)	OBW(33)
C _{0i}	-0.406093	-0.404162	-0.198408	0.043243	-0.253823	-0.122471	-0.023093
C _{1i}	0.161838	0.170080	0.156753	0.166119	0.181252	0.203842	0.224589
C _{2i}	-0.234179	-0.332526	-0.346782	-0.417471	-0.419193	-0.458147	-0.554216
C _{3i}	1.323648	1.243434	1.276779	1.116934	1.348622	1.375913	1.338322
C _{4i}	-0.000864	-0.000253	-0.000587	-0.000273	0.0000369	-0.002087	-0.001479
C _{5i}	0.171927	0.194823	0.191745	0.183170	0.205484	0.187174	0.152327
R ²	0.827739	0.801859	0.783620	0.835791	0.852847	0.853227	0.861755
Radjusted	0.801639	0.771838	0.750835	0.810910	0.830551	0.830988	0.840808
S.E	0.131442	0.162595	0.173362	0.157208	0.154711	0.161766	0.161282
F ratio	31.714009	26.709610	23.901904	33.592581	38.251160	38.367288	41.141228
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 27b: Regression coefficients for the IBW Models (Melt-in Mode Welding of A.S.S)							
	IBW(3)	IBW(8)	IBW(13)	IBW(18)	IBW(23)	IBW(28)	IBW(33)
C _{0i}	-1.676444	-1.842784	-1.843043	-0.939694	-0.561550	-0.230127	-0.348014
C _{1i}	0.274836	0.294543	0.284951	0.272085	0.254061	0.310185	0.335952
C _{2i}	-0.480592	-0.688858	-0.775376	-0.859097	-0.857585	-0.950821	-1.026301
C _{3i}	1.748874	1.772956	2.126085	1.938294	1.881814	1.909496	1.867471
C _{4i}	0.000529	0.001749	0.001187	0.001262	0.002320	-0.000098	0.000940
C _{5i}	0.134301	0.198699	0.246333	0.176007	0.180362	0.101590	0.091206
R ²	0.872031	0.880008	0.907343	0.911121	0.912638	0.890149	0.889444
Radjusted	0.852641	0.861827	0.893304	0.897654	0.899402	0.873504	0.872693
S.E	0.153225	0.184210	0.183973	0.176443	0.177070	0.192889	0.201829
F ratio	44.974867	48.403706	64.630702	67.657932	68.947943	53.481225	53.0981
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 27c: Input Parameter Range for the Developed Melt-in Mode Models of A.S.S		
Input parameter	Minimum Value	Maximum Value
WI(A)	8.2	15
WS (mm/min)	1.33	3.99
PGFR (l/min)	0.2	0.6
ESB (mm)	1.45	1.95

Table 28a: Regression coefficients for the OBW of the 316L models (SGC: 100% Ar)

	OBW(3)	OBW(8)	OBW(13)	OBW(18)	OBW(23)	OBW(28)	OBW(33)
d_{0i}	-0.165015	+0.483223	+0.588886	+1.037378	+0.598194	+1.85541	+1.846573
d_{1i}	+0.110127	+0.077168	+0.0617	+0.063724	+0.063267	+0.068274	+0.117913
d_{2i}	-0.103672	-0.161818	-0.129585	-0.209429	-0.178966	-0.27817	-0.499069
d_{3i}	-0.079689	+0.057714	-0.009167	-0.025943	+0.092514	+0.014415	+0.124649
d_{4i}	+0.432219	+0.004447	-0.022512	-0.032208	-0.007247	-0.01945	-0.093647
d_{5i}	+0.050462	+0.07157	+0.109209	+0.081546	+0.099891	+0.001311	-0.070083
R^2	0.810373	0.84225	0.869477	0.891595	0.879497	0.766171	0.89641
Radjusted	0.794571	0.829104	0.8586	0.882561	0.869455	0.746014	0.885619
S.E	0.118961	0.091813	0.0907908	0.084755	0.091982	0.099372	0.073499
F ratio	51.28222	64.06986	79.93801	98.69585	87.58249	38.00895	83.07285
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 28b: Regression coefficients for the IBW of the 316L models (SGC: 100% Ar)

	OBW(3)	OBW(8)	OBW(13)	OBW(18)	OBW(23)	OBW(28)	OBW(33)
d_{0i}	-1.539881	-0.204475	-0.868111	-0.910983	-0.98026	-0.011122	-1.237499
d_{1i}	+0.191546	+0.169138	+0.153512	+0.148245	+0.157582	+0.183991	+0.178919
d_{2i}	-0.198096	-0.452546	-0.361633	-0.339217	-0.395407	-0.592197	-0.44026
d_{3i}	+0.037468	-0.100748	+0.032543	+0.065539	+0.223378	+0.273347	+0.314108
d_{4i}	+0.06818	-0.117991	-0.159114	-0.163856	-0.159124	-0.09408	-0.10893
d_{5i}	+0.047473	+0.05102	+0.129309	+0.143593	+0.119516	+0.001106	+0.130056
R^2	0.8793	0.914077	0.939605	0.953267	0.946192	0.935357	0.93294
Radjusted	0.869242	0.906917	0.934572	0.949373	0.941708	0.929785	0.925954
S.E	0.128939	0.120237	0.109158	0.095997	0.10398	0.106514	0.116051
F ratio	87.42007	127.6605	186.6921	244.7795	211.0137	167.8481	133.5549
Sign. F (P value)	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 28c: Input parameters range for the developed Keyhole welding models

Input parameter	Minimum Value	Maximum Value
WI(A)	15	22
WS (mm/min)	1.66	3.99
PGFR (l/min)	1.9	2.3
ESB (mm)	1.3	2.0

Table 29a: Coding for fuzzy model development for undercut			
Labels	Codes	Type of defects associated with code number	
TYPE 1	0		NO UNDERCUT
TYPE 2	-0.5		
TYPE 3	-1		
TYPE 4	+0.5		
TYPE 5	+1	CUTTING	CUTTING

Table 29b: Regression coefficients for the undercut models			
	OBW(8)	OBW(18)	OBW(28)
e_{0i}	-3.095663	-3.126028	-4.133463
e_{1i}	+0.128955	+0.155408	+0.187346
e_{2i}	-0.145437	-0.214385	-0.23485
e_{3i}	+0.009484	-0.0338344	+0.01904
e_{4i}	-0.028372	-0.029624	+0.030997
e_{5i}	+0.128955	+0.10932	+0.176534
R^2	0.775667	0.762401	0.75376
Radj.	0.760712	0.746561	0.737344
S.E	0.239127	0.268298	0.366921
F-ratio	51.86494	48.13156	45.91627
Sign. F (P value)	0.000000	0.000000	0.000000

Table 29c: Input Parameters Range for the Developed Undercut Models for Keyhole welding of A.S.S		
Input parameter	Minimum Value	Maximum Value
WI(A)	14.5	22
WS (mm/min)	1.66	3.99
PGFR (l/min)	1.9	2.5
ESB (mm)	1.3	2.0

Table 30a: Results and Responses Obtained for Validation of the Models Developed for Plasma Welding of Ti-3Al-2.5V Tubes (OD: 0.50mm)

1st SEGMENT								2nd SEGMENT								RESPONSES AND NOMINAL DEVIATION													
No	Ist	Ip	tp	Ib	tb	PGFR	DT	HI ₁	Ip	tp	Ib	tb	WS	PGFR	ESB	SDT		O3	O8	O13	O18	O23	O28	I3	I8	I13	I18	I23	I28
1	10	15	50	5	50	0.5	2.5	8.5	12	50	5	50	1.50	0.5	2	2.15	OR	2.1	2.1	2.3	2.4	2.6	2.7	1.3	1.2	1.3	1.6	1.9	2
																	PR	2.09	2.18	2.3	2.39	2.56	2.62	1.18	1.23	1.37	1.7	1.9	1.96
																	ND	0.01	-0.08	0	0.01	0.04	0.08	0.12	-0.03	-0.07	-0.1	0	0.04
2	10	15	50	5	50	0.7	2	10	15	50	5	50	2.70	0.7	2	2.15	OR	2	2	2	2.1	2.2	2.3	1.2	1.1	1.2	1.3	1.5	1.6
																	PR	2.04	1.95	2.01	2.01	2.22	2.28	1.31	1.08	1.1	1.36	1.59	1.65
																	ND	-0.04	0.05	-0.01	0.09	-0.02	0.02	-0.11	0.02	0.1	-0.06	-0.09	-0.05
3	10	15	50	5	50	0.8	3	12.5	15	50	10	50	2.50	0.8	1.5	2.15	OR	2.6	2.7	2.8	2.9	3.1	3.3	2.2	2.1	2.3	2.6	2.9	3.1
																	PR	2.68	2.68	2.7	2.93	3.18	3.28	2.2	2.15	2.25	2.62	2.95	3.07
																	ND	-0.08	0.02	0.1	-0.03	-0.08	0.02	0	-0.05	0.05	-0.02	-0.05	0.03
4	10	15	50	5	50	0.4	2	11	15	50	7	50	2.50	0.4	2	2.15	OR	2.4	2.3	2.3	2.5	2.7	2.8	1.6	1.6	1.7	1.9	2.1	2.3
																	PR	2.31	2.3	2.37	2.43	2.65	2.72	1.73	1.62	1.67	1.95	2.23	2.27
																	ND	0.09	0	-0.07	0.07	0.05	0.08	-0.13	-0.02	0.03	-0.05	-0.13	0.03
5	10	15	50	5	50	0.5	3	14	15	50	13	50	2.90	0.5	1.2	2.15	OR	2.8	2.7	2.8	3	3.3	3.5	2.4	2.4	2.5	2.7	3.1	3.3
																	PR	2.9	2.84	2.83	3.13	3.41	3.5	2.54	2.47	2.49	2.82	3.25	3.38
																	ND	-0.1	-0.14	-0.03	-0.13	-0.11	0	-0.14	-0.07	0.01	-0.12	-0.15	-0.08

Table 30b: Results and Responses Obtained for Validation of the Models Developed for Plasma Welding of Ti-3Al-2.5V Tubes (OD: 0.79mm)

1st SEGMENT								2nd SEGMENT								RESPONSES AND NOMINAL DEVIATION													
No	Ist	Ip	tp	Ib	tb	PGFR	DT	HI ₁	Ip	tp	Ib	tb	WS	PGFR	ESB	SDT		O3	O8	O13	O18	O23	O28	I3	I8	I13	I18	I23	I28
1	10	15	50	5	50	0.6	2	13	21	50	5	50	3.10	0.6	1.7	2.2	OR	2.7	2.5	2.6	2.7	2.9	3	2	1.8	1.8	1.9	2.4	2.5
																	PR	2.57	2.49	2.5	2.68	2.92	3.03	1.96	1.75	1.79	2.06	2.53	2.6
																	ND	0.13	0.01	0.1	0.02	-0.02	-0.03	0.04	0.05	0.01	-0.16	-0.13	-0.1
2	10	15	50	5	50	0.8	2.5	11.5	17	50	5	50	1.90	0.8	1.5	2.2	OR	2.5	2.6	2.7	3.1	3.5	3.6	2	1.9	2.1	2.6	3	3.2
																	PR	2.69	2.72	2.78	3.24	3.41	3.52	2.06	2.01	2.28	2.76	3.06	3.17
																	ND	-0.19	-0.12	-0.08	-0.14	0.09	0.08	-0.06	-0.11	-0.18	-0.16	-0.06	0.03
3	10	15	50	5	50	0.5	3	8.5	12	50	5	50	2.10	0.5	1.5	2.2	OR	2.1	1.9	1.9	2.1	2.3	2.3	1.2	1	1.1	1.3	1.7	1.8
																	PR	2.06	1.89	1.82	2.04	2.19	2.25	1.26	0.98	1.02	1.31	1.6	1.7
																	ND	0.04	0.01	0.08	0.06	0.11	0.05	-0.06	0.02	0.08	-0.01	0.1	0.1
4	10	15	50	5	50	0.6	2	13	21	50	5	50	2.40	0.6	2	2.2	OR	2.7	2.8	2.9	3.1	3.4	3.5	2.2	2.1	2.4	2.8	3.1	3.3
																	PR	2.76	2.75	2.89	3.17	3.44	3.54	2.29	2.29	2.49	2.82	3.18	3.3
																	ND	-0.06	0.05	0.01	-0.07	-0.04	-0.04	-0.09	-0.19	-0.09	-0.02	-0.08	0
5	10	15	50	5	50	0.8	2.5	10	15	50	5	50	2.40	0.8	2	2.2	OR	2.2	2.1	2.1	2.3	2.4	2.6	1.4	1.2	1.3	1.5	1.8	2
																	PR	2.21	2.02	2.02	2.18	2.35	2.45	1.47	1.23	1.24	1.46	1.81	1.92
																	ND	-0.01	0.08	0.08	0.12	0.05	0.15	-0.07	-0.03	0.06	0.04	-0.01	0.08

where: Ist: Average Welding Current Before the Initiation of Torch Rotation (in Amps)
 HI₁: Average Welding Current During the Torch Rotation (in Amps)
 Ip: Peak Welding Current (in Amps) tp: Peak Current Time (in msec)
 OD: Orifice Diameter (in mm)
 OR: Obtained Response
 Ib: Background Welding Current (in Amps) tb: Background Current Time (in msec)
 WS: Welding Speed (in mm/sec) PGFR: Plasma Gas Flow Rate (in l/min)
 ESB: Electrode Set Back Distance (in mm) SDT (Stand Off Distance (in mm)
 DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)
 PR: Predicted Response ND: Nominal Deviation

Table 31: Results and Responses Obtained for Validation of the Models Developed for Plasma Welding (Keyhole Mode) of 316L Tubes

1st SEGMENT								2nd SEGMENT								RESPONSES AND NOMINAL DEVIATION															
No	Ist	Ip	tp	Ib	tb	PGFR	DT	HI ₁	Ip	tp	Ib	tb	WS	PGFR	ESB	SDT		O3	O8	O13	O18	O23	O28	O33	I3	I8	I13	I18	I23	I28	I33
1	15	25	50	5	50	0.3	1	9.00	15	20	5	30	1.5	0.3	1.45	1.6	OR	2.3	2.2	2.2	2.4	2.5	2.7	2.6	1.6	1.5	1.6	1.8	2.2	2.4	2.3
																	PR	2.13	2.17	2.22	2.35	2.39	2.56	2.48	1.41	1.50	1.68	1.86	2.09	2.32	2.24
																	ND	0.17	0.03	-0.02	0.05	0.11	0.14	0.12	0.19	0.00	-0.08	-0.06	0.11	0.08	0.06
2	15	25	50	5	50	0.3	1	11.00	20	20	5	30	1.5	0.3	1.95	1.6	OR	2.5	2.6	2.6	2.8	3.0	3.2	3.1	2.3	2.3	2.5	2.8	2.9	3.2	3.1
																	PR	2.66	2.77	2.79	2.92	3.02	3.21	3.13	2.14	2.36	2.57	2.64	2.84	3.07	3.04
																	ND	-0.16	-0.17	-0.19	-0.12	-0.02	-0.01	-0.03	0.16	-0.06	-0.07	0.16	0.06	0.13	0.06
3	15	25	50	5	50	0.4	1	14.20	28	20	5	30	2.8	0.4	1.95	1.6	OR	2.7	2.7	2.7	2.8	2.9	3.0	2.9	2.2	2.2	2.2	2.3	2.4	2.7	2.6
																	PR	2.64	2.56	2.54	2.61	2.73	2.98	2.92	2.26	2.13	2.13	2.19	2.32	2.79	2.76
																	ND	0.06	0.14	0.16	0.19	0.17	0.02	-0.02	-0.06	0.07	0.07	0.11	0.08	-0.09	-0.16
4	15	25	50	5	50	0.6	1	12.20	23	20	5	30	3.3	0.6	1.60	1.6	OR	2.2	2.1	2.0	2.0	2.2	2.4	2.4	1.5	1.3	1.4	1.5	1.7	1.8	1.8
																	PR	2.22	2.04	2.04	2.04	2.14	2.37	2.25	1.64	1.28	1.26	1.36	1.51	1.94	1.82
																	ND	-0.02	0.06	-0.04	-0.04	0.06	0.03	0.15	-0.14	0.02	0.14	0.14	0.19	-0.14	-0.02
5	15	25	50	5	50	0.4	1	12.20	23	20	5	30	2.1	0.4	1.60	1.6	OR	2.5	2.6	2.6	2.8	2.8	3	3	2	2.2	2.2	2.4	2.6	2.8	2.9
																	PR	2.60	2.60	2.61	2.70	2.81	3.04	2.97	2.15	2.17	2.29	2.38	2.54	2.91	2.87
																	ND	-0.10	0.00	-0.01	0.10	-0.01	-0.04	0.03	-0.15	0.03	-0.09	0.02	0.06	-0.11	0.03

Table 32: Results and Responses Obtained for Validation of the Models Developed for Plasma Welding (Keyhole Mode) of 316L Tubes

1st SEGMENT								2nd SEGMENT								RESPONSES AND NOMINAL DEVIATION															
No	Ist	Ip	tp	Ib	tb	PGFR	DT	HI ₁	Ip	tp	Ib	tb	WS	PGFR	ESB	SDT		O3	O8	O13	O18	O23	O28	O33	I3	I8	I13	I18	I23	I28	I33
1	16.5	28	20	5	20	2.3	2	16.50	28	20	5	20	2.66	1.9	1.60	1.6	OR	2.1	1.9	1.9	1.9	2	2.3	2.2	1.5	1.3	1.2	1.3	1.5	1.8	1.9
																	PR	2.23	1.89	1.89	1.94	1.95	2.25	2.12	1.57	1.32	1.31	1.39	1.48	1.83	1.77
																	ND	-0.13	0.01	0.01	-0.04	0.05	0.05	0.08	-0.07	-0.02	-0.11	-0.09	0.02	-0.03	0.13
2	16.5	28	20	5	20	2.3	2	17.50	28	20	7	20	2.46	1.9	2.00	1.6	OR	2.3	2.1	2.1	2.1	2.1	2.2	2.3	1.8	1.7	1.6	1.7	1.9	2.2	2.2
																	PR	2.58	2.06	2.06	2.10	2.14	2.36	2.23	1.87	1.58	1.59	1.67	1.76	2.09	2.11
																	ND	-0.28	0.04	0.04	0.00	-0.04	-0.16	0.07	-0.07	0.12	0.01	0.03	0.14	0.11	0.09
3	16.5	28	20	5	20	2.3	2	21.50	28	20	15	20	2.6	2.2	2.00	1.6	OR	3	2.5	2.4	2.4	2.5	2.8	C	2.5	2.2	2.3	2.5	2.6	2.9	C
																	PR	3.04	2.45	2.42	2.42	2.51	2.60	2.59	2.67	2.22	2.31	2.40	2.54	2.83	3.01
																	ND	-0.04	0.05	-0.02	-0.02	-0.01	0.20	C	-0.17	-0.02	-0.01	0.10	0.06	0.07	C
4	16.5	28	20	5	20	2.3	2	18.00	28	20	8	20	3.04	2.3	1.60	1.6	OR	2.4	2	2	2.1	2.1	2.3	2.1	1.6	1.4	1.5	1.5	1.7	1.9	1.9
																	PR	2.34	1.92	1.90	1.93	1.95	2.24	2.12	1.77	1.39	1.37	1.44	1.53	1.88	1.84
																	ND	0.06	0.08	0.10	0.17	0.15	0.06	-0.02	-0.17	0.01	0.13	0.06	0.17	0.02	0.06
5	16.5	28	20	5	20	2.3	2	19.00	28	20	10	20	2.56	1.9	1.60	1.6	OR	2.6	2.2	2.3	2.3	2.3	2.5	2.4	2	1.8	1.9	2.1	2.2	2.3	2.5
																	PR	2.58	2.18	2.19	2.22	2.25	2.45	2.38	2.12	1.85	1.89	1.97	2.06	2.35	2.42
																	ND	0.02	0.02	0.11	0.08	0.05	0.05	0.02	-0.12	-0.05	0.01	0.13	0.14	-0.05	0.08

where: Ist: Average Welding Current Before the Initiation of the Torch Rotation (in Amps) Ib: Background Welding Current (in Amps) tb: Background Current Time (in msec)
 HI₁: Average Welding Current During the Torch Rotation (in Amps) WS: Welding Speed i(in mm/sec) PGFR : Plasma Gas Flow Rate (in l/min)
 Ip: Peak Welding Current (in Amps) tp: Peak Current Time (in msec) ESB: Electrode Set Back Distance (in mm) SDT (Stand Off Distance (in mm)
 DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)
 OR: Obtained Response PR: Predicted Response ND: Nominal Deviation

Table 33: Parameter Combinations Utilised and Results Obtained for Keyhole Plasma Welding of 316L Tubes (SGC: Ar+10%H₂)

1st SEGMENT									2nd SEGMENT									ESB	SDT					
No	Ist	Ip	tp	Ib	tb	PGFR	DT	HI ₁	Ip	tp	Ib	tb	WS	PGFR										
1	16.5	28	20	5	20	1.9	2.0	11.5	18	20	5	20	2.66	1.9	1.00	1.60								
2	16.5	28	20	5	20	1.9	2.0	11.5	18	20	5	20	2.10	1.9	1.00	1.60								
3	16.5	28	20	5	20	1.6	2.0	13.0	21	20	5	20	2.66	1.6	1.00	1.60								
4	16.5	28	20	5	20	1.9	2.0	11.5	18	20	5	20	2.10	1.9	1.00	1.60								
5	16.5	28	20	5	20	1.6	2.0	13.0	21	20	5	20	2.10	1.6	1.00	1.60								
6	16.5	28	20	5	20	1.6	2.0	14.0	23	20	5	20	2.10	1.6	1.00	1.60								
7	16.5	28	20	5	20	1.6	2.0	10.0	15	20	5	20	1.54	1.6	1.00	1.60								
8	16.5	28	20	5	20	1.6	2.0	8.5	12	20	5	20	1.54	1.6	1.00	1.60								
9	16.5	28	20	5	20	1.9	2.0	14.5	24	20	5	20	3.69	1.9	1.00	1.60								
10	16.5	28	20	5	20	1.4	2.0	14.5	24	20	5	20	2.46	1.4	1.00	1.60								
11	16.5	28	20	5	20	1.4	2.0	15.5	26	20	5	20	2.46	1.4	1.00	1.60								
12	16.5	28	20	5	20	1.4	2.0	16.0	27	20	5	20	3.38	1.4	1.00	1.60								
13	16.5	28	20	5	20	1.4	2.0	16.0	27	20	5	20	3.69	1.4	1.00	1.60								
14	16.5	28	20	5	20	1.6	2.0	10.0	15	20	5	20	2.66	1.6	1.00	1.60								
15	16.5	28	20	5	20	1.6	2.0	10.0	15	20	5	20	2.66	1.6	1.00	1.60								
16	16.5	28	20	5	20	1.6	2.0	12.0	19	20	5	20	3.32	1.6	1.00	1.60								
17	16.5	28	20	5	20	1.9	2.0	14.0	23	20	5	20	3.99	1.9	1.00	1.60								
18	16.5	28	20	5	20	1.6	2.0	16.5	28	20	5	20	2.99	1.6	1.00	1.60								
19	16.5	28	20	5	20	1.6	2.0	16.5	28	20	5	20	3.99	1.6	1.00	1.60								
20	16.5	28	20	5	20	1.4	2.0	17.5	28	20	7	20	3.99	1.4	1.00	1.60								
21	16.5	28	20	5	20	1.6	2.0	18.0	28	20	8	20	3.32	1.6	1.00	1.60								
22	16.5	28	20	5	20	1.6	2.0	17.5	28	20	7	20	2.66	1.6	1.00	1.60								
23	16.5	28	20	5	20	1.9	2.0	13.0	21	20	5	20	1.33	1.9	1.00	1.60								
24	16.5	28	20	5	20	1.9	2.0	20.0	28	20	12	20	2.66	1.9	1.00	1.60								
25	16.5	28	20	5	20	1.9	2.0	21.0	28	20	14	20	3.33	1.9	1.00	1.60								
26	16.5	28	20	5	20	1.9	2.0	22.0	28	20	16	20	3.99	1.9	1.00	1.60								
27	16.5	28	20	5	20	1.4	2.0	19.0	28	20	10	20	2.66	1.4	1.00	1.60								
28	16.5	28	20	5	20	1.6	2.0	20.0	28	20	12	20	3.99	1.6	1.00	1.60								
29	16.5	28	20	5	20	1.4	2.0	16.5	28	20	5	20	2.00	1.4	1.00	1.60								
30	16.5	28	20	5	20	1.9	2.0	11.0	17	20	5	20	3.99	1.9	1.00	1.60								
31	16.5	28	20	5	20	1.6	2.0	7.0	9	20	5	20	1.54	1.6	1.00	1.60								
32	16.5	28	20	5	20	1.6	2.0	7.0	9	20	5	20	1.32	1.6	1.00	1.60								
POSITION-OBW									POSITION-IBW									ESB	SDT					
No	3	8	13	18	23	28	33	3	8	13	18	23	28	33										
1	2.0	1.9	2.1	2.1	2.1	2.0	2.0	1.5	1.4	1.6	1.7	1.6	1.7	1.6										
2	2.0	2.0	2.2	2.3	2.1	2.1	2.1	1.5	1.7	1.9	2.1	2.3	2.3	2.4										
3	2.1	2.1	2.2	2.2	2.2	2.0	2.1	1.6	1.5	1.6	1.7	1.7	0.9	2.0										
4	2.0	2.0	2.2	2.1	2.0	NW	NW	1.5	1.5	1.6	1.6	1.6	NW	NW										
5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1	1.9	2.2	2.2	2.3	2.4	2.4										
6	2.3	2.3	2.4	2.4	2.3	2.2	2.2	2.3	2.4	2.5	2.5	2.5	2.5	2.6										
7	2.1	2.2	2.3	2.2	2.2	2.1	2.2	1.8	1.6	1.8	1.9	2.0	2.0	2.2										
8	1.9	2.1	2.2	2.2	1.9	1.9	2.2	1.2	1.2	1.4	1.4	1.4	1.6	1.7										
9	2.2	2.1	2.1	2.1	2.1	2.1	2.1	1.8	1.6	1.5	1.6	1.6	1.7	1.7										
10	2.5	2.3	2.5	2.3	2.3	2.3	2.4	2.6	2.3	2.4	2.4	2.4	2.6	2.8										
11	2.4	2.3	2.5	2.6	2.6	2.7	2.7	2.4	2.3	2.5	2.5	2.5	2.7	2.8										
12	2.4	2.2	2.3	2.3	2.3	2.3	2.3	2.2	1.8	1.9	2.1	2.1	2.2	2.2										
13	2.4	2.3	2.3	2.3	2.3	2.2	2.2	2.1	1.6	1.8	1.8	1.9	1.9	2.1										
14	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.4	1.4	1.3	1.3	1.2	1.3	1.4										
15	1.9	2.0	1.9	2.0	1.9	2.0	2.0	1.4	1.2	1.2	1.3	1.3	1.4	1.4										
16	2.1	2.0	2.0	2.0	1.9	1.9	2.0	1.5	1.3	1.4	1.2	1.2	1.3	1.3										
17	2.0	2.1	2.0	2.0	2.0	2.2	2.2	1.3	1.5	1.5	1.5	1.6	1.6	1.7										
18	2.3	2.3	2.3	2.3	2.3	2.3	2.4	2.3	2.3	2.3	2.3	2.3	2.3	2.3										
19	2.2	2.3	2.3	2.2	2.2	2.2	2.2	1.8	1.7	1.7	1.7	1.8	1.9	2.1										
20	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	2.0	1.9	1.9	2.0	2.0	2.0										
21	CUTTING							where: Ist: Average Welding Current Before the Initiation of Torch Rotation (in Amps)									ESB	SDT						
22	CUTTING							HI ₁ : Average Welding Current During the Torch Rotation (in Amps)																
23	CUTTING							Ip: Peak Welding Current (in Amps)				tp: Peak Current Time (in msec)												
24	CUTTING							Ib: Background Welding Current (in Amps)				tb: Background Current Time (in msec)												
25	CUTTING							WS: Welding Speed (in mm/sec)				PGFR : Plasma Gas Flow Rate (in l/min)												
26	CUTTING							ESB: Electrode Set Back Distance (in mm)				SDT: Stand Off Distance (in mm)												
27	CUTTING							DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)																
28	CUTTING							SGC: Shielding Gas Composition																
29	CUTTING							where: OBW: Outer Bead Width (in mm)																
30	HUMPING							IBW: Inner Bead Width (in mm)																
31	HUMPING							NW: Not Welded																
32	HUMPING																							

Table 34:Parameter Combinations Utilised and Results Obtained for Keyhole Plasma Welding of 316L Tubes (SGC: Ar+5%H₂)

1st SEGMENT								2nd SEGMENT								ESB	SDT
No	Ist	Ip	tp	Ib	tb	PGFR	DT	HI ₁	Ip	tp	Ib	tb	WS	PGFR			
1	16.5	28	20	5	20	1.9	2	11.5	18	20	5	20	2.66	1.9	1.0	1.6	
2	16.5	28	20	5	20	1.9	2	11.5	18	20	5	20	2.66	1.6	1.0	1.6	
3	16.5	28	20	5	20	1.9	2	11.5	18	20	5	20	2.10	1.6	1.0	1.6	
4	16.5	28	20	5	20	1.9	2	11.5	18	20	5	20	3.31	1.9	1.0	1.6	
5	16.5	28	20	5	20	1.9	2	14.0	23	20	5	20	2.66	1.6	1.0	1.6	
6	16.5	28	20	5	20	1.9	2	14.0	23	20	5	20	3.99	1.8	1.0	1.6	
7	16.5	28	20	5	20	1.9	2	14.0	23	20	5	20	2.10	1.6	1.0	1.6	
8	16.5	28	20	5	20	1.9	2	16.0	27	20	5	20	3.99	1.8	1.0	1.6	
9	16.5	28	20	5	20	1.9	2	16.0	27	20	5	20	2.77	1.6	1.0	1.6	
10	16.5	28	20	5	20	1.9	2	10.0	15	20	5	20	2.10	1.6	1.0	1.6	
11	16.5	28	20	5	20	1.9	2	17.5	28	20	7	20	3.31	1.8	1.0	1.6	
12	16.5	28	20	5	20	1.9	2	12.5	20	20	5	20	2.15	1.7	1.0	1.6	
13	16.5	28	20	5	20	1.9	2	12.5	20	20	5	20	2.66	1.6	1.0	1.6	
14	16.5	28	20	5	20	1.9	2	12.5	20	20	5	20	1.69	1.6	1.0	1.6	
15	16.5	28	20	5	20	1.9	2	12.0	16	20	7	20	1.69	2.1	1.0	1.6	
16	16.5	28	20	5	20	1.9	2	18.0	28	20	7	20	2.66	1.6	1.0	1.6	
17	16.5	28	20	5	20	1.9	2	16.0	27	20	5	20	2.31	1.6	1.0	1.6	

POSITION-OBW								POSITION-IBW							
No	3	8	13	18	23	28	33	3	8	13	18	23	28	33	
1	1.8	2.0	2.0	2.1	2.1	2.0	2.0	1.3	1.2	1.3	1.4	1.4	1.6	1.5	
2	2.0	2.0	2.1	2.0	1.9	2.0	2.0	1.3	1.2	1.3	1.3	1.3	1.4	1.4	
3	2.0	2.3	2.3	2.3	2.4	2.4	2.4	1.4	1.4	1.7	1.8	1.8	1.9	1.9	
4	2.0	1.8	1.8	1.8	1.8	1.9	1.9	1.3	1.0	1.0	1.0	1.0	1.2	1.2	
5	2.3	2.3	2.3	2.3	2.3	2.3	2.4	1.8	1.6	1.7	1.8	1.8	2.0	2.0	
6	2.7	2.5	2.4	2.4	2.2	2.2	2.2	1.8	1.9	1.9	2.2	2.1	2.5	2.5	
7	2.0	1.8	1.8	1.8	1.8	1.9	1.9	1.2	1.0	1.1	1.1	1.1	1.2	1.2	
8	2.1	2.0	2.0	1.9	1.9	2.0	2.1	1.6	1.4	1.4	1.4	1.4	1.6	1.6	
9	2.5	2.5	2.7	2.7	2.8	2.9	2.8	2.1	1.9	2.0	2.1	2.1	2.3	2.4	
10	2.1	2.0	1.9	1.8	1.9	2.0	2.0	1.3	1.1	1.0	1.2	1.3	1.5	1.5	
11	2.5	2.3	2.4	2.3	2.1	2.3	2.4	2.1	1.9	2.0	2.0	1.9	2.1	2.4	
12	2.5	2.5	2.5	2.4	2.3	2.4	2.4	1.5	1.6	1.7	1.8	1.7	1.9	2.0	
13	2.0	1.9	2.0	2.0	2.0	2.1	2.2	1.4	1.3	1.3	1.4	1.6	1.8	1.7	
14	2.2	2.4	2.6	2.4	2.4	2.5	2.6	1.5	1.8	2.2	2.3	2.3	2.6	2.6	

15 CUTTING	where: Ist: Average Welding Current Before the Initiation of the Torch Rotation (in Amps)
16 CUTTING	HI ₁ : Average Welding Current During the Torch Rotation (in Amps)
17 CUTTING	Ip: Peak Welding Current (in Amps) tp: Peak Current Time (in msec)
	Ib: Background Welding Current (in Amps) tb: Background Current Time (in msec)
	WS: Welding Speed (in mm/sec) PGFR : Plasma Gas Flow Rate (in l/min)
	ESB: Electrode Set Back Distance (in mm) SDT: Stand Off Distance (in mm)
	DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)
	SGC: Shielding Gas Composition
	where: OBW: Outer Bead Width (in mm)
	IBW: Inner Bead Width (in mm)
	NW: Not Welded

Table 35: Influence of Current Frequency on Weld Bead Characteristics in Keyhole Welding of 316L Tubes (SGC: Ar+5%H₂)

1st SEGMENT								2nd SEGMENT								
No	Ist	Ip	tp	lb	tb	PGFR	DT	HI1	Ip	tp	lb	tb	WS	PGFR	ESB	SDT
1	14	23	30	5	30	1.8	2	14	23	30	5	30	2.66	1.8	1.0	1.6
2	14	23	50	5	50	1.8	2	14	23	50	5	50	2.66	1.8	1.0	1.6
3	14	23	70	5	70	1.8	2	14	23	70	5	70	2.66	1.8	1.0	1.6
4	14	23	90	5	90	1.8	2	14	23	90	5	90	2.66	1.8	1.0	1.6
5	14	23	99	5	99	1.8	2	14	23	99	5	99	2.66	1.8	1.0	1.6
6	14	23	250	5	250	1.8	2	14	23	250	5	250	2.66	1.8	1.0	1.6
7	14	23	500	5	500	1.8	2	14	23	500	5	500	2.66	1.8	1.0	1.6
8	14	14	20	14	20	1.8	2	14	14	20	14	20	2.66	1.8	1.0	1.6
9	16.5	28	20	5	20	1.8	2	12.5	20	30	5	30	1.70	1.8	1.0	1.6
10	16.5	28	20	5	20	1.8	2	12.5	20	50	5	50	1.70	1.8	1.0	1.6
11	16.5	28	20	5	20	1.8	2	12.5	20	99	5	99	1.70	1.8	1.0	1.6
12	16.5	28	20	5	20	1.8	2	12.5	20	200	5	200	1.70	1.8	1.0	1.6
13	16.5	28	20	5	20	1.8	2	12.5	20	400	5	400	1.70	1.8	1.0	1.6

POSITION-OBW								POSITION-IBW							
No	3	8	13	18	23	28	33	3	8	13	18	23	28	33	
1	2.1	2.1	2.2	2.2	2.2	2.1	2.1	1.4	1.4	1.6	1.6	1.6	1.8	1.7	
2	2.2	2.1	2.2	2.2	2.1	2.2	2.2	1.6	1.5	1.6	1.7	1.6	1.8	1.7	
3	2.3	2.1	2.3	2.2	2.2	2.3	2.3	1.6	1.5	1.6	1.7	1.8	2.0	2.0	
4	2.6	2.6	2.6	2.5	2.4	2.5	2.5	2.0	1.9	2.1	2.3	2.3	2.4	2.5	
5	2.6	2.5	2.4	2.4	2.5	2.6	2.5	2.0	1.9	2.0	2.2	2.2	2.2	2.2	
6	INTERMITTENT STITCHES														
7	INTERMITTENT STITCHES														
8	2.3	2.1	2.1	2.2	2.2	2.3	2.1	1.8	2.0	2.1	2.2	2.2	2.4	2.3	
9	2.3	2.4	2.5	2.5	2.6	2.4	2.5	1.6	1.7	2.0	2.0	2.3	2.6	2.7	
10	2.4	2.5	2.5	2.5	2.6	2.4	2.5	1.6	1.8	1.9	2.1	2.2	2.6	2.7	
11	CUTTING														
12	CUTTING														
13	CUTTING														

where: Ist: Average Welding Current Before the Initiation of the Torch Rotation (in Amps)
HI₁: Average Welding Current During the Torch Rotation (in Amps)
I_p: Peak Welding Current (in Amps)
I_b: Background Welding Current (in Amps)
WS: Welding Speed (in mm/sec)
ESB: Electrode Set Back Distance (in mm)
DT: Period Between Arc Initiation and Initiation of Torch Rotation (in sec)
SGC: Shielding Gas Composition

where: OBW: Outer Bead Width (in mm)
IBW: Inner Bead Width (in mm)

Figures

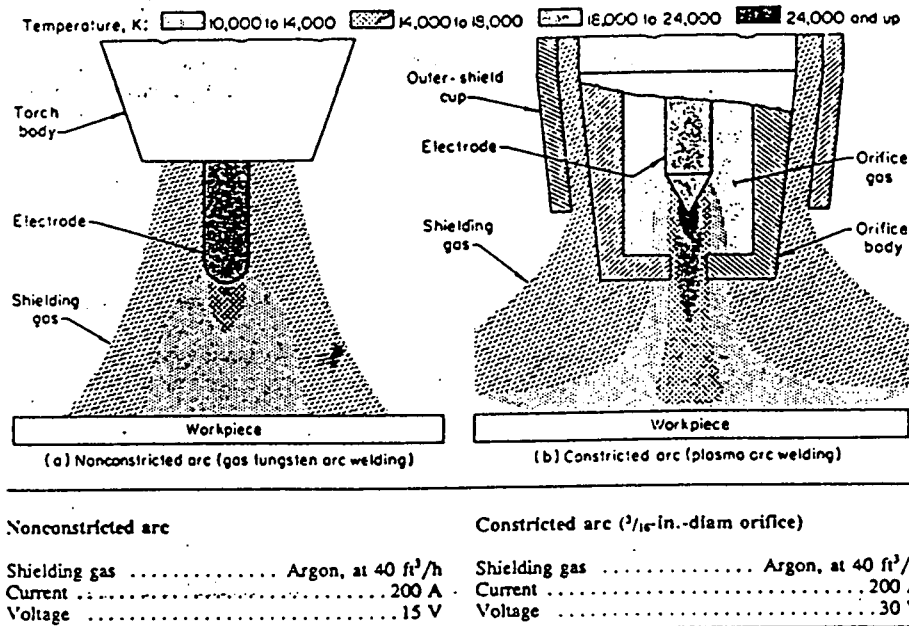


Figure 1: Comparison of a nonconstricted arc used for GTAW with a constricted arc used for PAW. It shows the effect of constriction on temperature and heat (from 8).

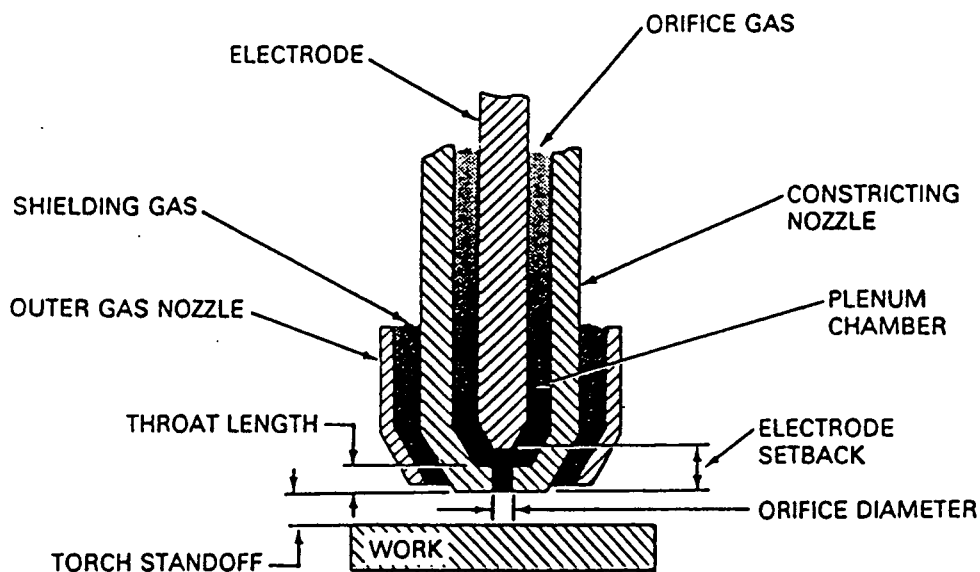


Figure 2: Main features and terms of a plasma arc torch (from 11).

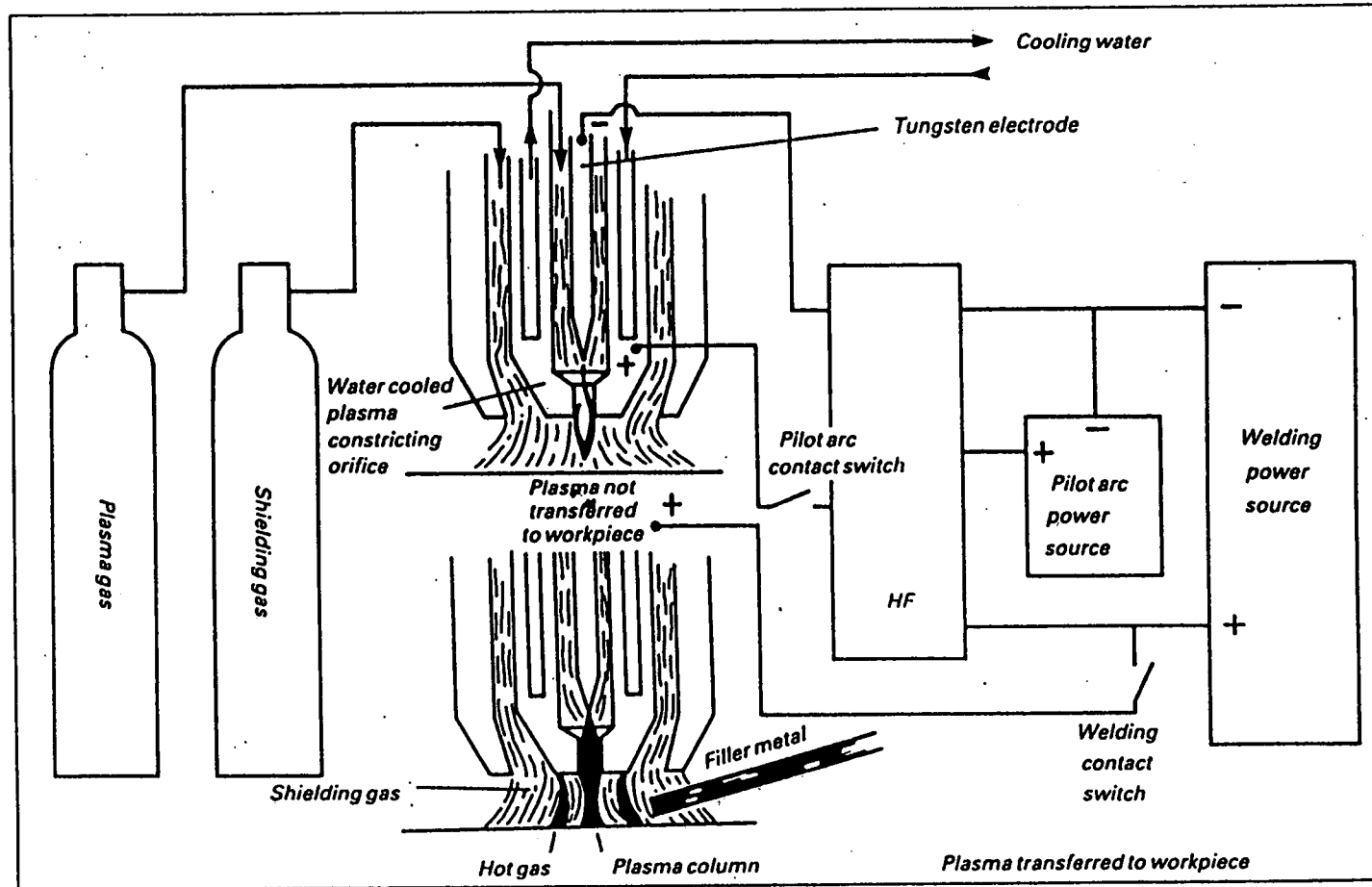


Figure 3: A simplified schematic view of a plasma arc welding installation. The pilot arc (non-transferred) is used to ignite the arc and may participate during welding (arc transferred) by assisting in the ionisation of the gas (from 12).

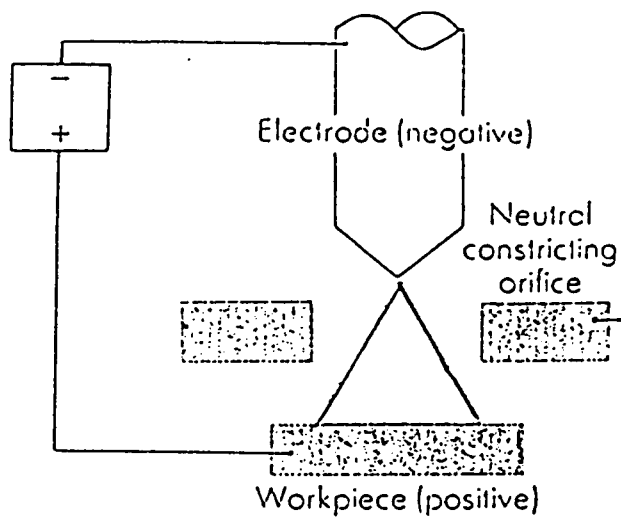


Figure 4a: The transferred arc mode (from 13).

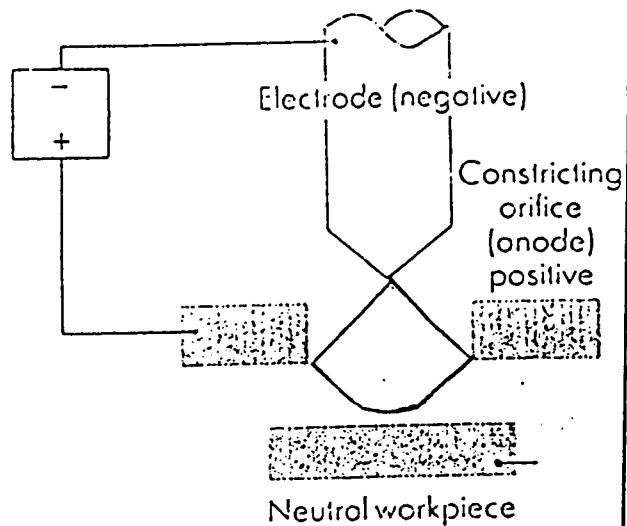


Figure 4b: The non-transferred arc mode (from 13).

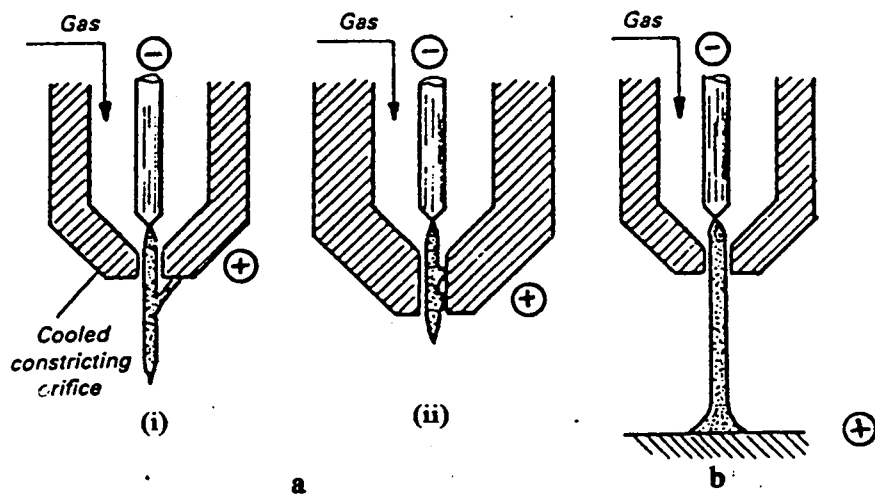


Figure 5a, 5b: Different types of plasma arc, (a) Non-transferred plasma arc (i: blown arc), (b) Transferred plasma arc (from 16).

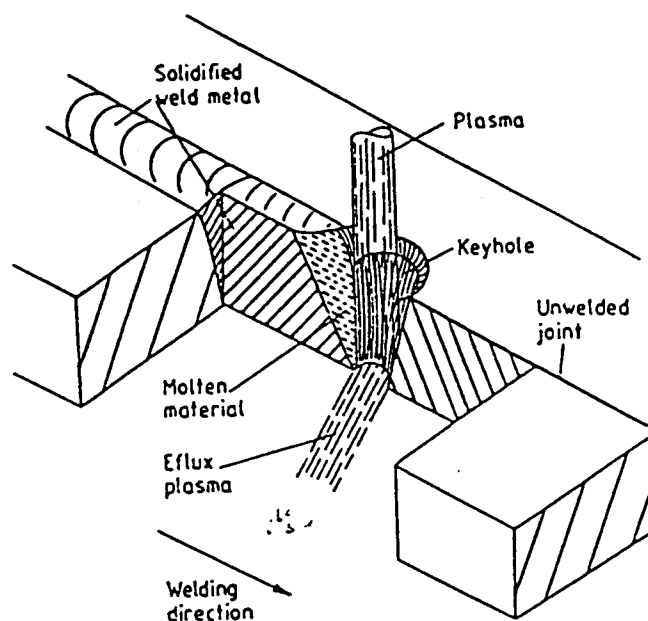


Figure 6: Mechanism of keyhole welding (from 18).

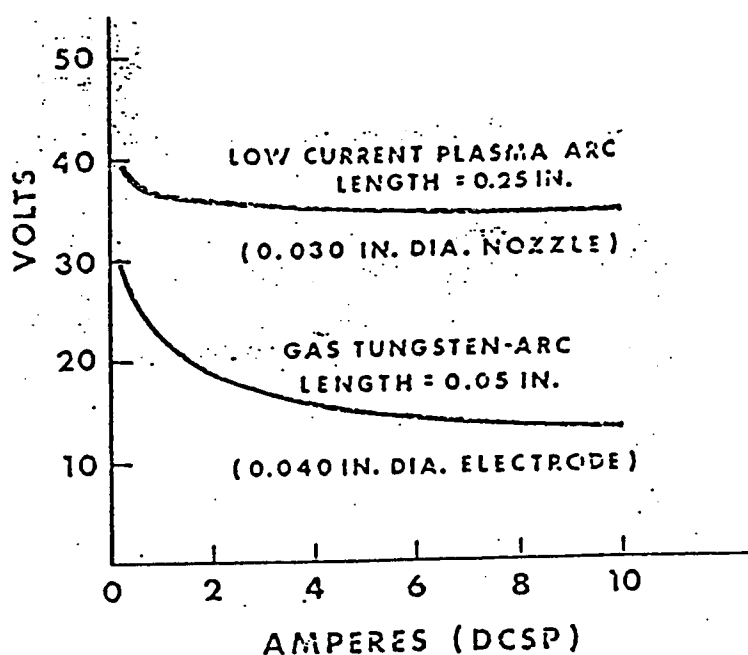
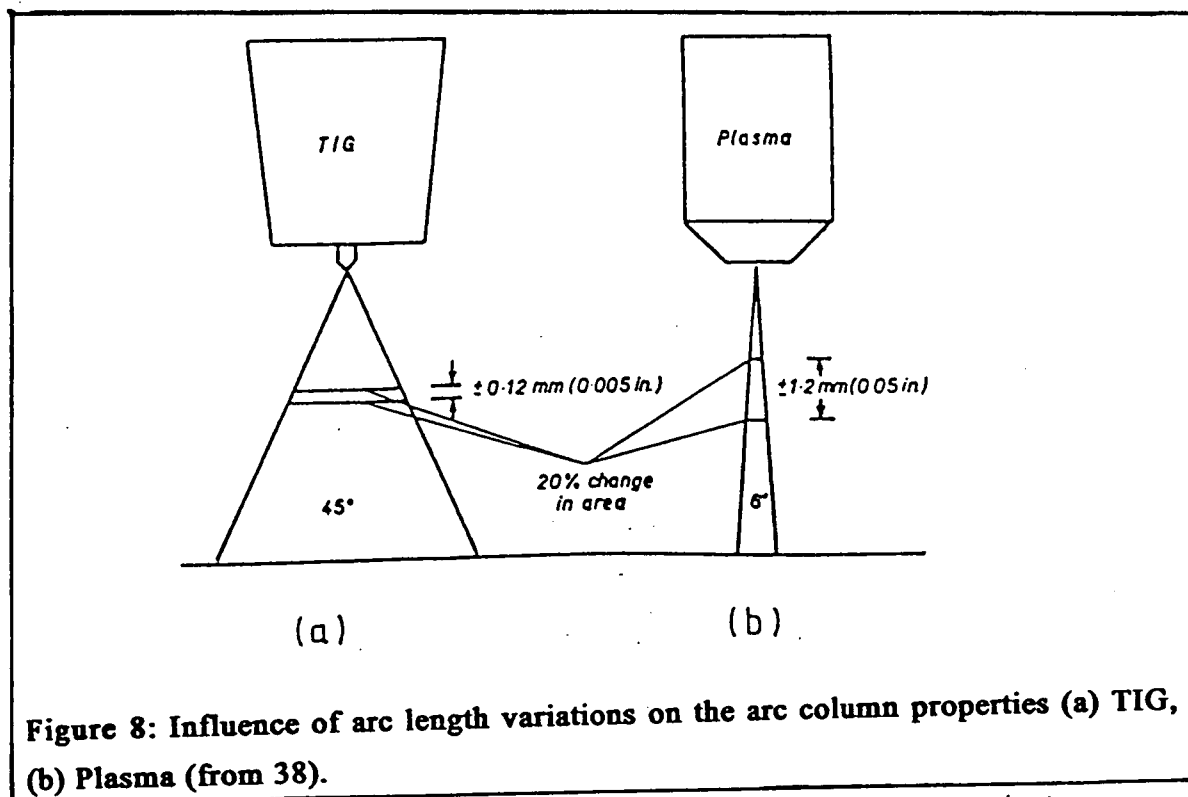
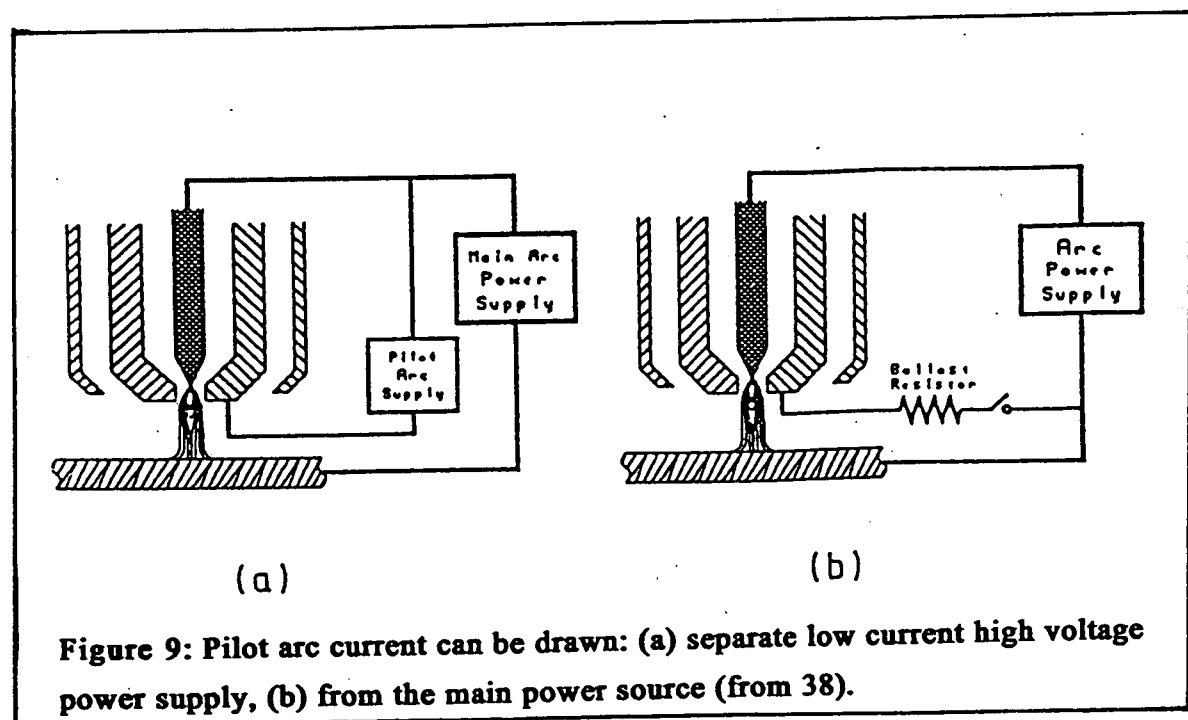


Figure 7: Volt-amp characteristics of plasma and GTAW arcs for very low current applications. The significant influence of arc length variations in the produced arc current can be observed for the GTAW arc. The micro-plasma arc is less sensitive to such variations (from 62).



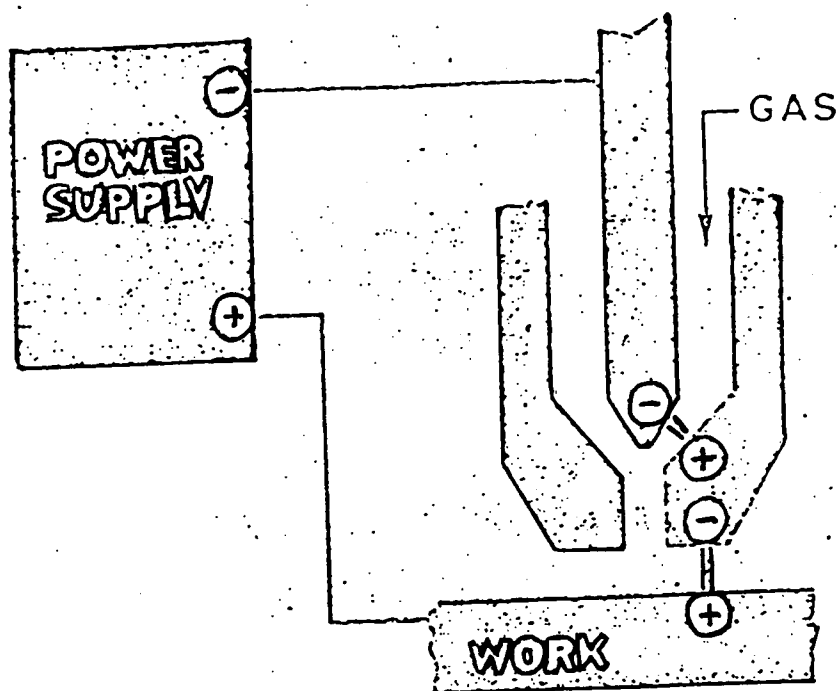
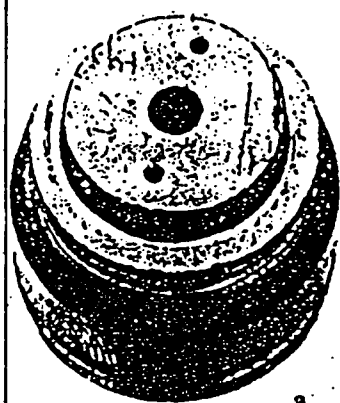
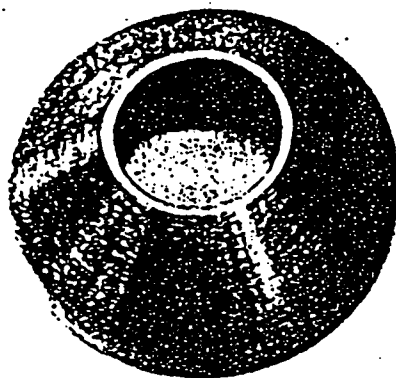


Figure 10: Double arcing - the torch nozzle becomes part of the current path to the ground (from 35).



a



b

Figure 11a, b: Multiport nozzle with (a) an additional hole on either side of the constricting duct, (b) use of a conically shaped single port nozzle with a standard shape shielding gas cup for arc focusing (from 55).

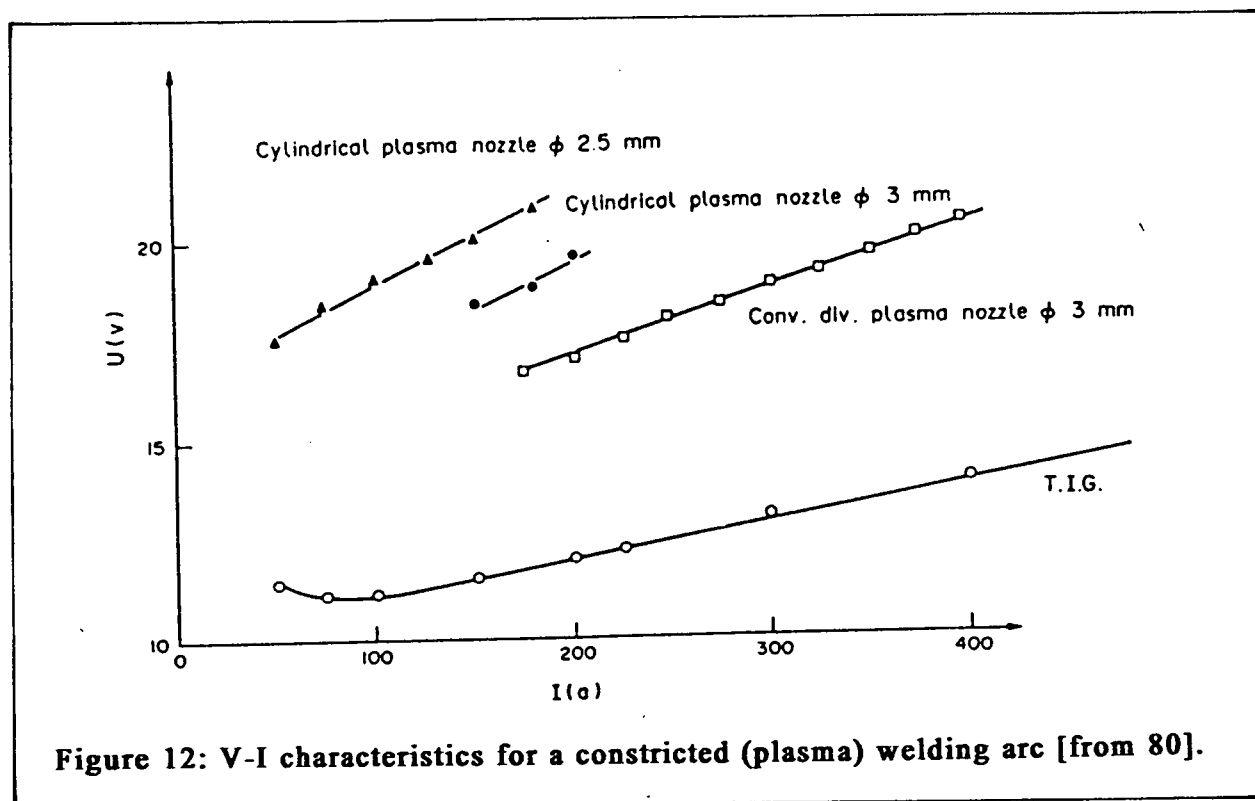


Figure 12: V-I characteristics for a constricted (plasma) welding arc [from 80].

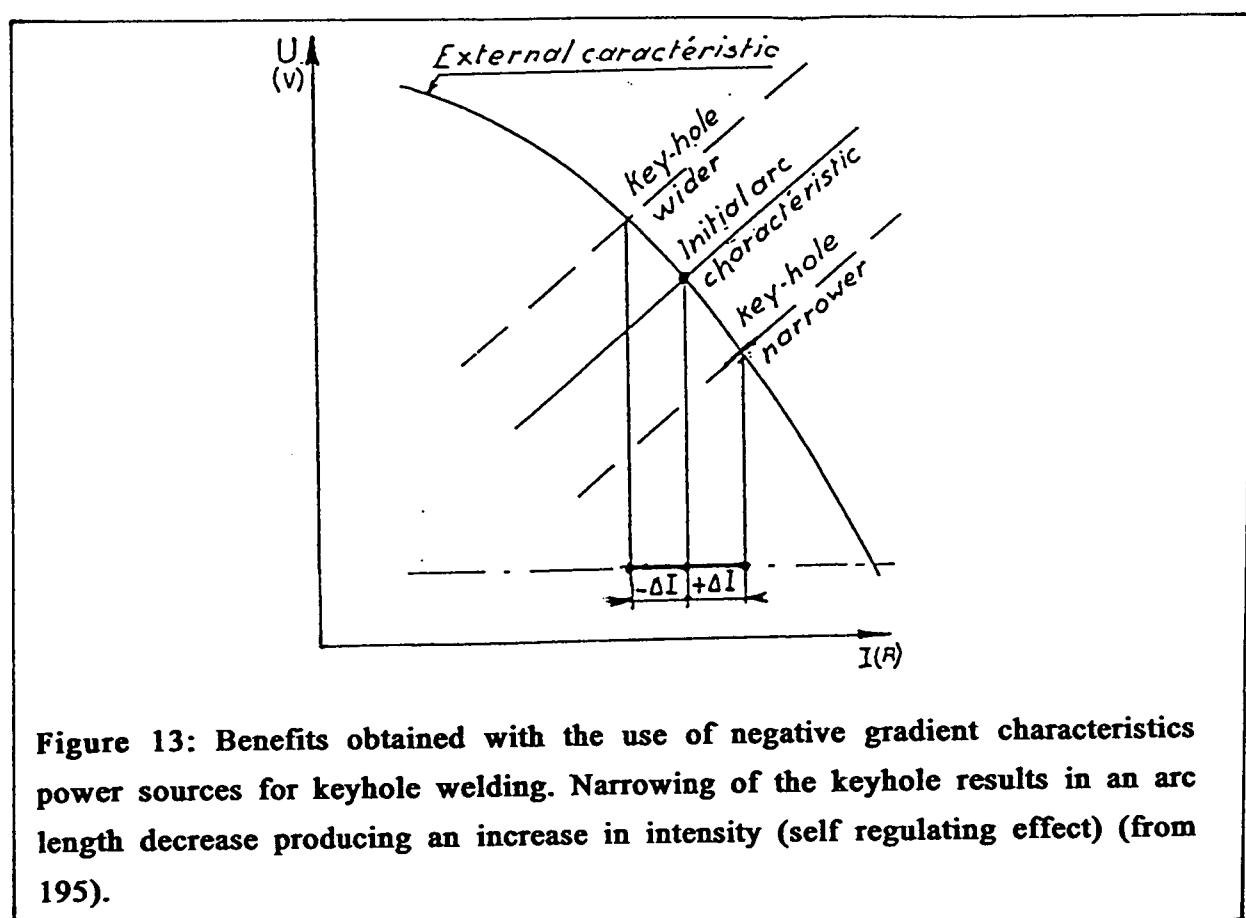


Figure 13: Benefits obtained with the use of negative gradient characteristics power sources for keyhole welding. Narrowing of the keyhole results in an arc length decrease producing an increase in intensity (self regulating effect) (from 195).

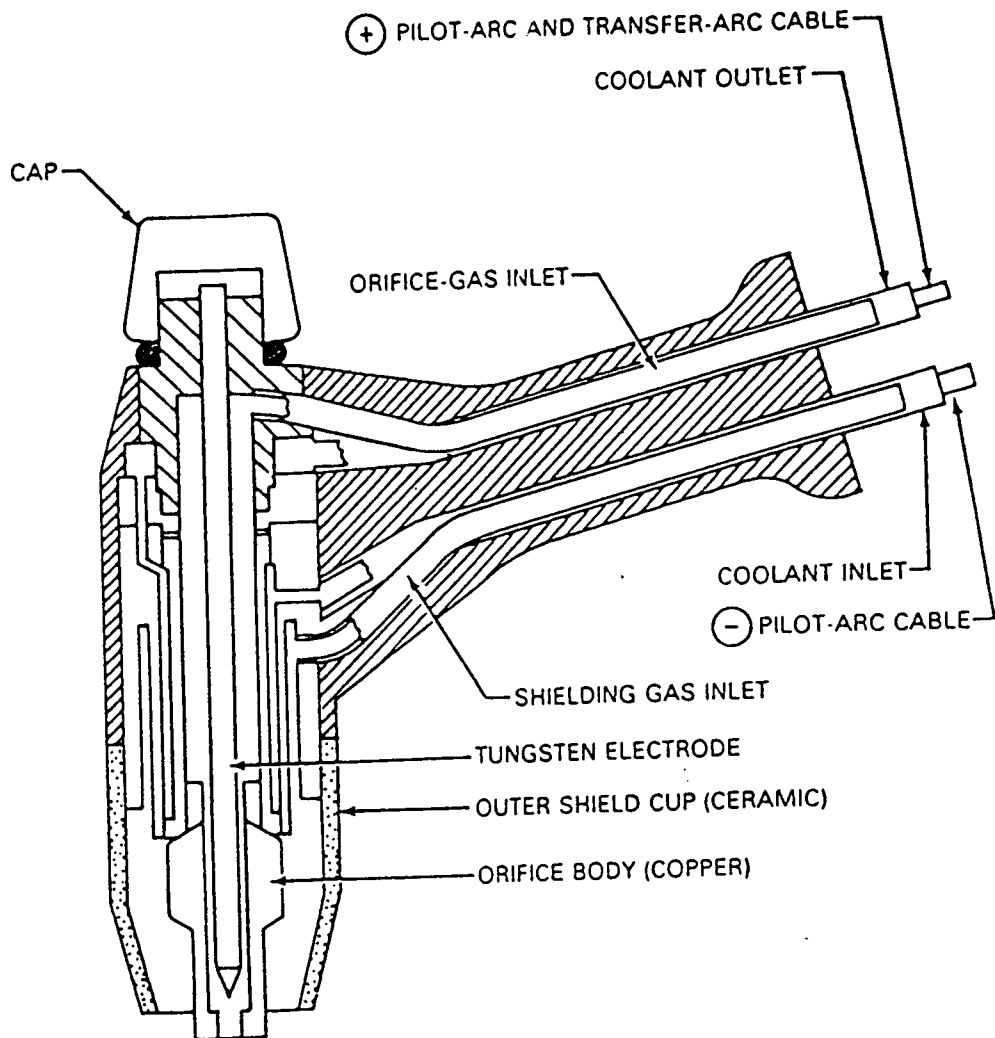


Figure 14: Basic configuration of a manual plasma welding torch (from 11).

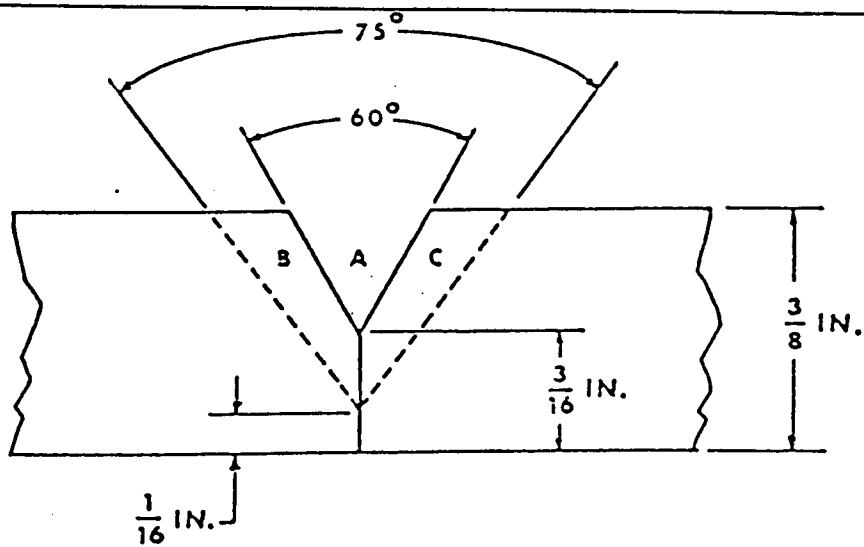
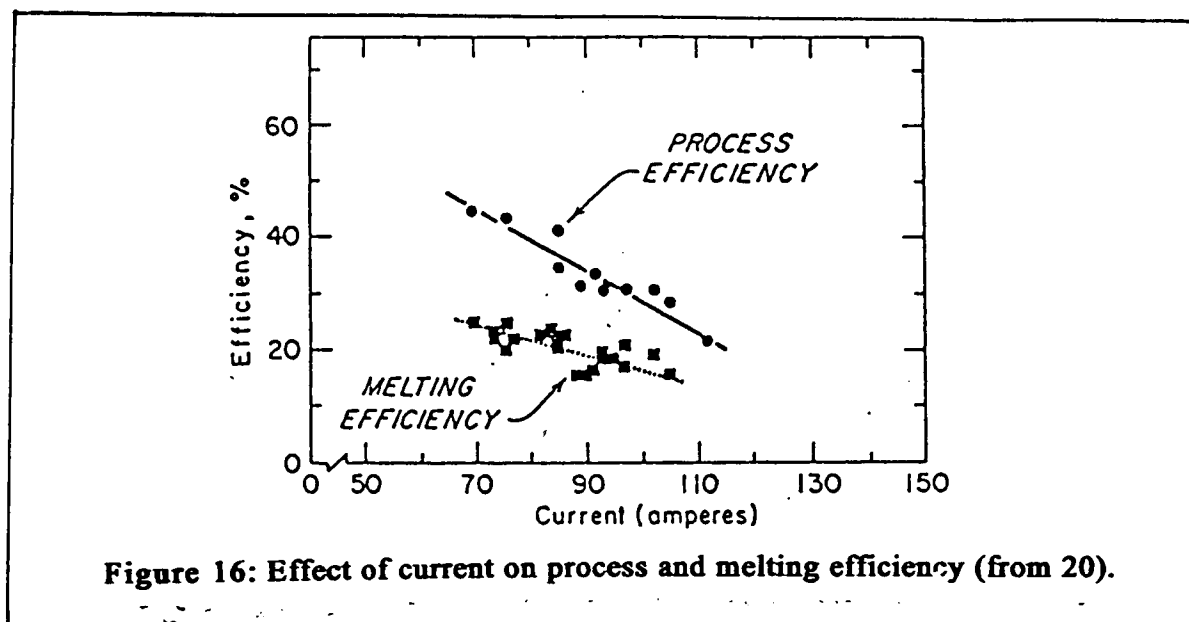
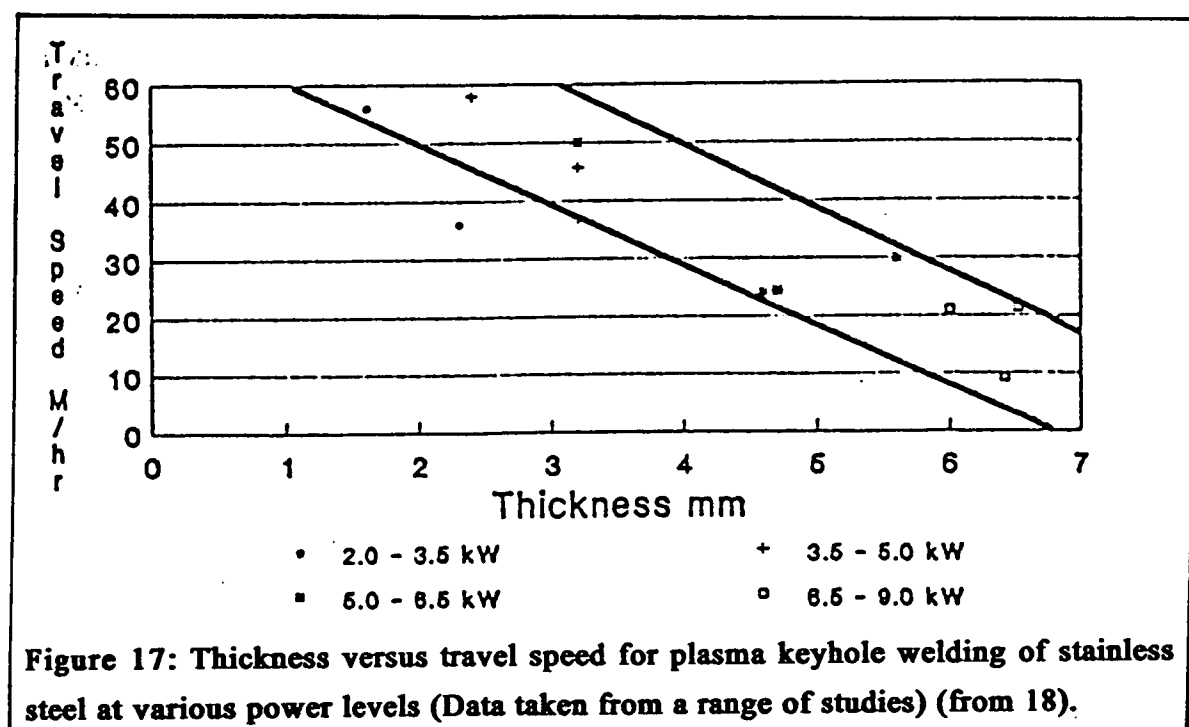


Figure 15: Typical joint preparation for welding of 3/8in. thick high strength steel. Weld metal area of gas tungsten-arc welding = A+B+C; weld metal area for plasma arc welding = A (from 116).



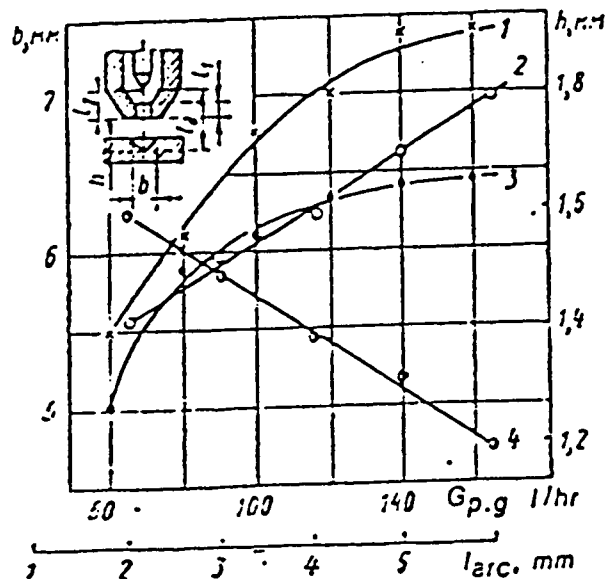


Figure 18: Effect of the flow rate of the plasma-forming gas and the arc length on the seam parameters (from 164): 1 - $h=f(G_{p.g})$; 2 - $b=f(l_{arc})$; 3 - $b=f(G_{p.g})$; 4 - $h=f(l_{arc})$;

1,3 - $l_{arc}=7.5\text{mm}$; 2,4 - $G_{p.g}=75\text{l/hr}$

($I_w=100\text{A}$, $v_w=10\text{m/hr}$, $l_1=3\text{mm}$; $l_2=4.5\text{mm}$).

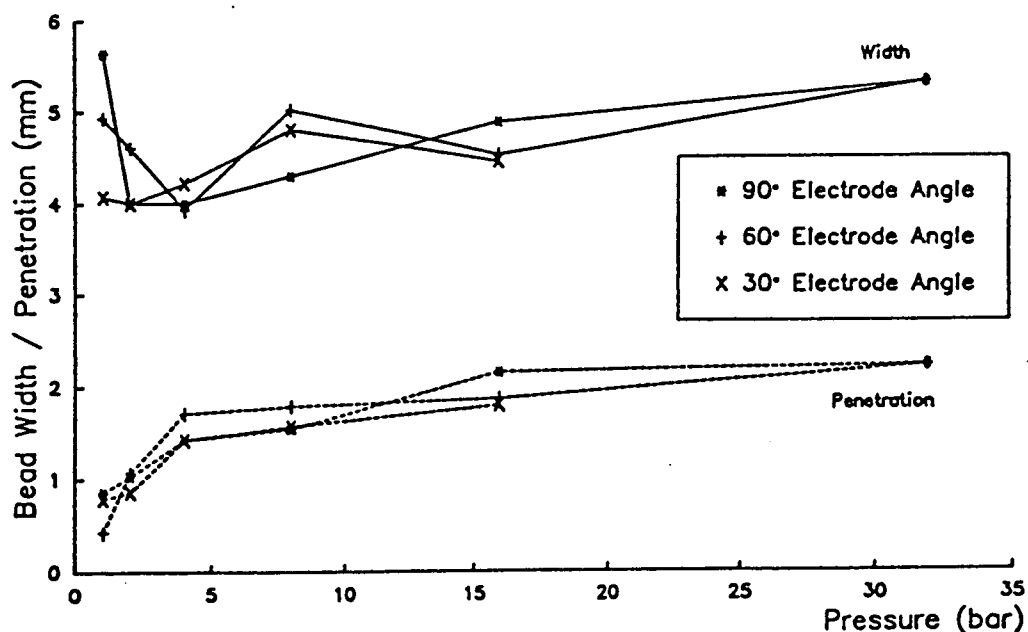


Figure 19a: Influence of electrode vertex angle on weld bead and HAZ areas under various pressures (from 38).

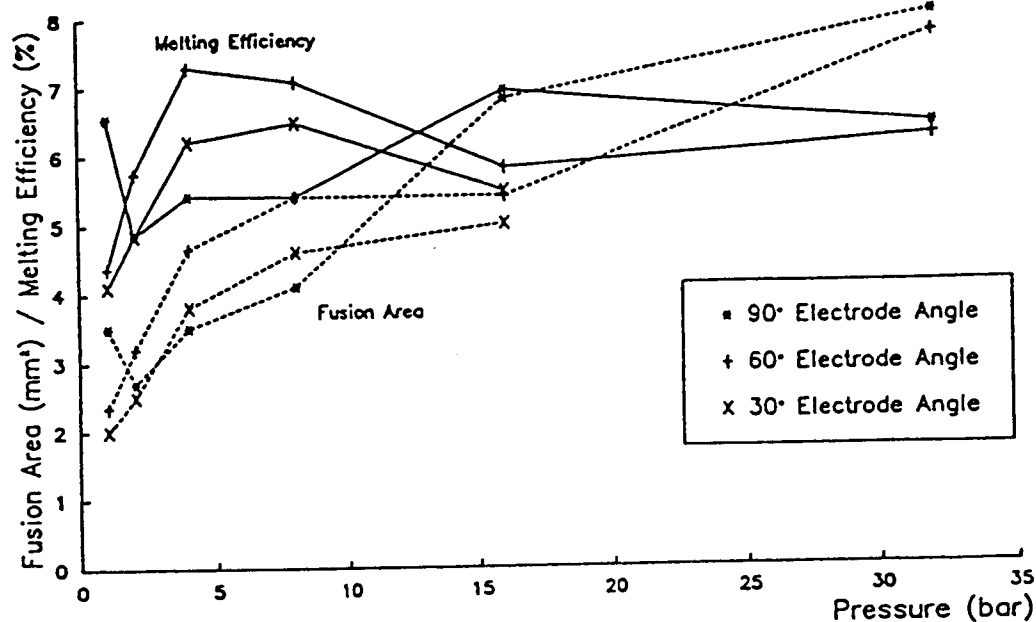


Figure 19b: Significant scatter observed in fusion area and corresponding melting efficiencies for three different electrode angles (from 38).

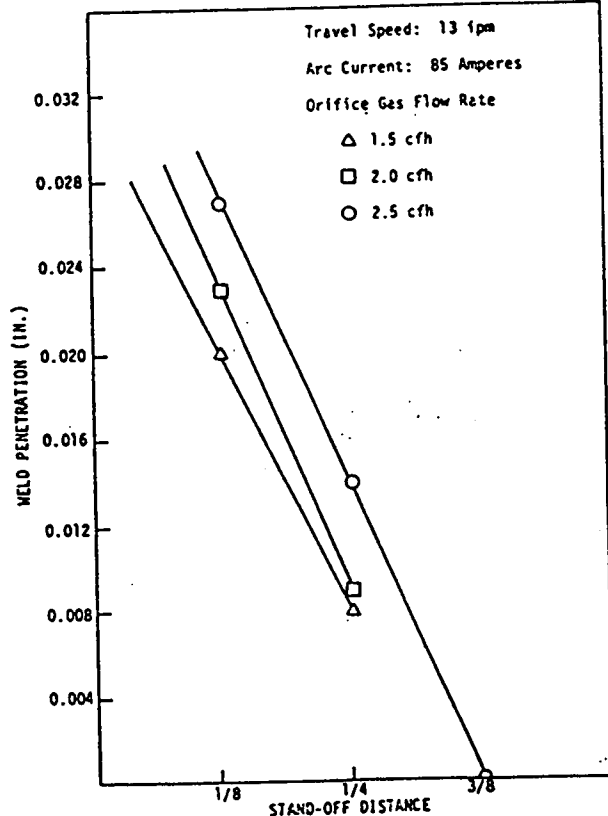


Figure 20: Influence of stand-off distance on penetration for three different plasma gas flow rates in plasma welding of Inconel 600 (from 85).

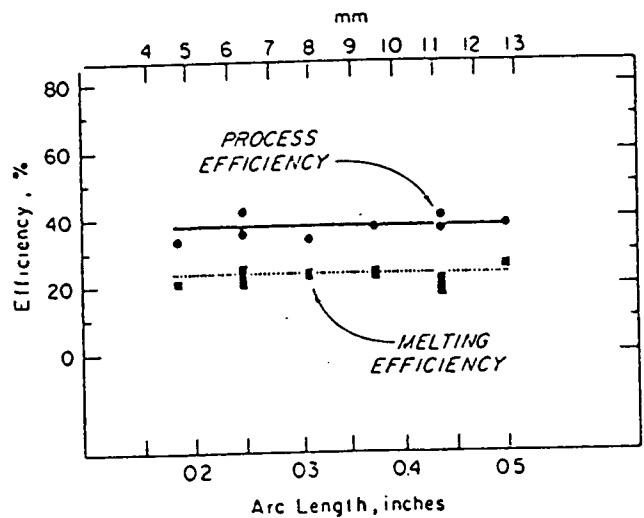
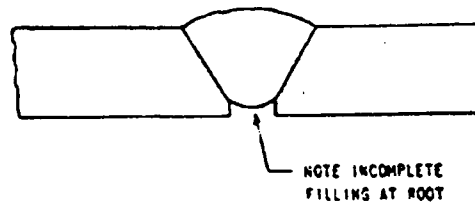


Figure 21: Effect of arc length on melting and process efficiency in keyhole welding of 3mm thick stainless steel (from 20).

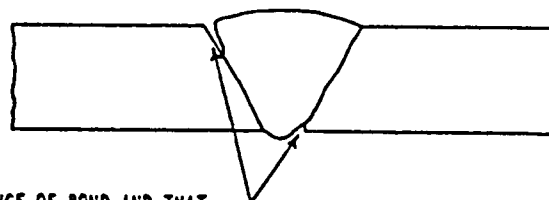


ONE OR BOTH BEVELS
MAY BE INADEQUATELY
FILLED AT INSIDE
SURFACE

FIGURE 10

INADEQUATE PENETRATION OF WELD GROOVE

Figure 22: Inadequate penetration of weld groove. Penetration is the depth that the fusion zone extends below the original surface of the parts being welded (from 128).



NOTE ABSENCE OF BOND AND THAT
DISCONTINUITY IS SURFACE CONNECTED

Figure 23: Incomplete fusion at root of bead or top of the joints (from 128).

Undercutting at the toes of the weld

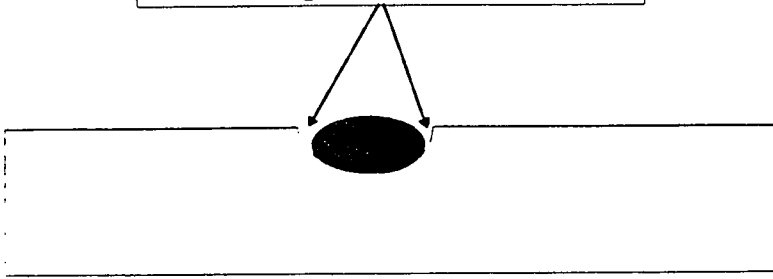
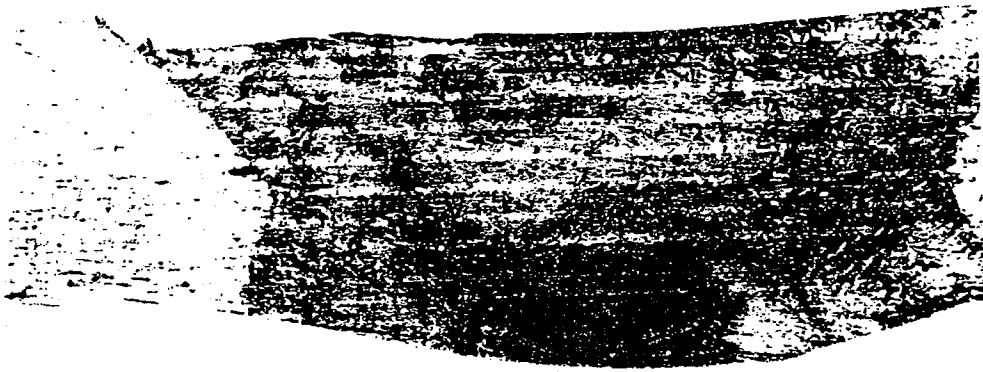


Figure 24: Undercutting at the toes of the weld.

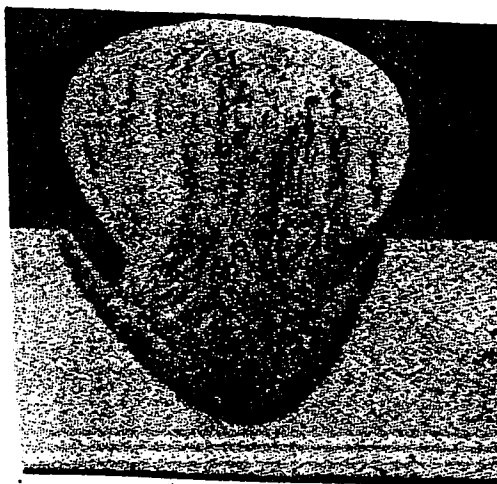


Figure 25: Transverse section of a hump (from 1).

Circumferential keyhole weld on D-6 AC steel $\frac{3}{8}$ -in. thick

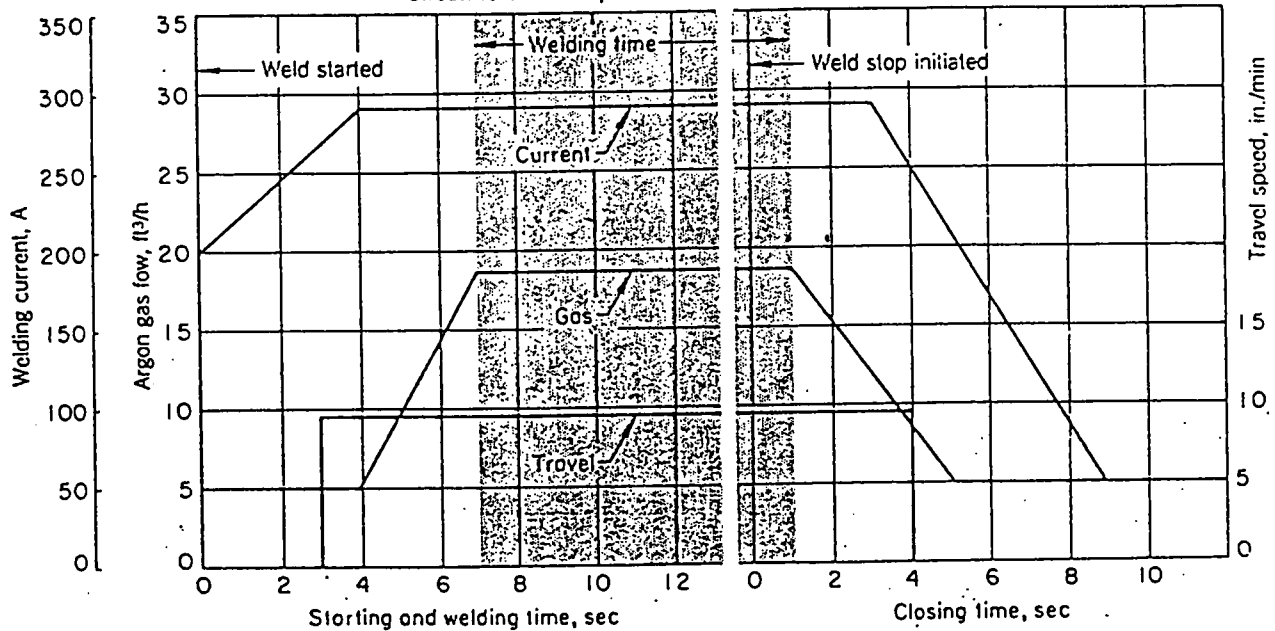


Figure 26: Slope control pattern for welding current and orifice-gas flow for starting and terminating a keyhole weld in $\frac{3}{8}$ -in. D-6 AC steel. The pattern is typical of welding other thicknesses or other metals (from 8).

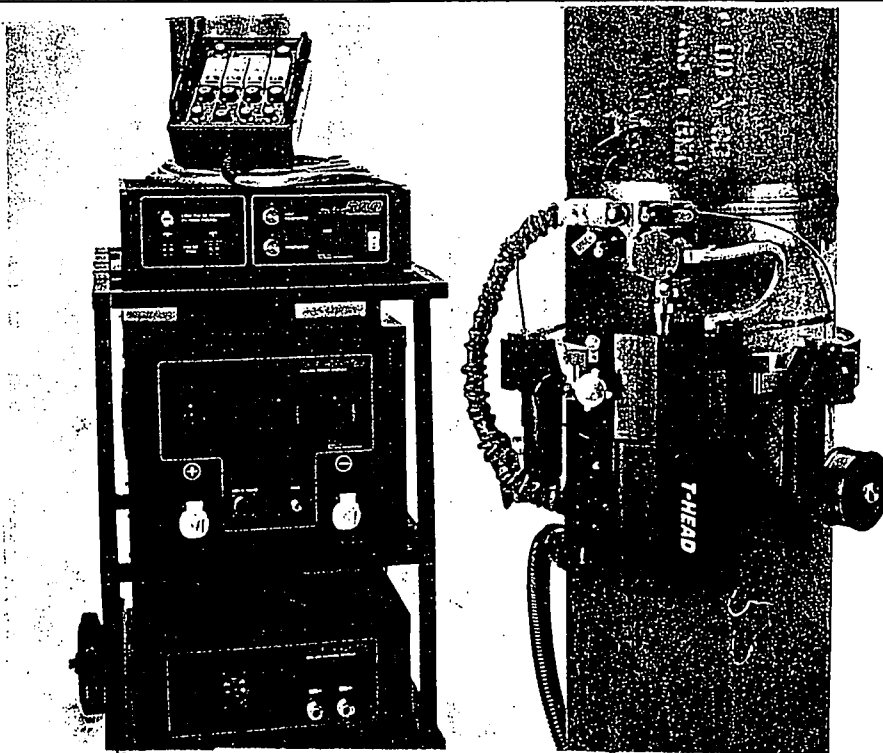


Figure 27: Typical GMAW welding head application for orbital welding applications of large diameter pipes.

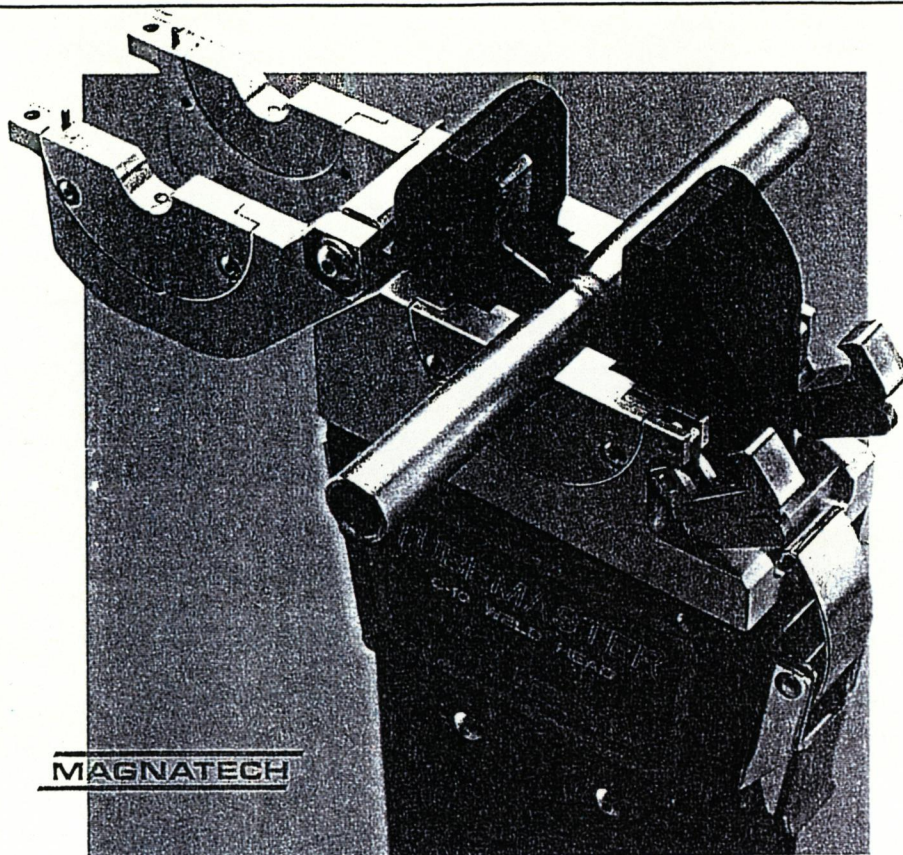
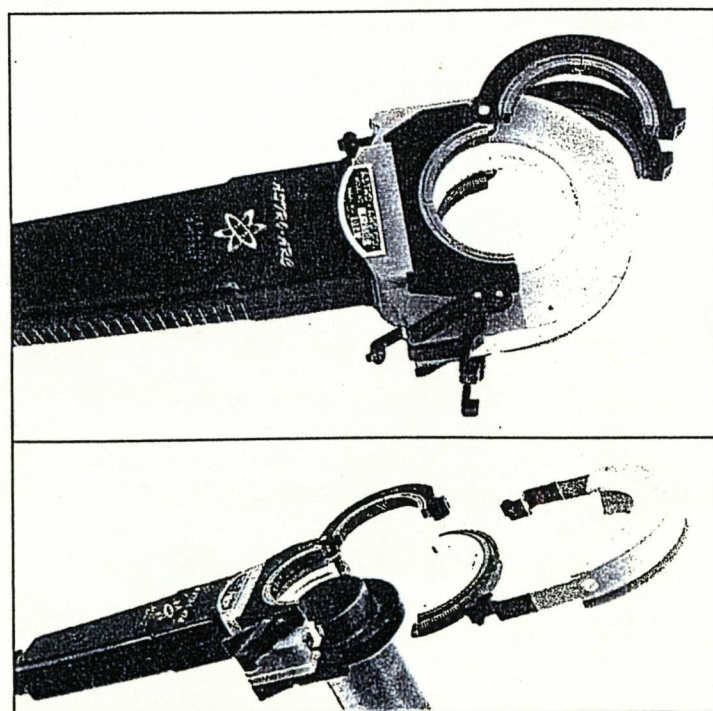


Figure 28: Typical examples of various GTAW totally enclosed welding heads.

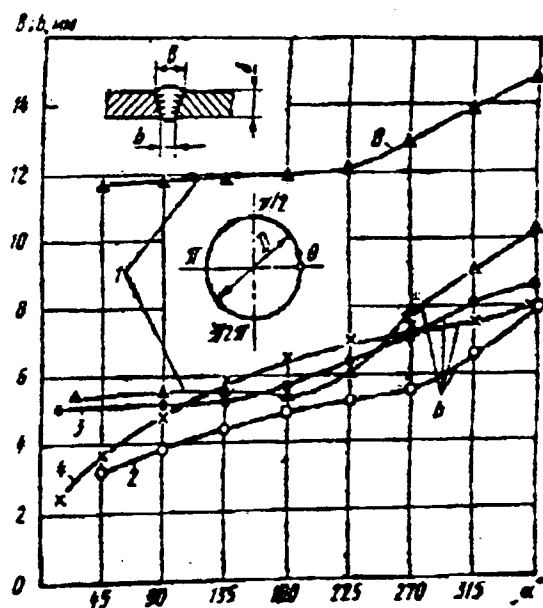


Figure 29: 1 Curves of variation of penetration zone width in argon-arc welding components made of different materials: 1) VT20 alloy, $D = 50$ mm, $\delta = 3$ mm, $I_w = 125$ A, $v_w = 11.5$ m/hr; 2) The same, $D = 30$ mm, continuous arc, $I_w = 130$ A, $v_w = 19$ m/hr; 3) EI696A, $\delta = 3.5$ mm, $D = 50$ mm, $I_w = 130$ A, $v_w = 7$ m/hr; 4) MI copper, $\delta = 1.2$ mm, $D = 30$ mm, $I_w = 50$ A, $v_w = 10$ m/hr.

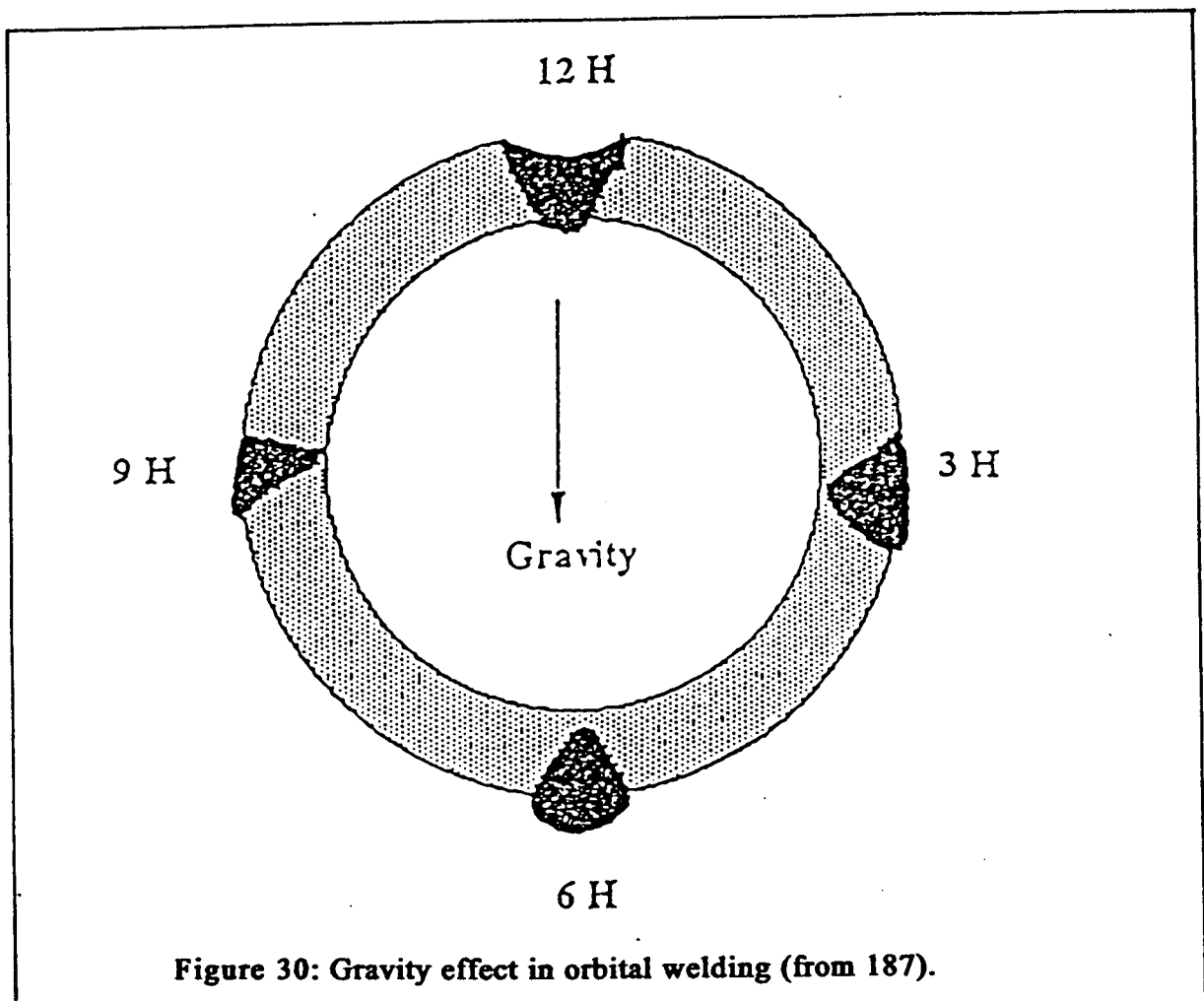


Figure 30: Gravity effect in orbital welding (from 187).

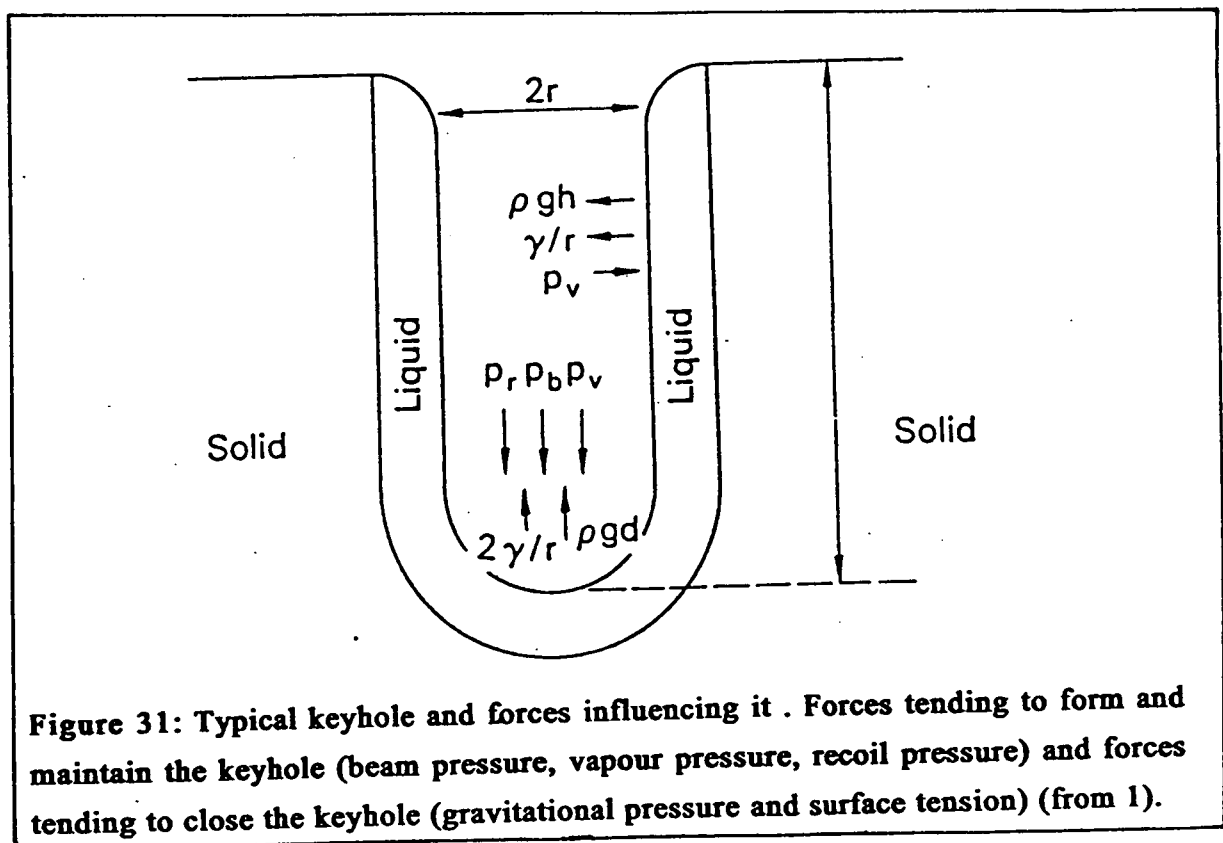


Figure 31: Typical keyhole and forces influencing it . Forces tending to form and maintain the keyhole (beam pressure, vapour pressure, recoil pressure) and forces tending to close the keyhole (gravitational pressure and surface tension) (from 1).

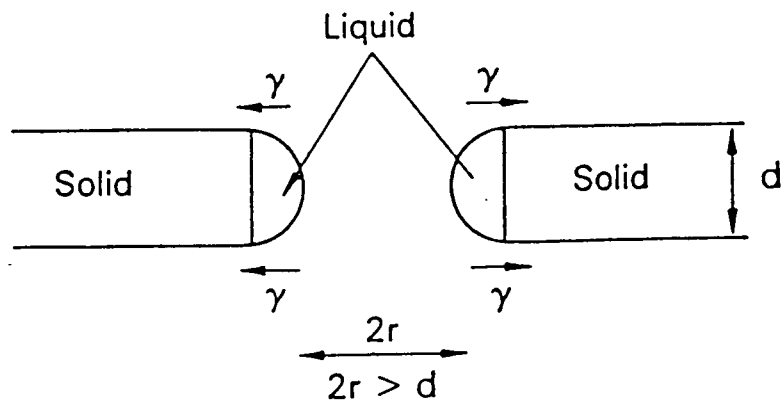


Figure 32: Effect of surface tension in materials thinner than the keyhole (production of a cut in a fully penetrating weld) (from 1).

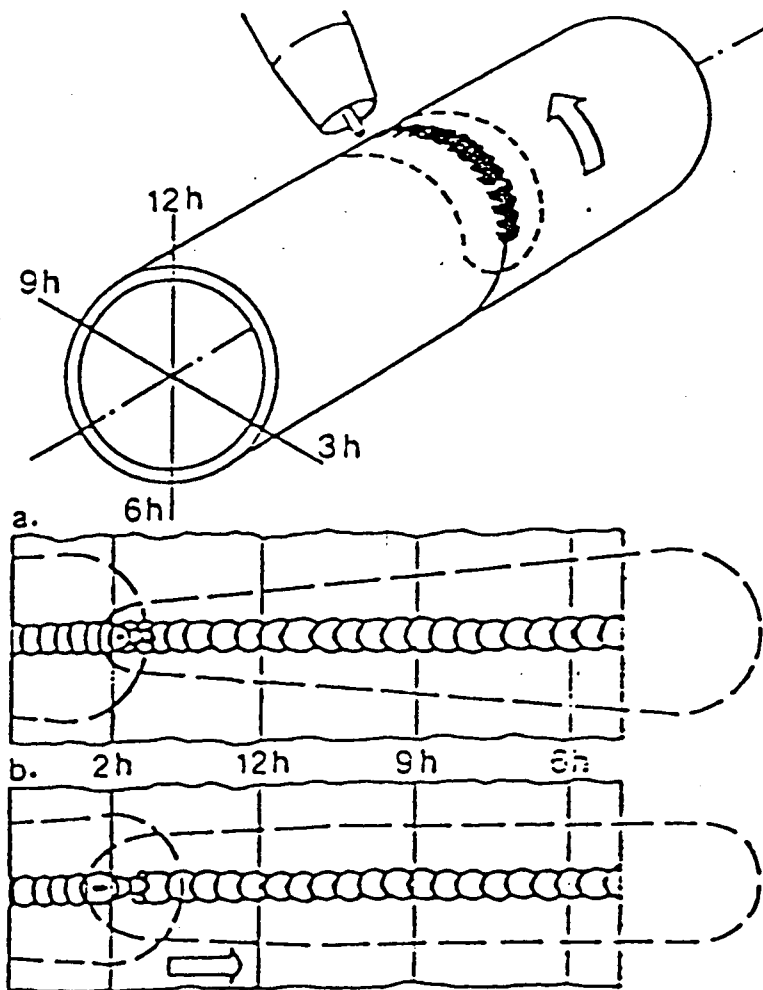
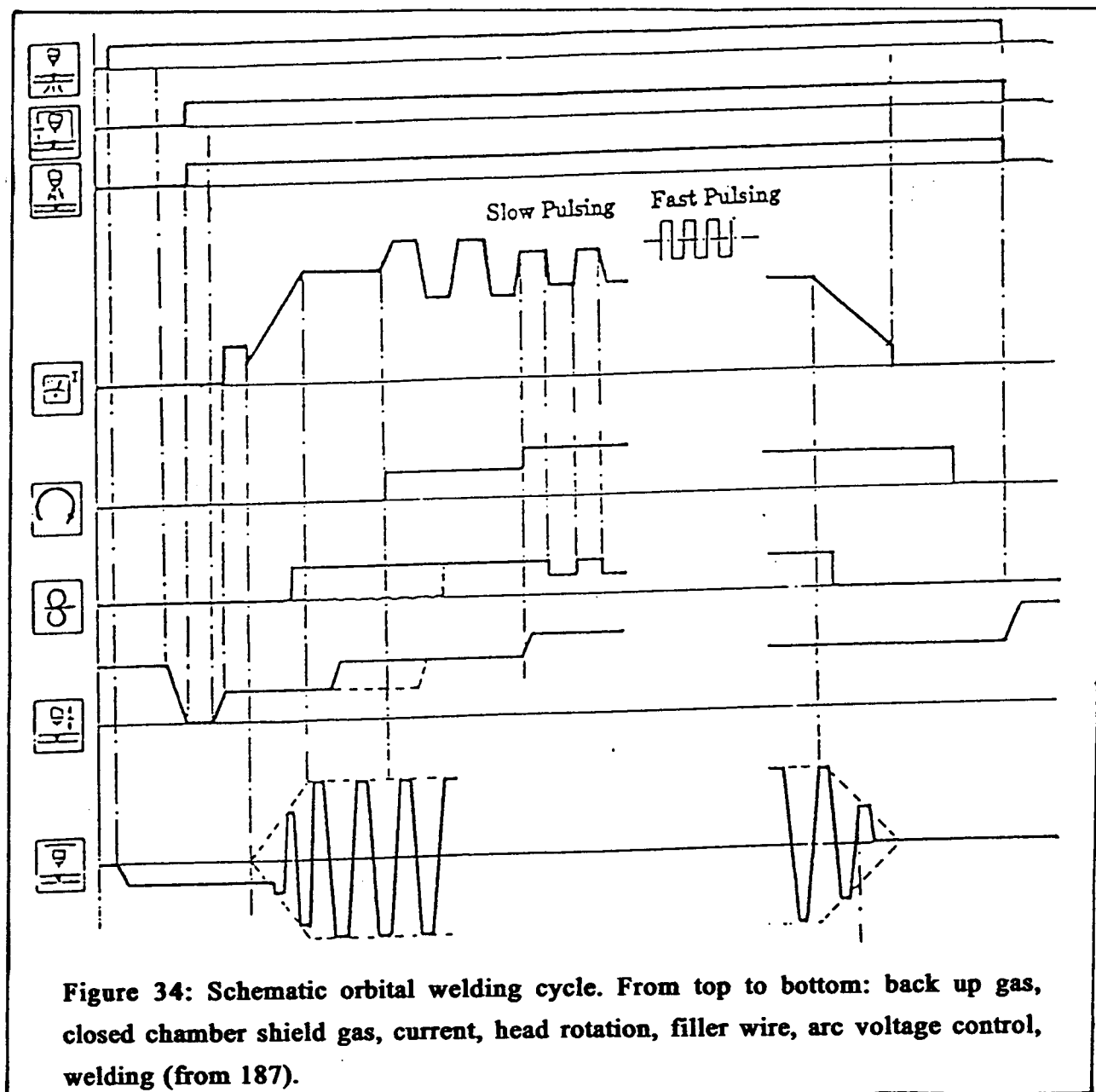


Figure 33: Temperature control by current pulsation during orbital welding (from 187).



The AMOS Rack

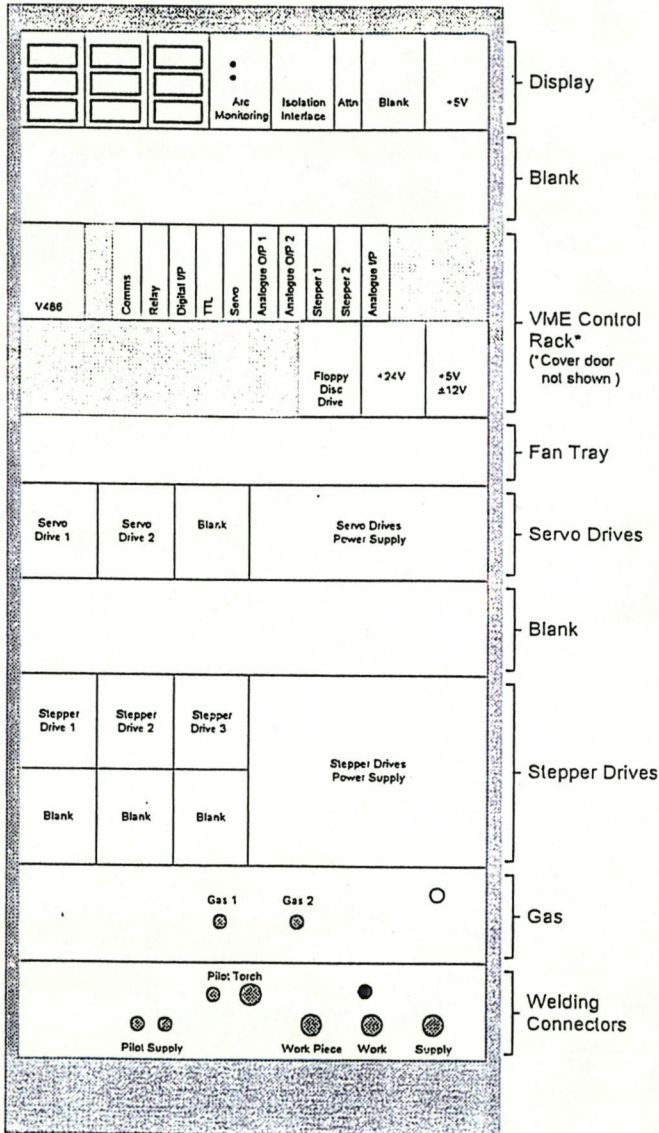
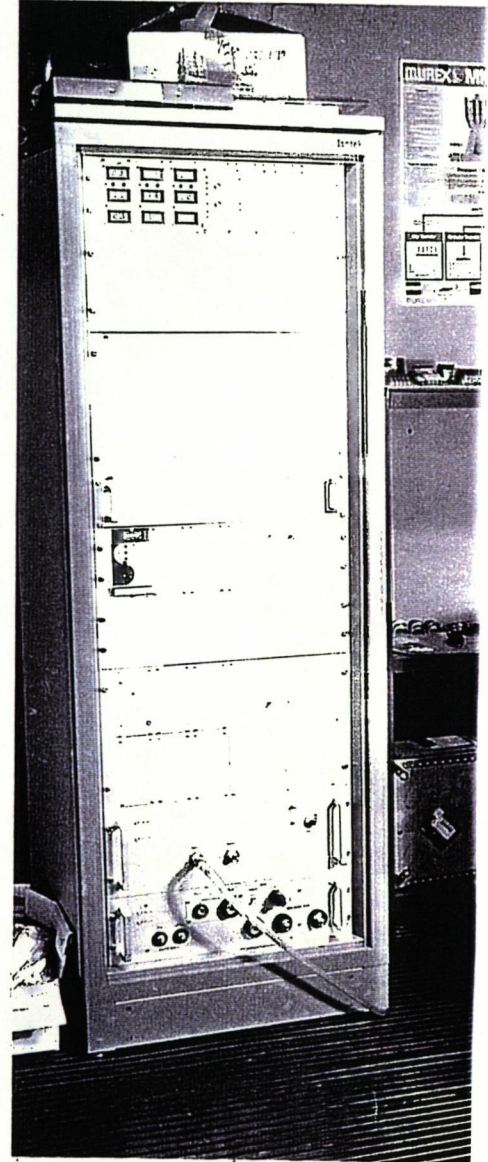


Figure 35: The Adaptable Modular Orbital System (AMOS) Rack.

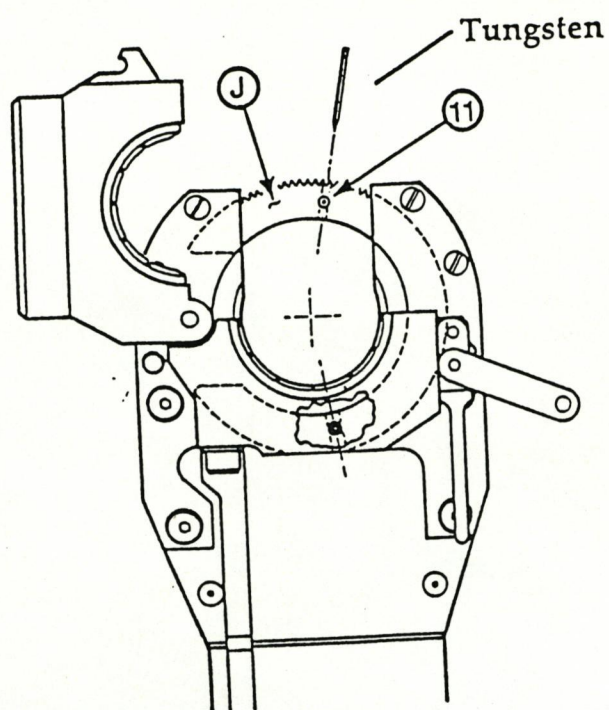
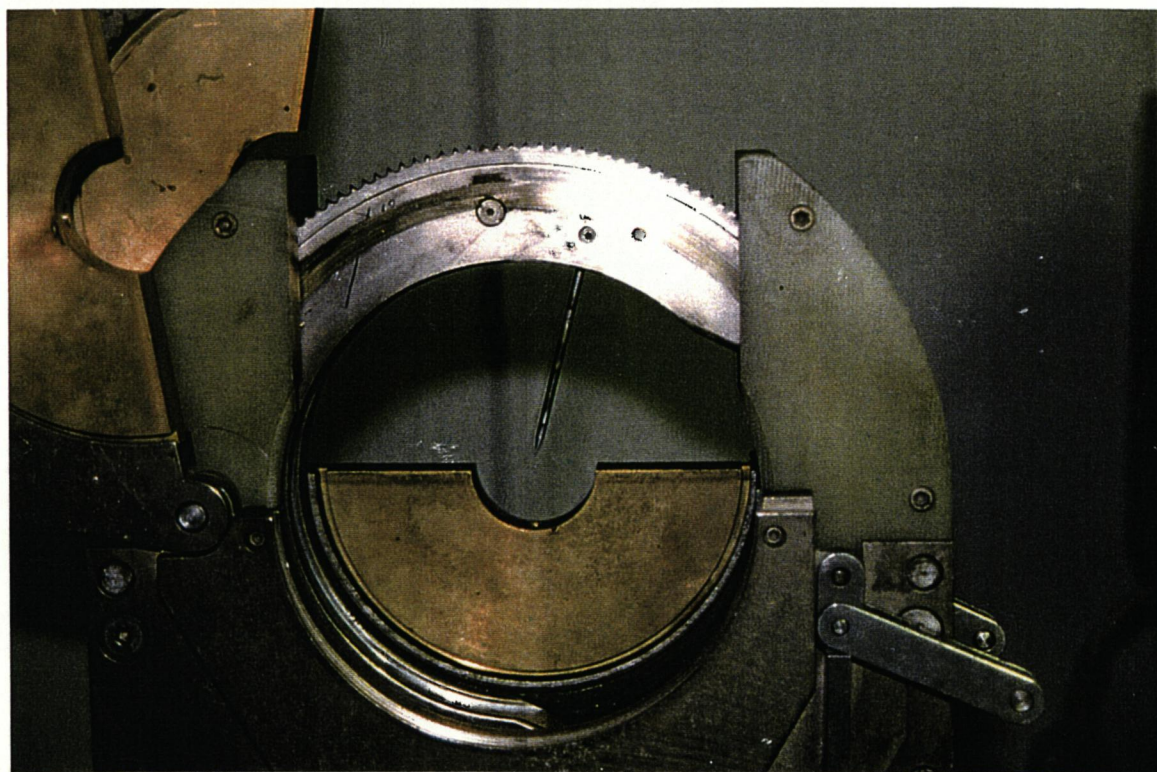


Figure 36: The Arc Machines Instruments (AMI) 9-4500 Welding Head.

TRIPLE BDH 320 and BDH 550

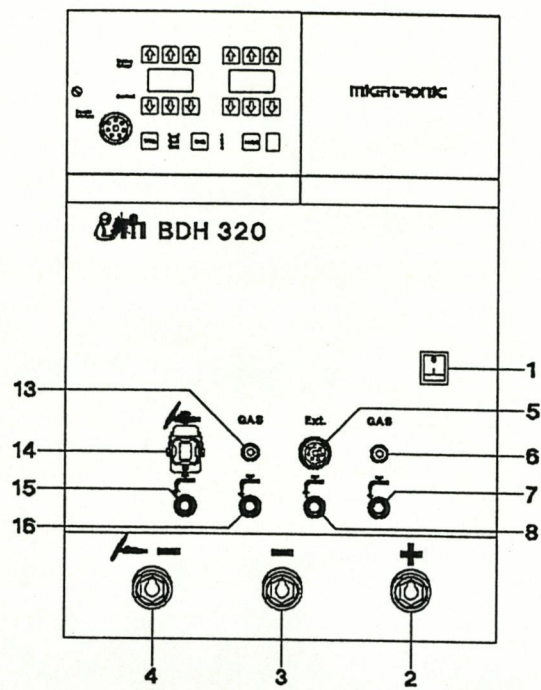
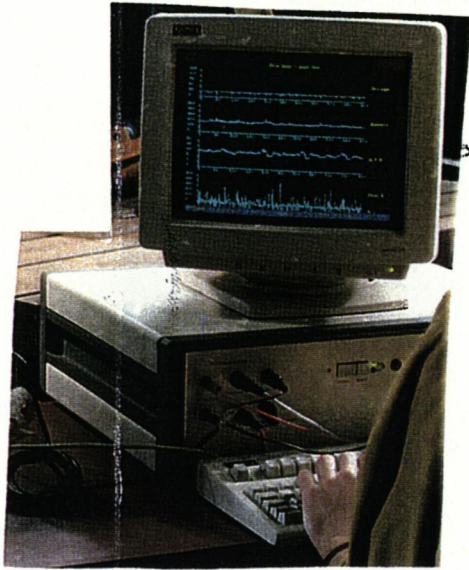
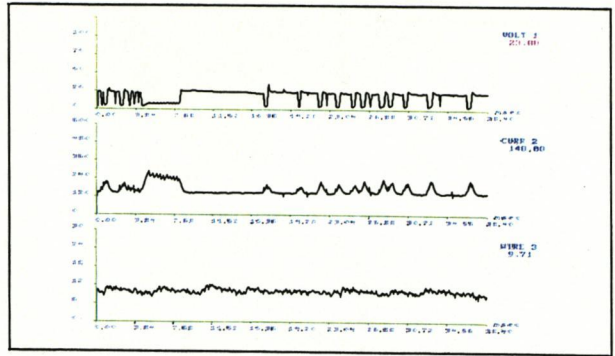
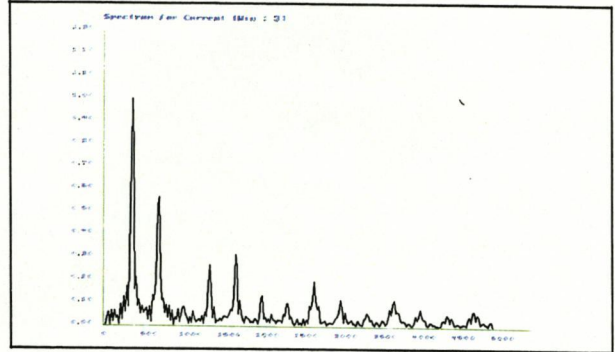
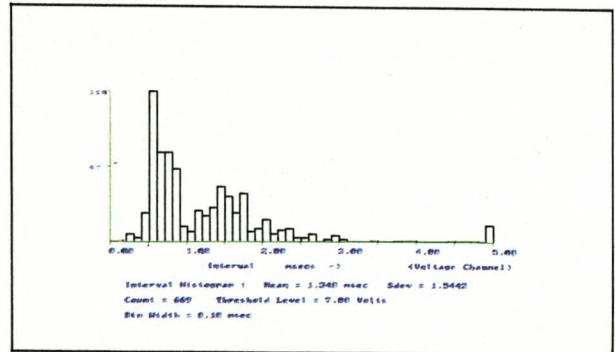


Figure 37: The Migatronik Commander BDH 320 power source.



**Typical graphical display
of the results**

Figure 38: The Arcwatch Data Monitoring System (A/D 93).

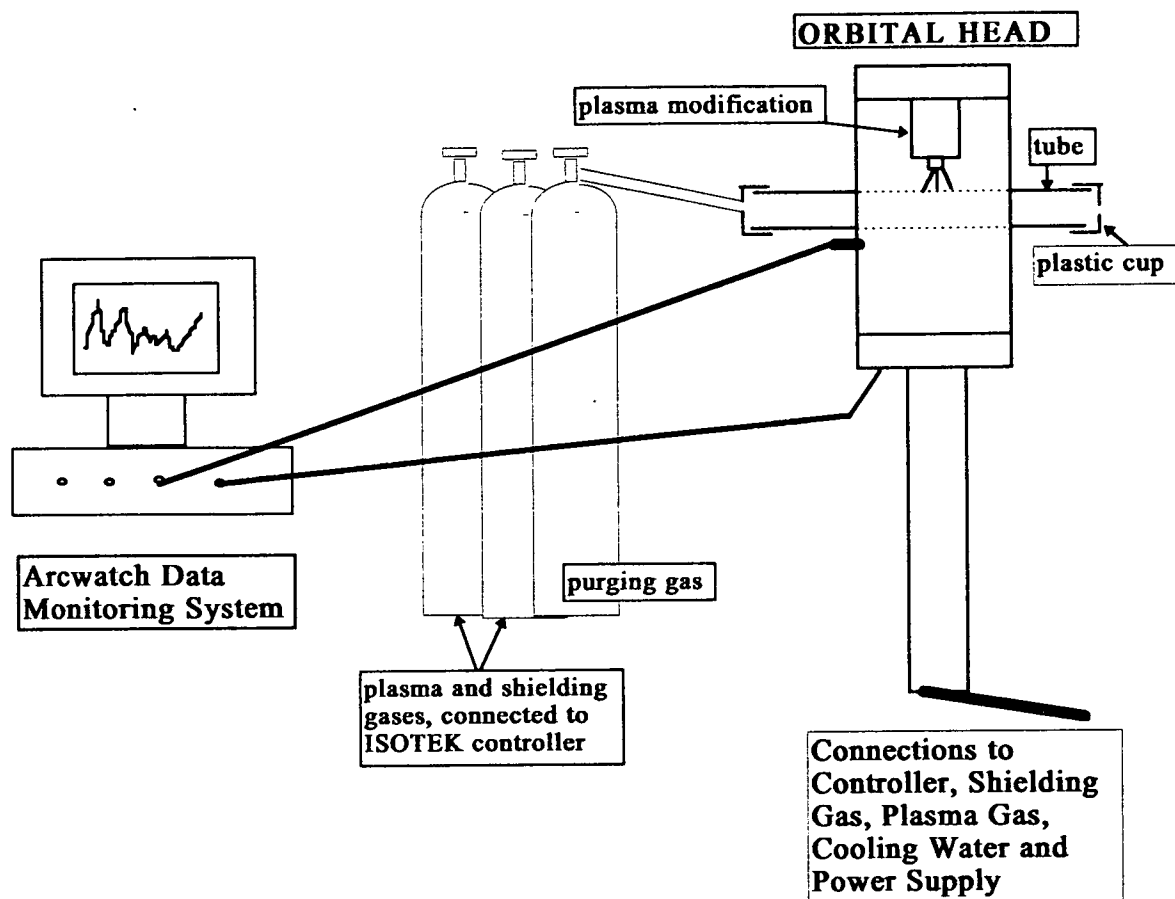


Figure 39: Welding Area.

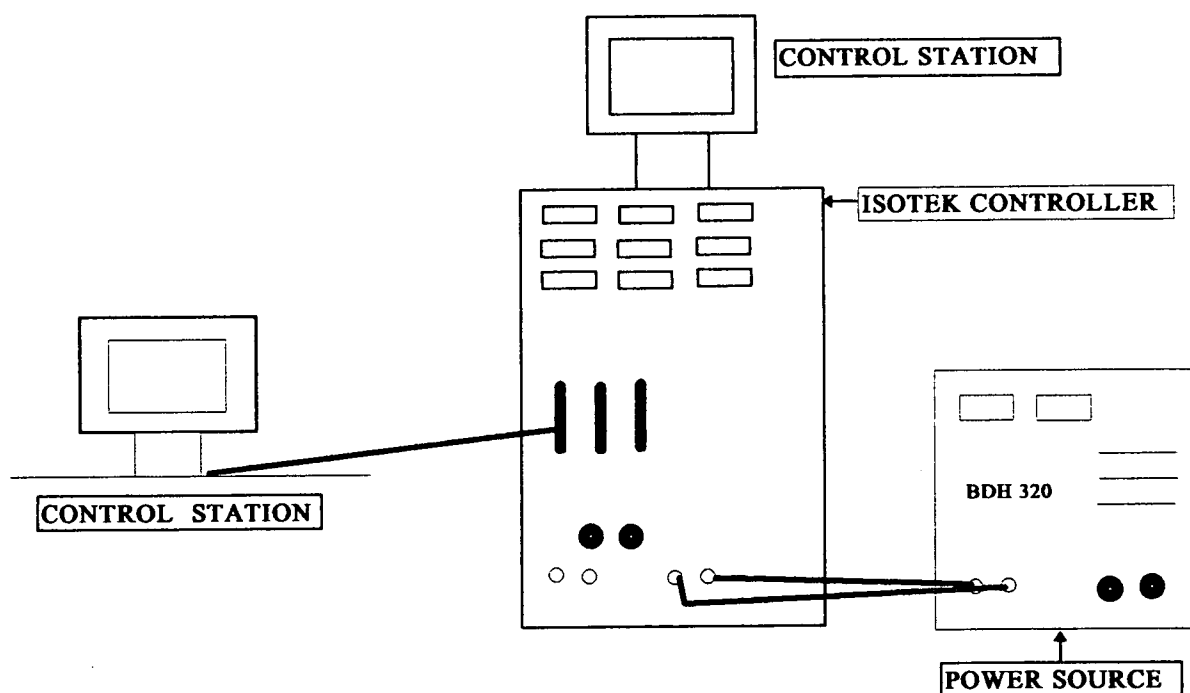


Figure 40: Control of the Process Area.

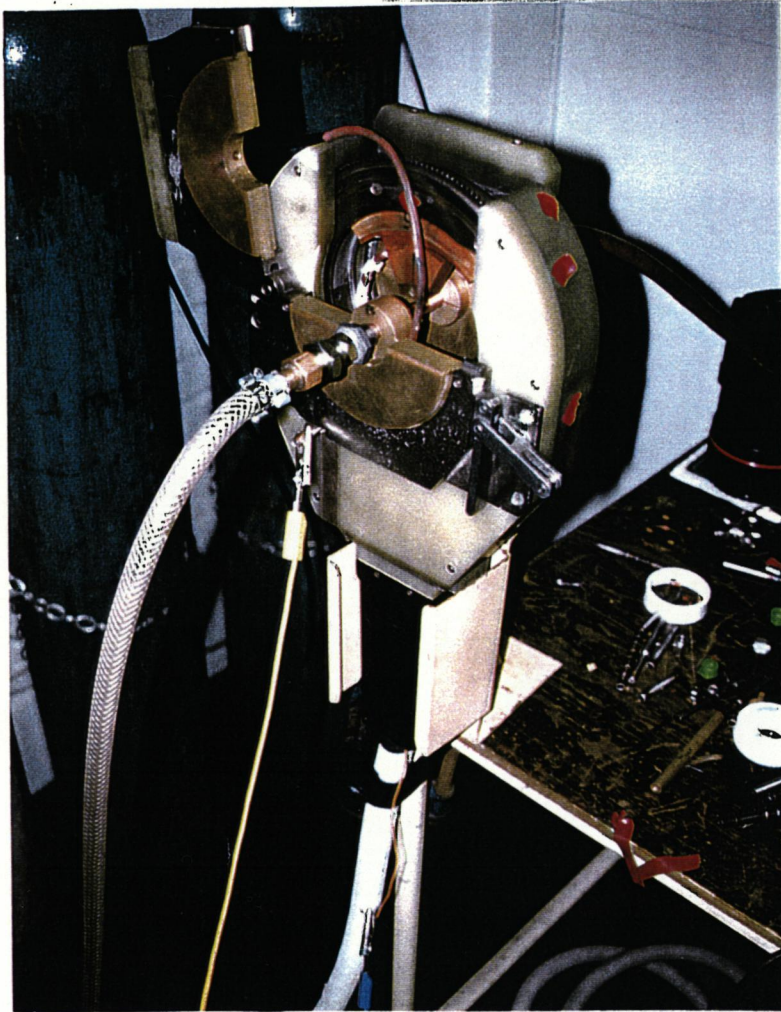


Figure 41: Tube clamp inserts placed on both sides of the welding head for welding tube-to-tube, pipe-to-pipe or fitting with sufficient straight section.

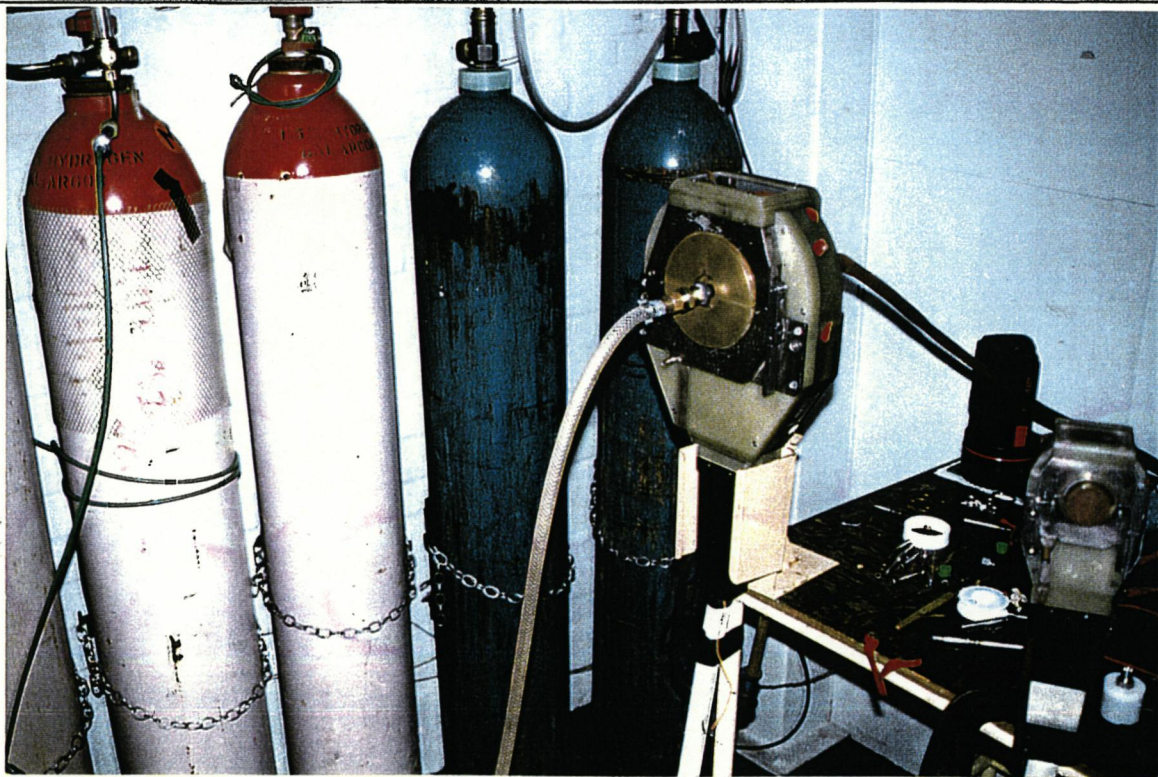


Figure 42: Experimental set-up for temperature measurements.

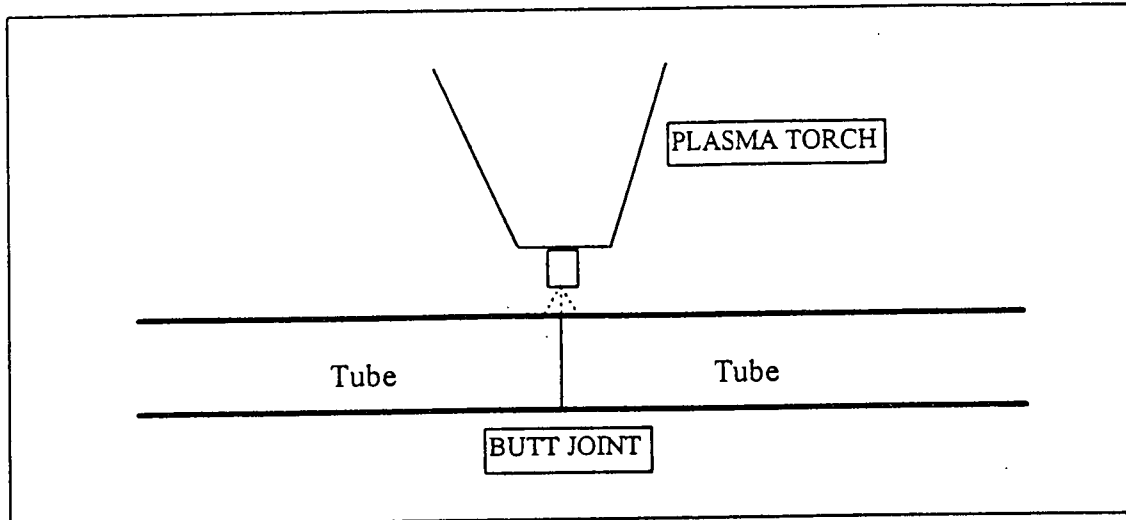


Figure 43: Joint preparation design employed during the investigation.

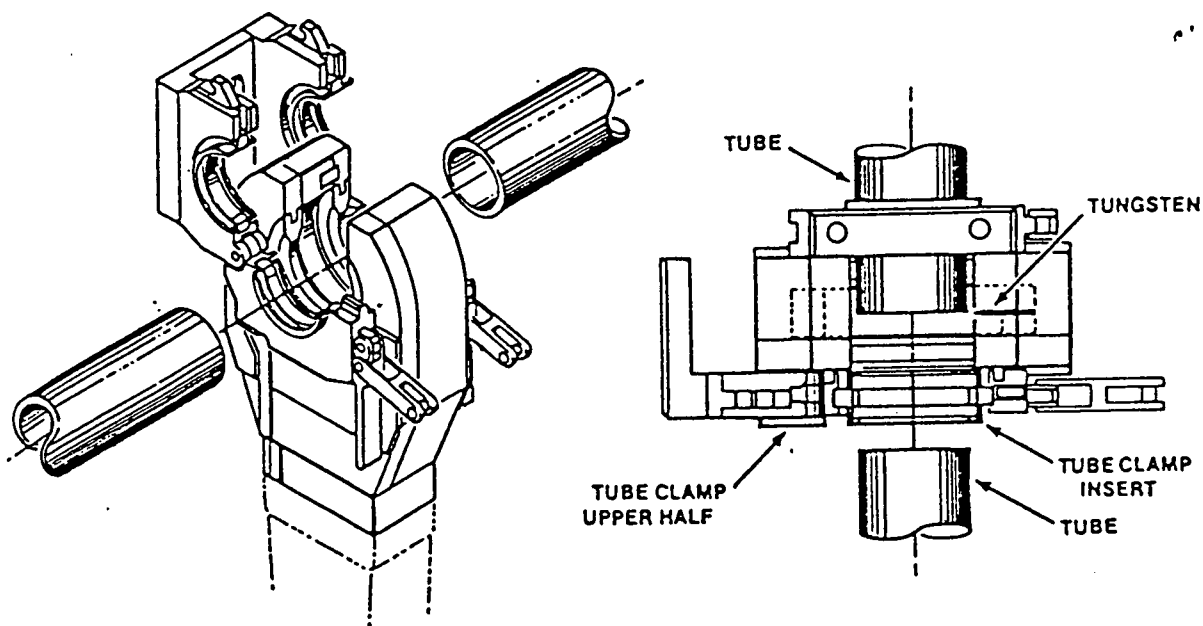


Figure 44: Model 9-400 Weld Head tube installation (see also figure 41).

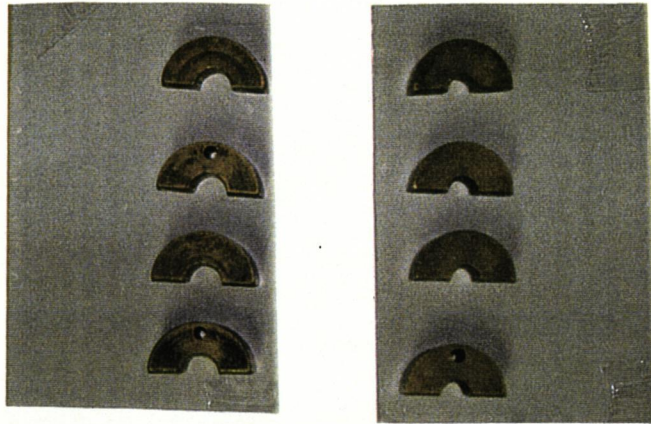
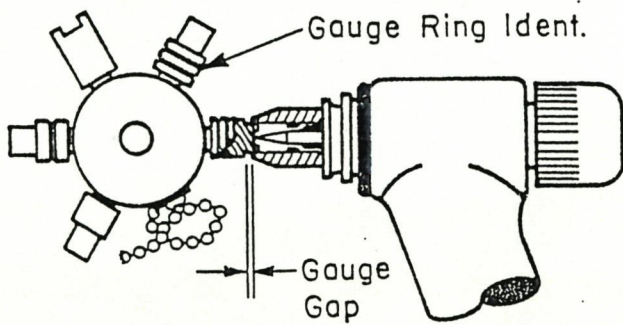
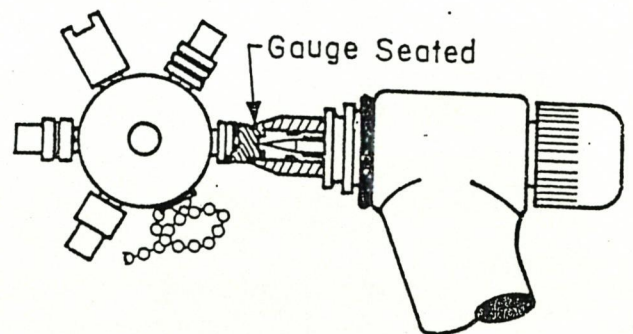


Figure 44b: Brass Rings Utilised for the Alignment of Different Tube Diameters.



Step 1



Step 2

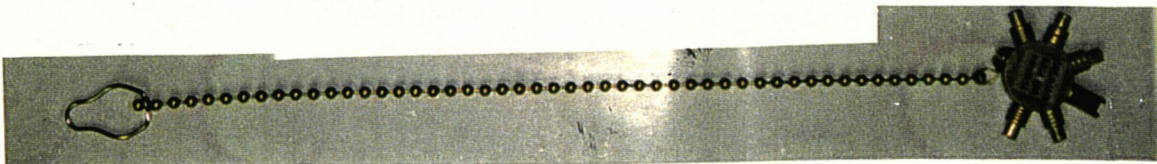


Figure 45: Electrode Set Back Adjustment for a Common Plasma Torch.

Brite PM Top Station

Setup Edit Run Control Exit

Pass id: Test

Version: 0

Ignition: Test

Start: Test

Stop: Test

Segment: Test

Weave: Test

Hotkey: Test

Gas 1 Gas 2

Plasma gas:

Shield gas:

AVC gain: 0 / 0

Figure 46: Menu for setting of all relevant process parameters.

TIG Segment Details

Name Test

Segment index	1	2	3	4	5	6	7	8	9
Duration time (s)	0.1	0.1							
Current sloping?	☒	☐	☐	☐	☐	☐	☐	☐	☐
High current (A)	0.0	0.0							
Low current (A)	10.0	0.0							
High on-time (ms)	0.0	0.0							
Low on-time (ms)	0.0	0.0							
High wire feed (m/min)	5.0	0.0							
Low wire feed (m/min)	0.0	0.0							
High weld speed (mm/s)	0.0	0.0							
Low weld speed (mm/s)	0.0	0.0							
AVC (V)	0.0	0.0							
Arc mode	???	???							
Weave index	1	1							
Gas sloping?	☐	☐	☐	☐	☐	☐	☐	☐	☐
Gas (valve 1) (l/min)	0.0	0.0							
Gas (valve 2) (l/min)	0.0	0.0							

OK

Cancel

Copy

Paste

Insert

Remove

Figure 47: Menu for setting the plasma welding segment details.

TIG Start Details		
Name: <input type="text" value="Test"/>		
Current		
Step current	<input type="text" value="0.0"/>	A
High on-time	<input type="text" value="0.0"/>	ms
Low on-time	<input type="text" value="0.0"/>	ms
Slope up delay	<input type="text" value="0.1"/>	s
Slope up time	<input type="text" value="0.1"/>	s
Gas		
Prepurge time	<input type="text" value="0.1"/>	s
Slope up delay	<input type="text" value="0.1"/>	s
Slope up time	<input type="text" value="0.1"/>	s
Valve 1 flow	<input type="text" value="0.0"/>	l/min
Valve 2 flow	<input type="text" value="0.0"/>	l/min
AVC start delay <input type="text" value="0.1"/> s		
Rotation		
Delay	<input type="text" value="0.0"/>	s
Speed	<input type="text" value="0.0"/>	mm/s
Duration	<input type="text" value="0.1"/>	s
Wire feed		
Delay	<input type="text" value="0.0"/>	s
Speed	<input type="text" value="0.0"/>	m/min
Duration	<input type="text" value="0.1"/>	s
<input type="button" value="OK"/> <input type="button" value="Cancel"/>		

Figure 48: Menu for setting the plasma welding start details.

TIG Stop Details		
Name: <input type="text" value="Test"/>		
Current		
Final value	<input type="text" value="0.0"/>	A
Slope down delay	<input type="text" value="0.0"/>	s
Slope down time	<input type="text" value="0.1"/>	s
Gas		
Postpurge	<input type="text" value="0.1"/>	s
Slope down delay	<input type="text" value="0.0"/>	s
Slope down time	<input type="text" value="0.1"/>	s
Valve 1 flow	<input type="text" value="0.0"/>	l/min
Valve 2 flow	<input type="text" value="0.0"/>	l/min
Rotation		
Delay	<input type="text" value="0.0"/>	s
Final speed	<input type="text" value="0.0"/>	mm/s
Duration	<input type="text" value="0.1"/>	s
Wire feed		
Delay	<input type="text" value="0.0"/>	s
Final rate	<input type="text" value="0.0"/>	m/min
Duration	<input type="text" value="0.1"/>	s
Retract speed	<input type="text" value="1.0"/>	m/min
Retract distance	<input type="text" value="0.000"/>	mm
Torch withdrawl speed <input type="text" value="0.1"/> mm/s		
AVC stop delay <input type="text" value="0.1"/> s		
<input type="button" value="OK"/> <input type="button" value="Cancel"/>		

Figure 49: Menu for setting the plasma welding stop details.

TIG Ignition details

Name:

Ignition type:

☒ HF strike

☐ LIFTIG

☐ Touch start

Arc check time: s

Gas flow:

Valve 1: l/min

Valve 2: l/min

HF Strike/LIFTIG details:

Current: A

Touch start details:

No. of attempts:

Current:

Pilot: A

Draw: A

Preset: A

Torch:

Touch speed: mm/s

Withdrawal speed: mm/s

Up distance: mm

Touch indication:

Voltage: V

Current: A

Figure 50: Menu for setting the plasma welding ignition details.

Select Pass to Run

Pass list:

Time period:

Start:

Stop:

Head direction:

☒ Forward

☐ Reverse

Weld diameter:

Deposit:

Figure 51: Menu for setting the direction of the head rotation along with the desired pass from a pass list.

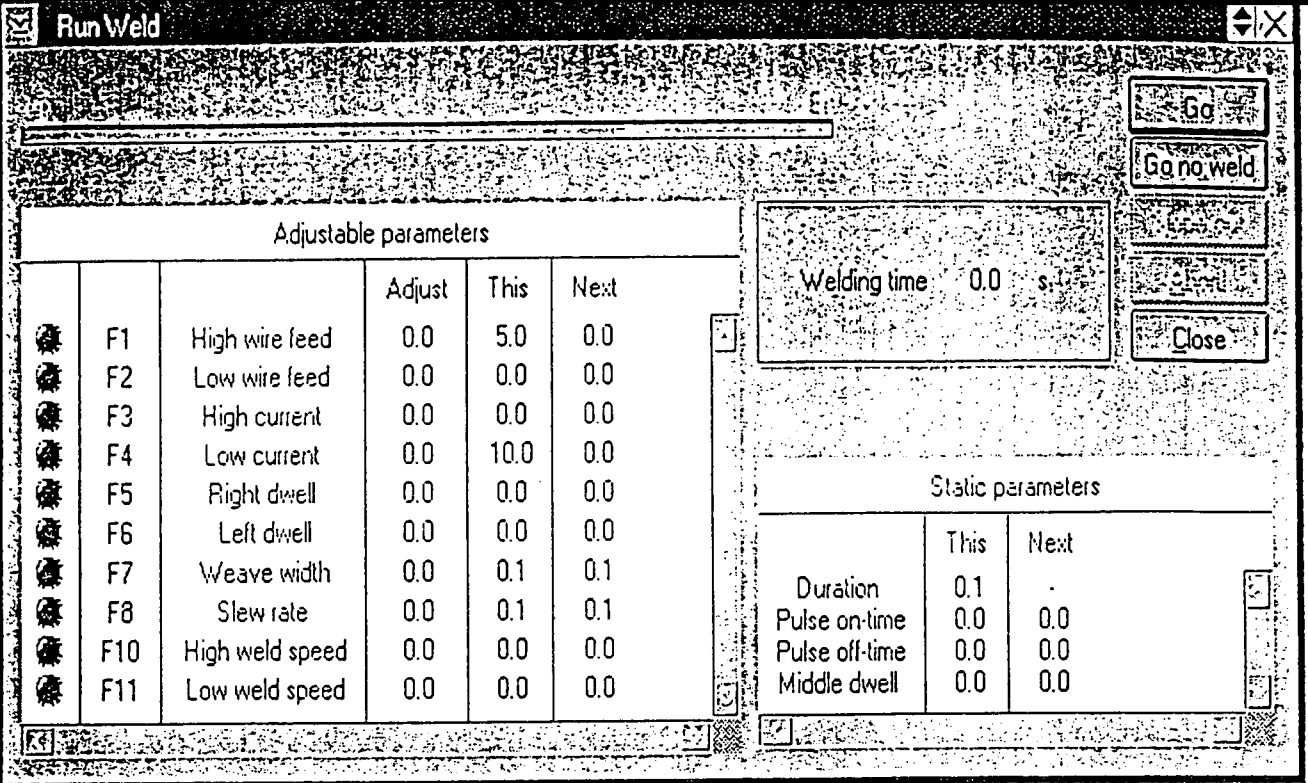


Figure 52: Menu illustrating a summary of the selected welding parameters before the initiation of the welding cycle.

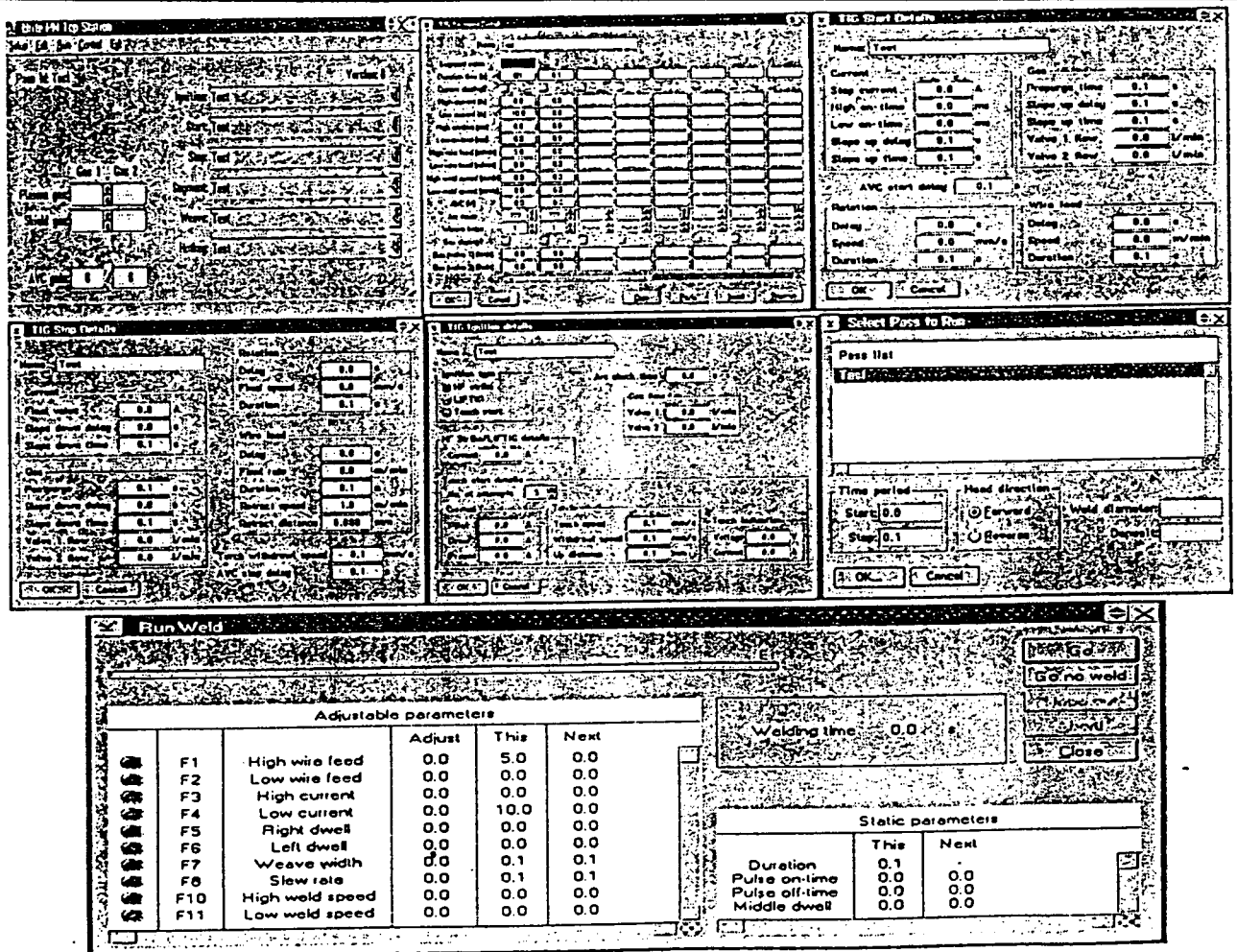


Figure 53: Summary of the menu sequence (from left to right and top to bottom).

1) Weld Bead Width:

(a) Maximum Width $\leq 2t + 3.0\text{mm}$ (t: tube thickness), maximum variation of 1t

(b) Minimum Width $\geq 1t$ (t: tube thickness), maximum variation of 1t

2) Concavity:

10% Maximum

3) Weld Face Reinforcement Height:

0.3*t maximum (t: tube thickness)

4) Weld Root Reinforcement Height:

0.3t maximum (t: tube thickness)

5) Undercutting:

Class A: Not Acceptable - Repair Once Maximum

Class B: Not Acceptable - Repair Twice Maximum

6) Cracks:

Not Acceptable

7) Overlaps:

Not Acceptable

8) Incomplete Fusion/Penetration:

Not Acceptable

9) Burn-Through:

Not Acceptable

10) Surface Porosity/Inclusions:

Not Acceptable-Repair

11) Sub-Surface Porosity and Inclusions:

Largest Dimension: 0.33t (t: tube thickness)

Maximum Length of all Defects: Weld length/20mm

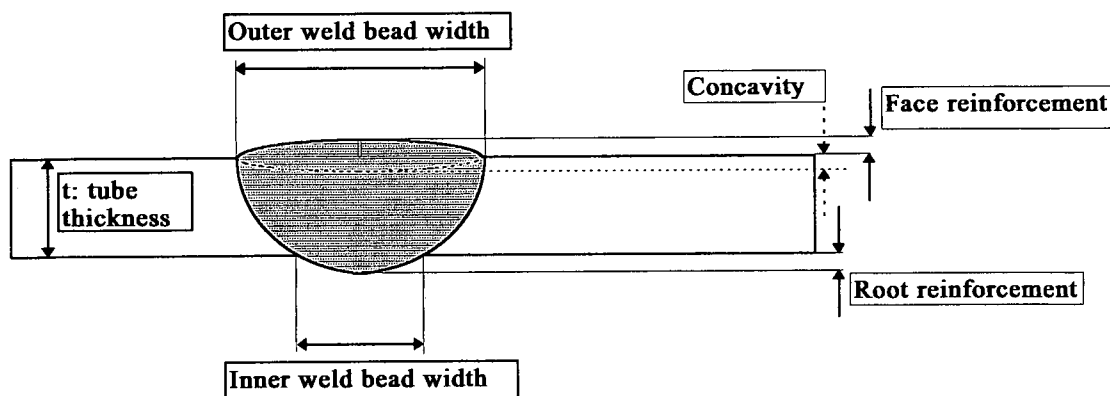


Figure 54: Representative Specification Employed for Assessment of the Weld Quality.

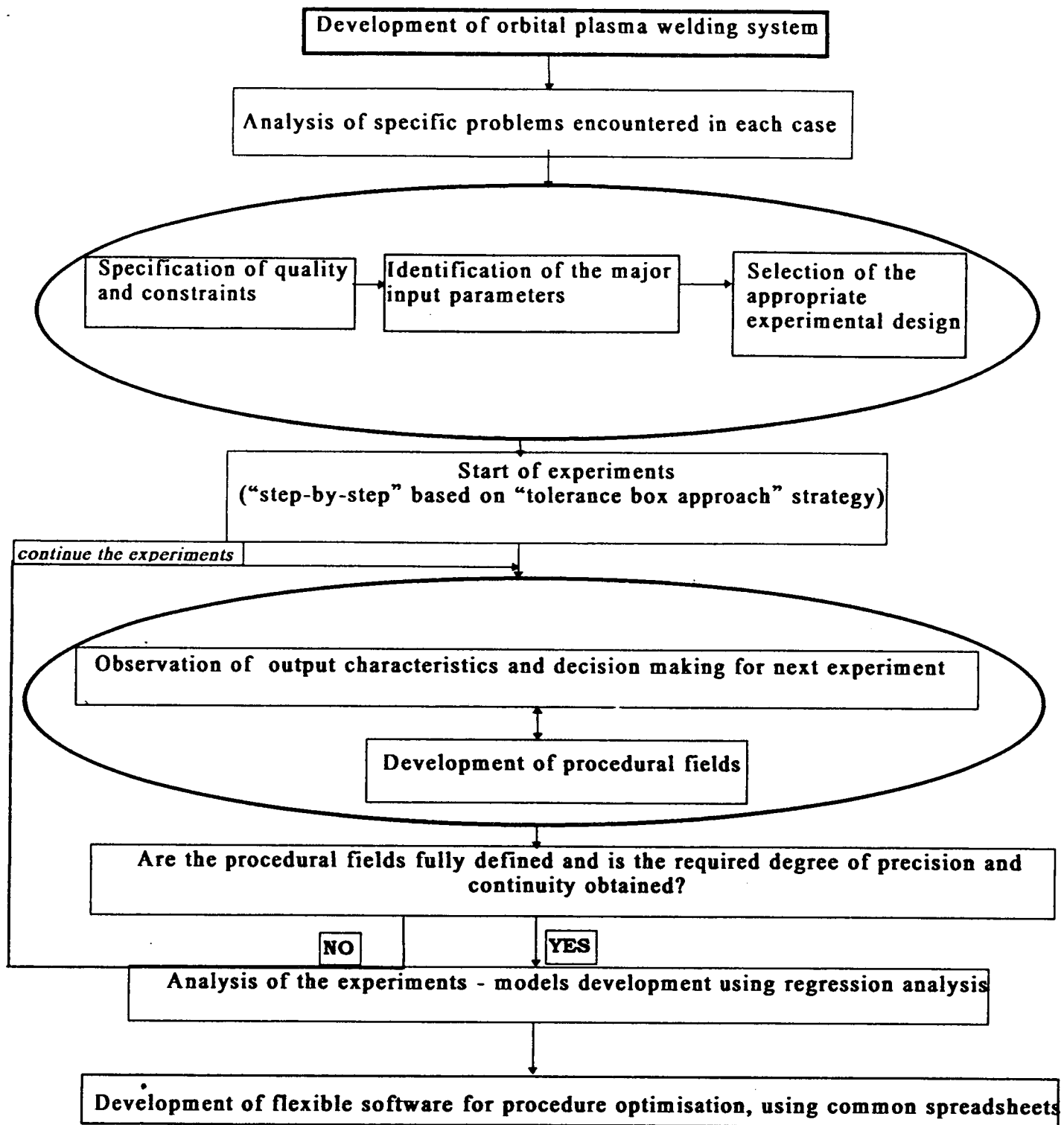


Figure 55: The general modelling and optimisation concept.

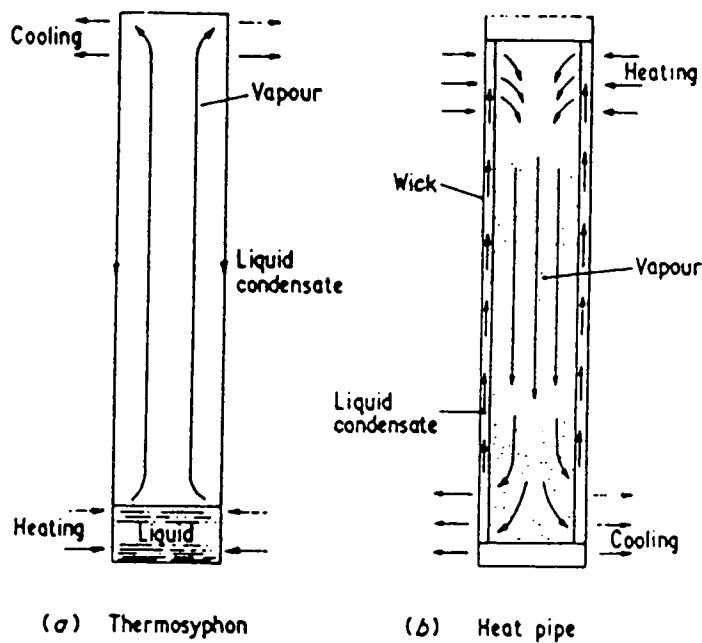


Figure 56a: The heat pipe and thermosyphon. A representation of their basic operation which follows the same principle (from 242).

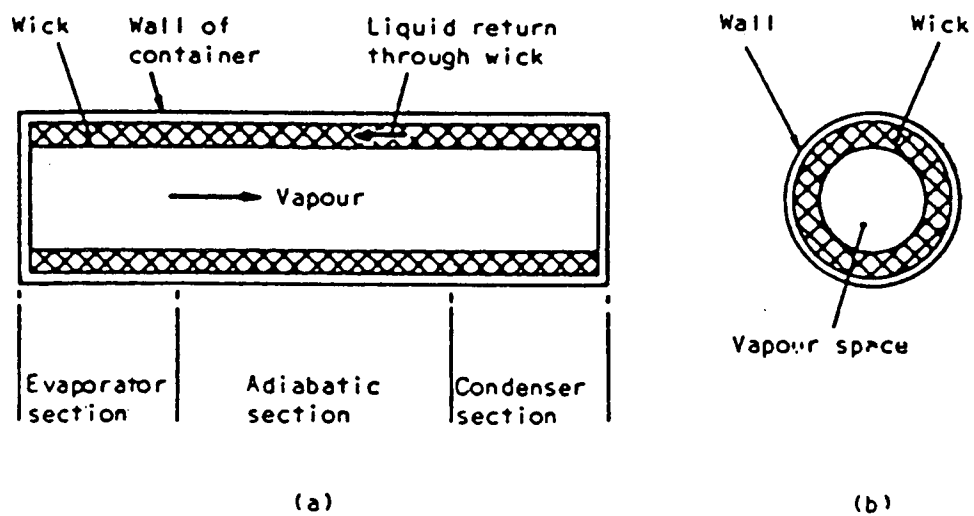


Figure 56b: The main regions of a tubular heat pipe (from 242).

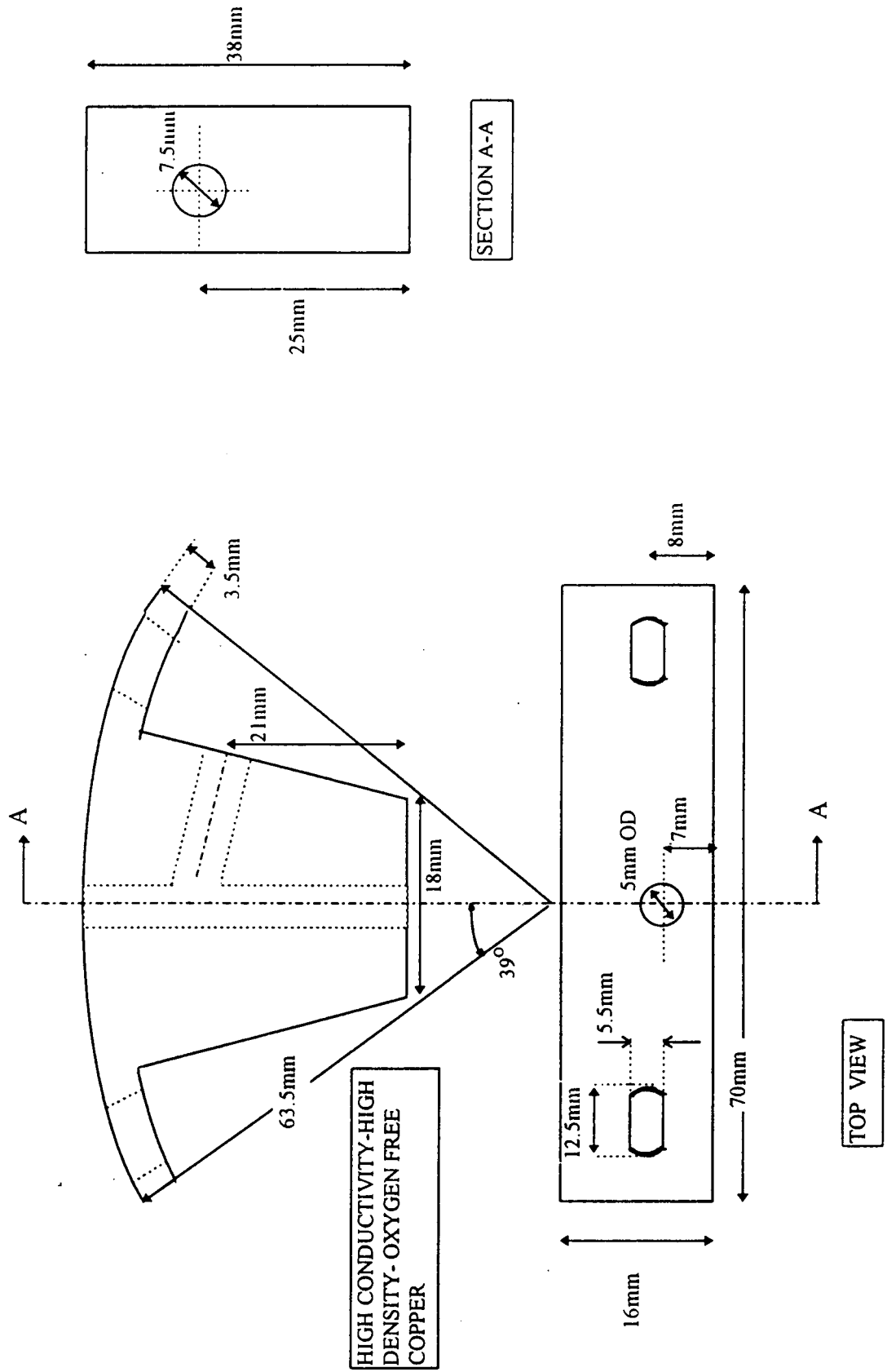


Figure 57: Design of the copper torch body.



Figure 58: Copper Torch Body Developed and Adapted to the Orbital Welding Head for Low Current Plasma Applications.

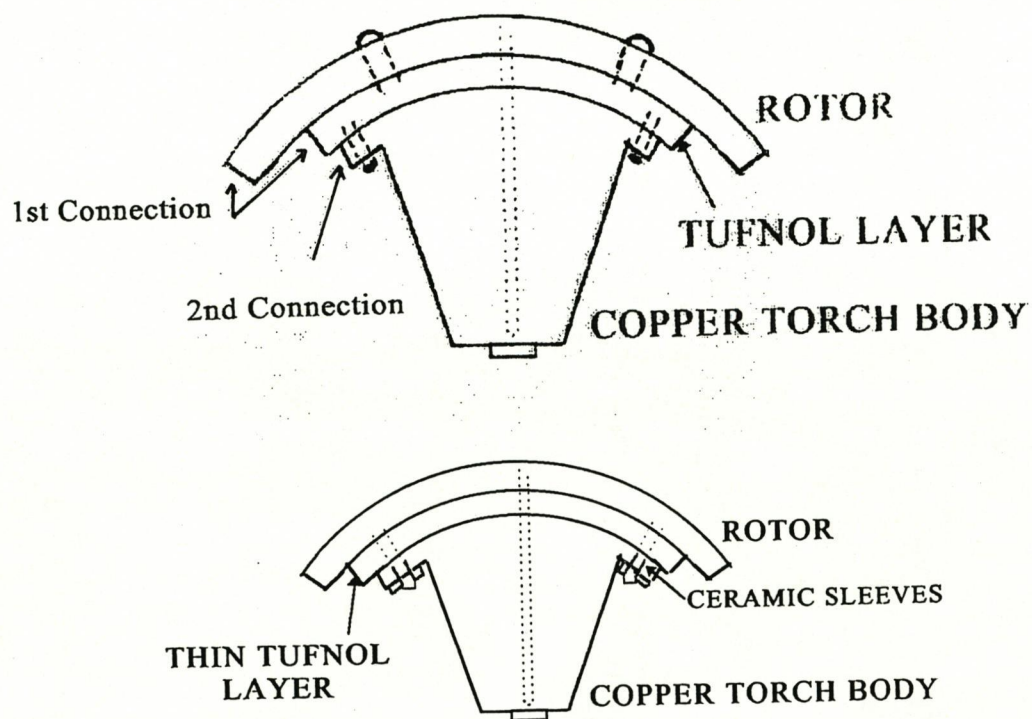


Figure 59: Torch Assembly Sequence for thin and thick Tufnol Layers.

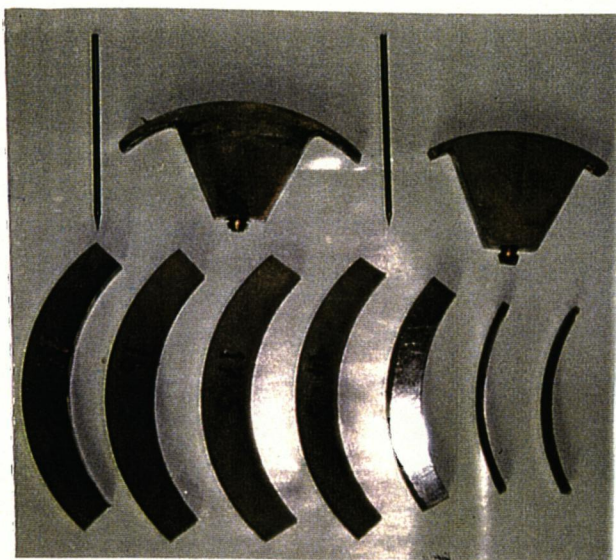


Figure 60: Main Parts Utilised for the Development of the Modification (Copper Torch Bodies, Tufnol Layers).

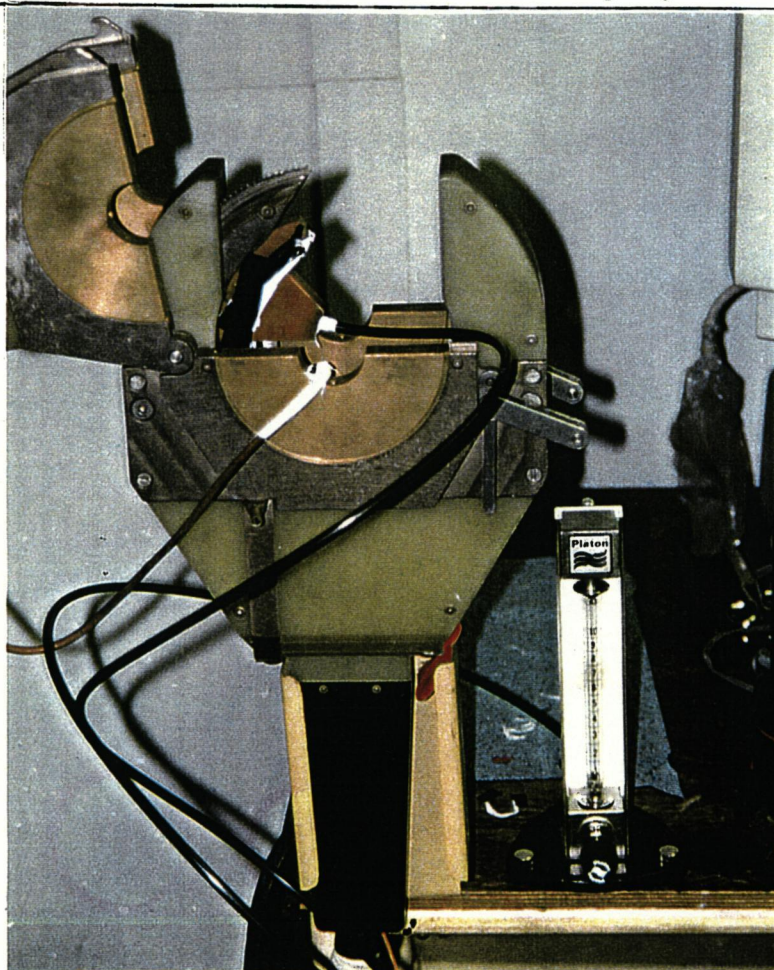


Figure 61: Experimental Set-up Employed for Gas Leakage Measurements and Calibration of the Plasma Gas Flow Rate.

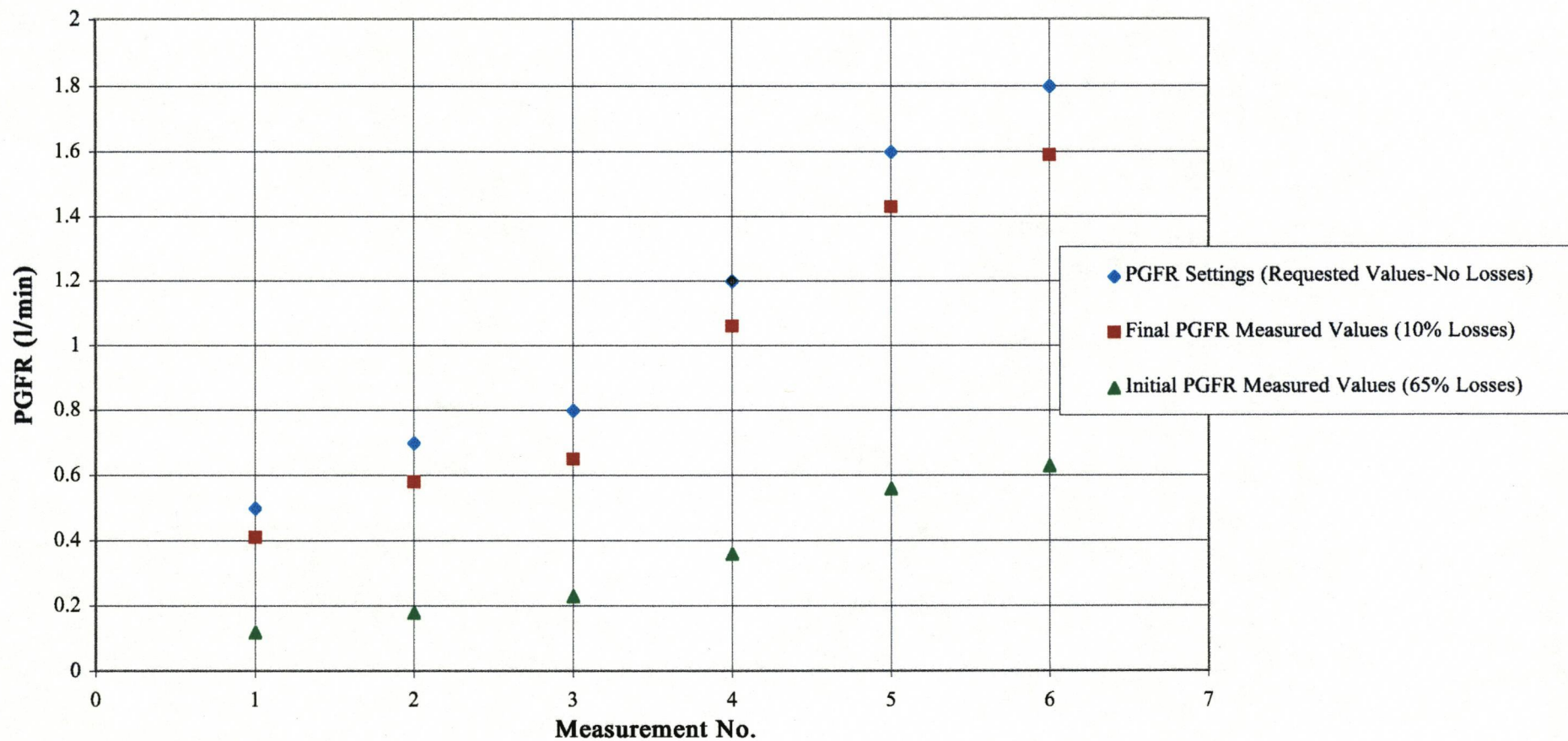


Figure 62: Plasma Gas Flow Rate (PGFR) Measurements for Gas Leakage Detection. Improved Torch Design Resulted in Reduction of Losses from Approximately 65% to 10% of the Requested Values.

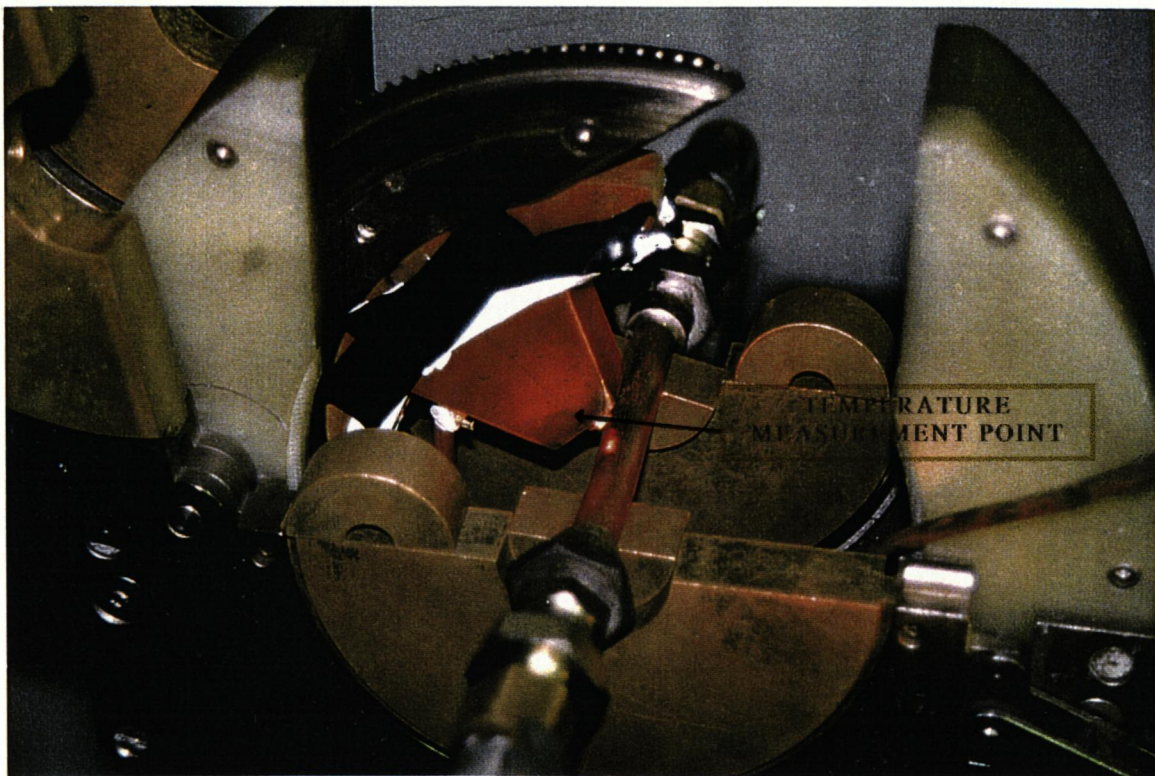
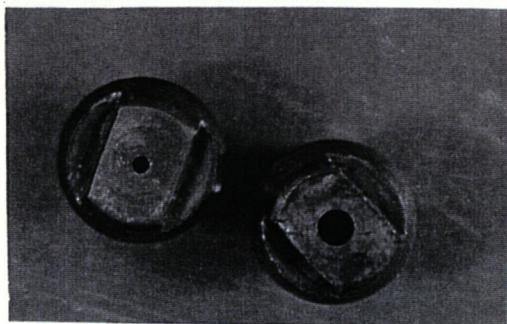
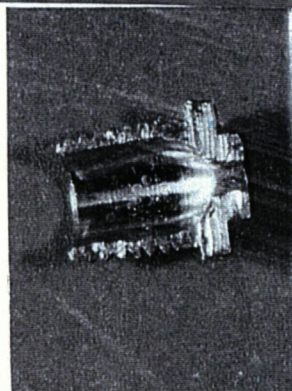


Figure 63: Experimental Set-up for Torch Temperature and Arc Voltage Measurements (see also figures 41 and 42).

Appropriate Orifices (0.79mm and 1.63mm Orifice Diameters)



Inside of an 1.63mm Diameter Orifice



Damaged Orifices (due to use with excessive currents)

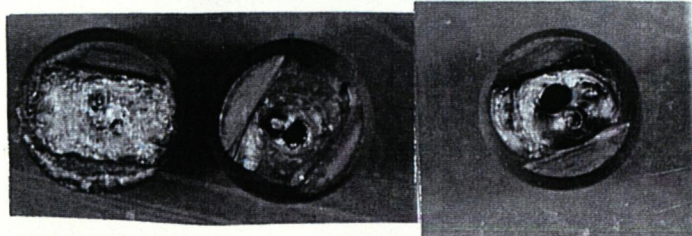


Figure 64: Typical Damaged and Appropriate Orifices.

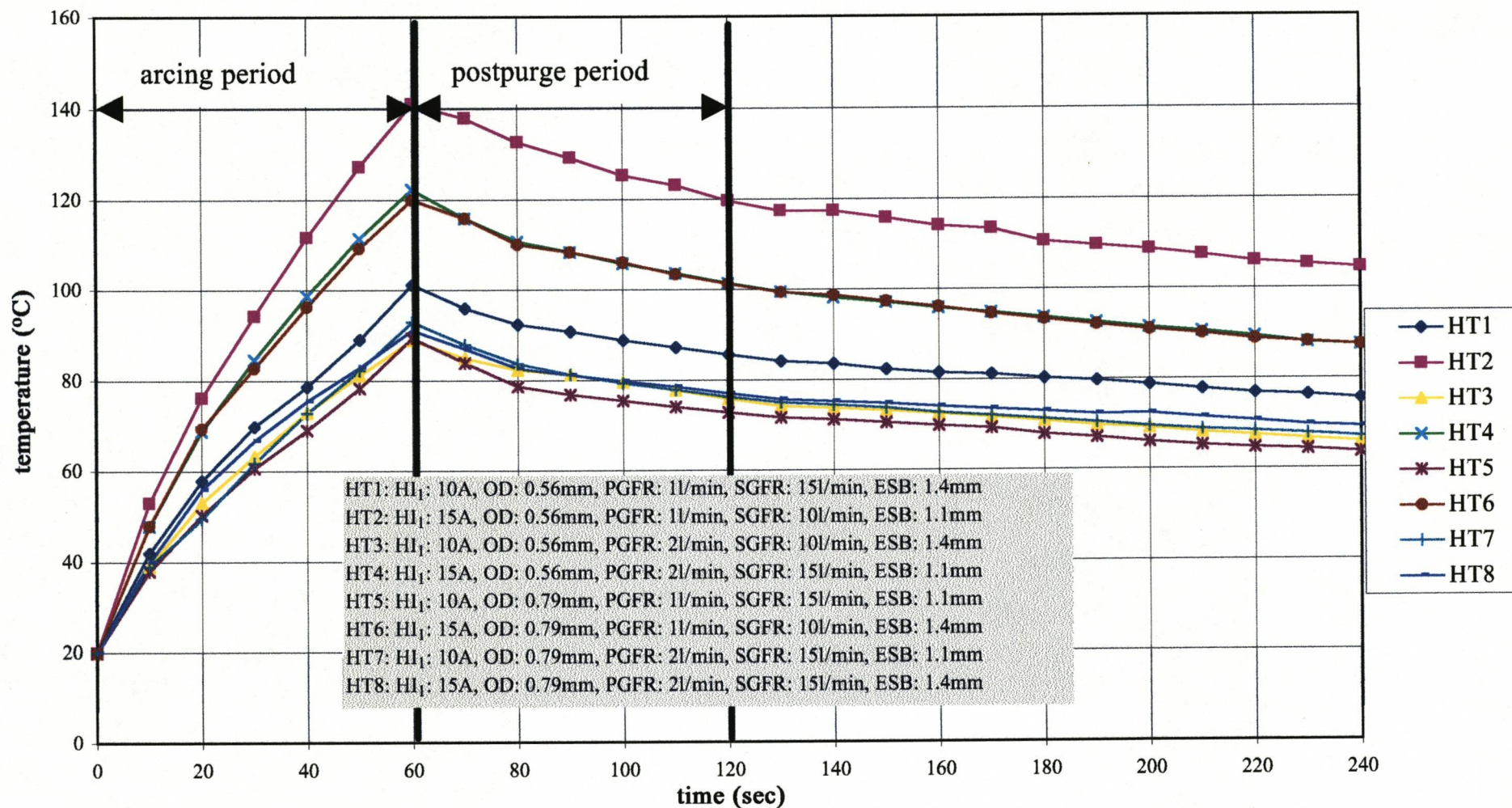
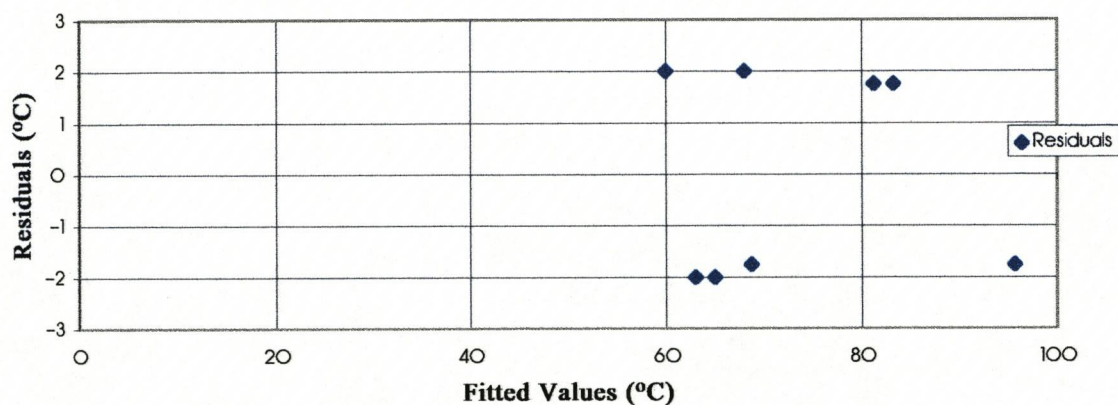
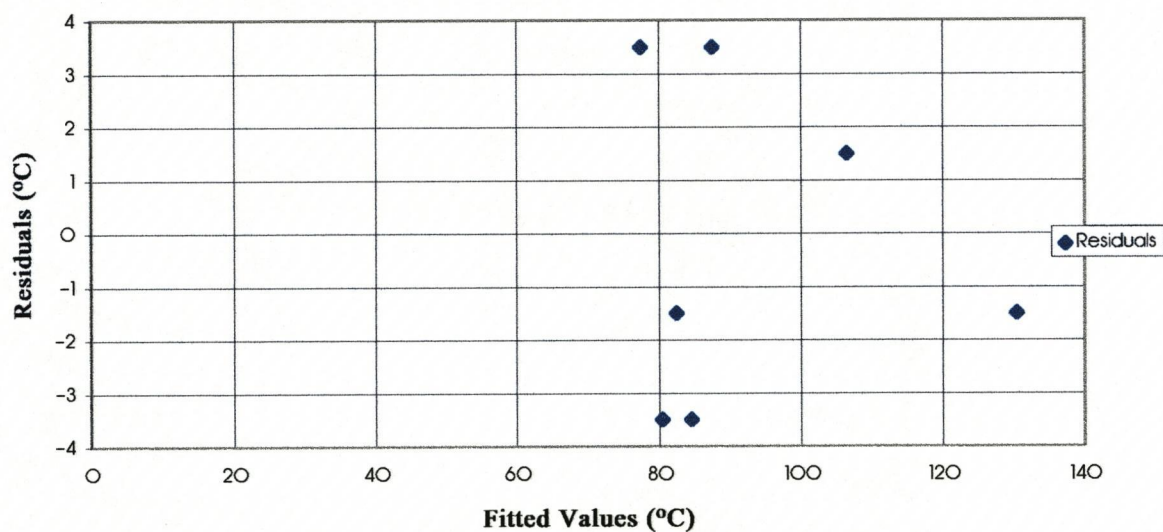


Figure 65: Torch Temperature Cycles Constructed Using Average Recorded Temperature Measurements at 10sec Intervals After Arc Initiation (see Table B1, Appendix B for Results).

Residual Versus Fitted Values for the 30sec Temperature Measurement Model



Residual Versus Fitted Values for the 90sec Temperature Measurement Model



Residual Versus Fitted Values for the 180sec Temperature Measurement Model

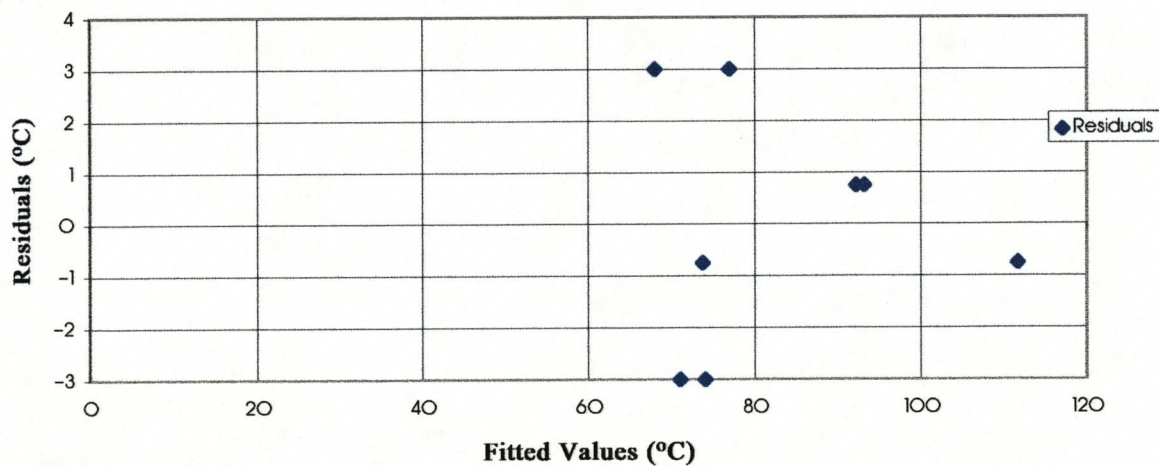
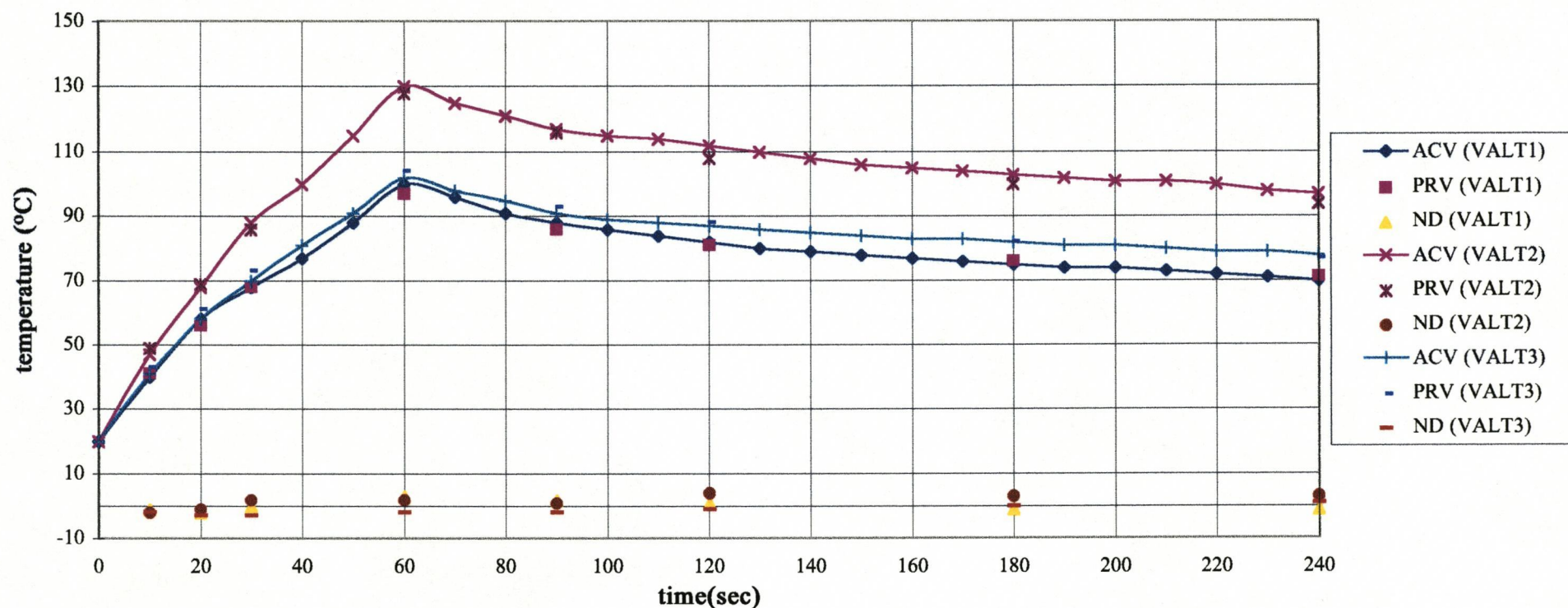


Figure 66: Sample Plots of Residuals Versus Fitted Values (Temperature Measurement Models).



ACV: Actual Temperature Measurements Recorded
 PRV: Predicted Temperature Measurements
 ND: Nominal Deviation
 VALT1: Validation Trial No. 1: HI₁: 11A, OD: 0.56mm, PGFR: 1.8l/min, SGFR: 14l/min, ESB: 1.3mm
 VALT2: Validation Trial No. 2: HI₁: 13A, OD: 0.56mm, PGFR: 1.5l/min, SGFR: 9l/min, ESB: 1.1mm
 VALT3: Validation Trial No. 3: HI₁: 14A, OD: 0.79mm, PGFR: 1.3l/min, SGFR: 12l/min, ESB: 1.4mm

Figure 67: Torch Temperature Cycles of the Validation Trials, Predicted Results and Nominal Deviations for Validation of the Torch Temperature Models.

TORCH BODY TEMPERATURE MEASUREMENTS

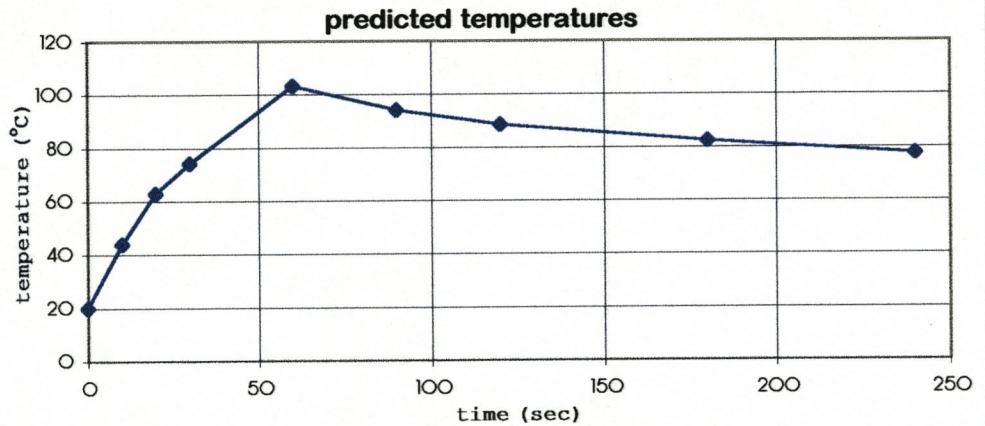
Predicted temperatures

sec	°C
0	20
10	44
20	63
30	74
60	103
90	94
120	89
180	82
240	77

Values

HI₁	15	← █ █ █ █ █ █ █ █ █ █ █ █ █ █ █ →
OD	0.79	← █ █ █ █ █ █ █ █ █ █ █ █ █ █ █ →
PGFR	1.5	← █ █ █ █ █ █ █ █ █ █ █ █ █ █ █ →
SGFR	10	← █ █ █ █ █ █ █ █ █ █ █ █ █ █ █ →
ESB	1.6	← █ █ █ █ █ █ █ █ █ █ █ █ █ █ █ →

Rt	1.39
R₂₀	2.14
R₆₀	1.01
Ft	-0.14
F₁₂₀	-0.24
F₂₄₀	-0.09



TORCH BODY TEMPERATURE MEASUREMENTS

Predicted temperatures

sec	°C
0	20
10	48
20	71
30	84
60	118
90	110
120	103
180	95
240	89

Values

HI ₁	15	←		→
OD	0.56	←		→
PGFR	1.5	←		→
SGFR	10	←		→
ESB	1.6	←		→

Rt	1.64
R₂₀	2.53
R₆₀	1.19
Ft	-0.16
F₁₂₀	-0.26
F₂₄₀	-0.11

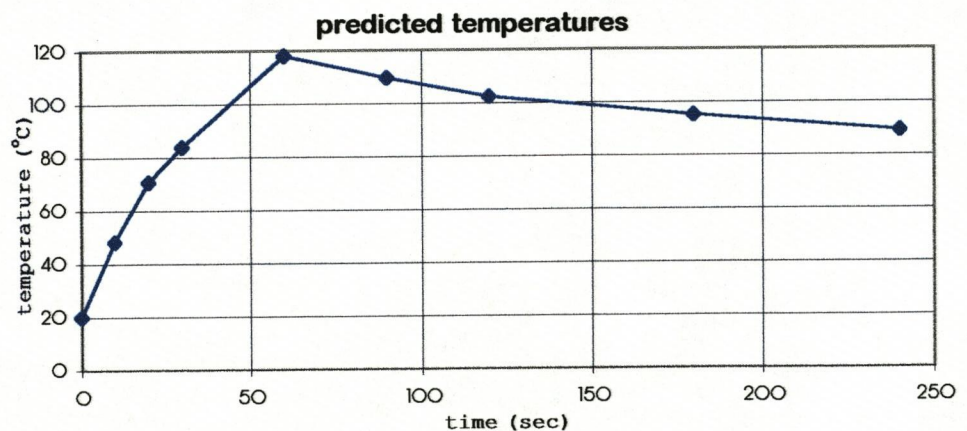


Figure 68: Sample Shots from the Developed Software Utilised for the Investigation

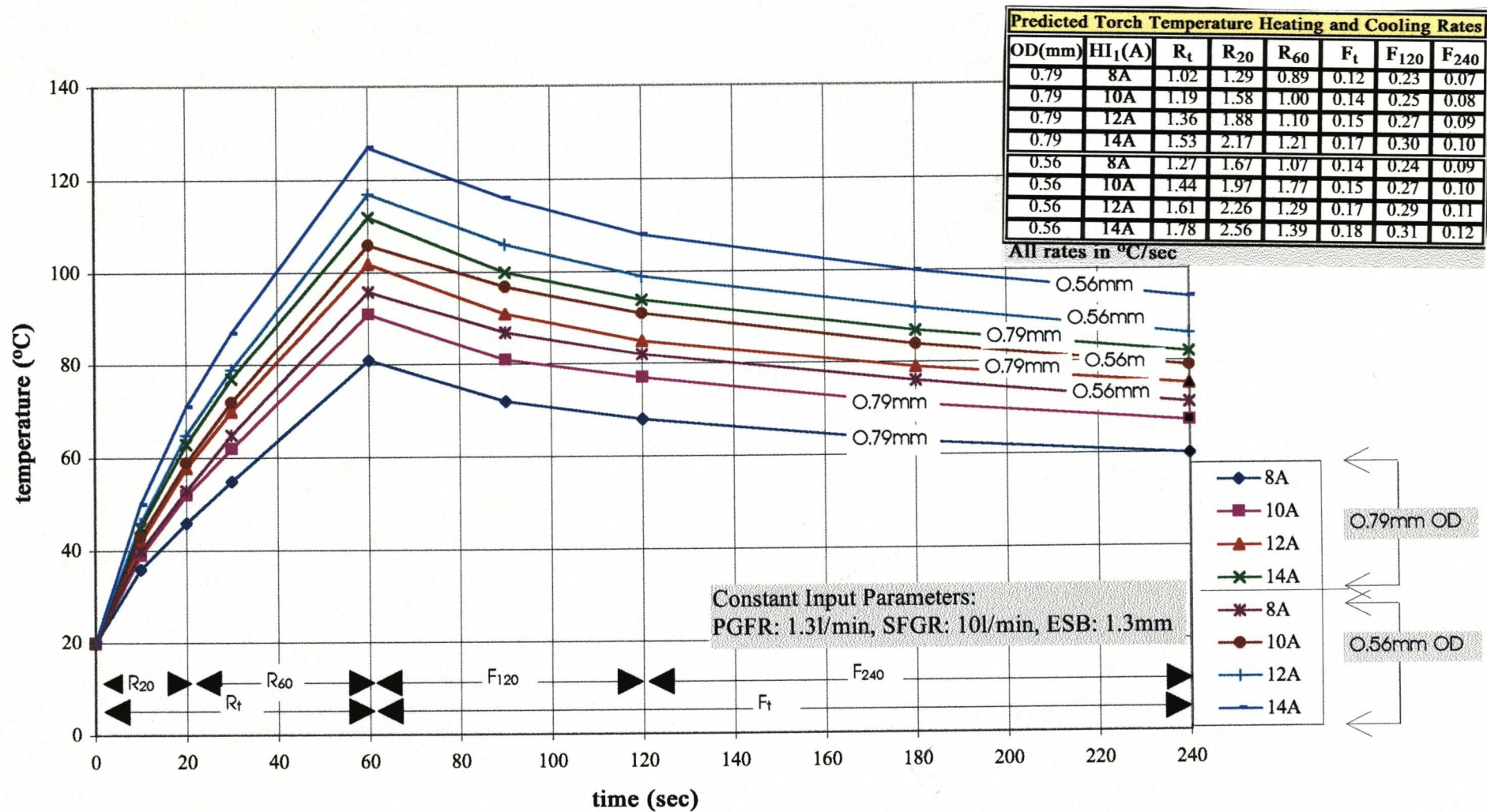


Figure 69a: Welding Current (HI₁) Influence on Torch Temperature Based on Predicted Temperatures for Four Different Average Welding Current Values (8A, 10A, 12A, 14A).

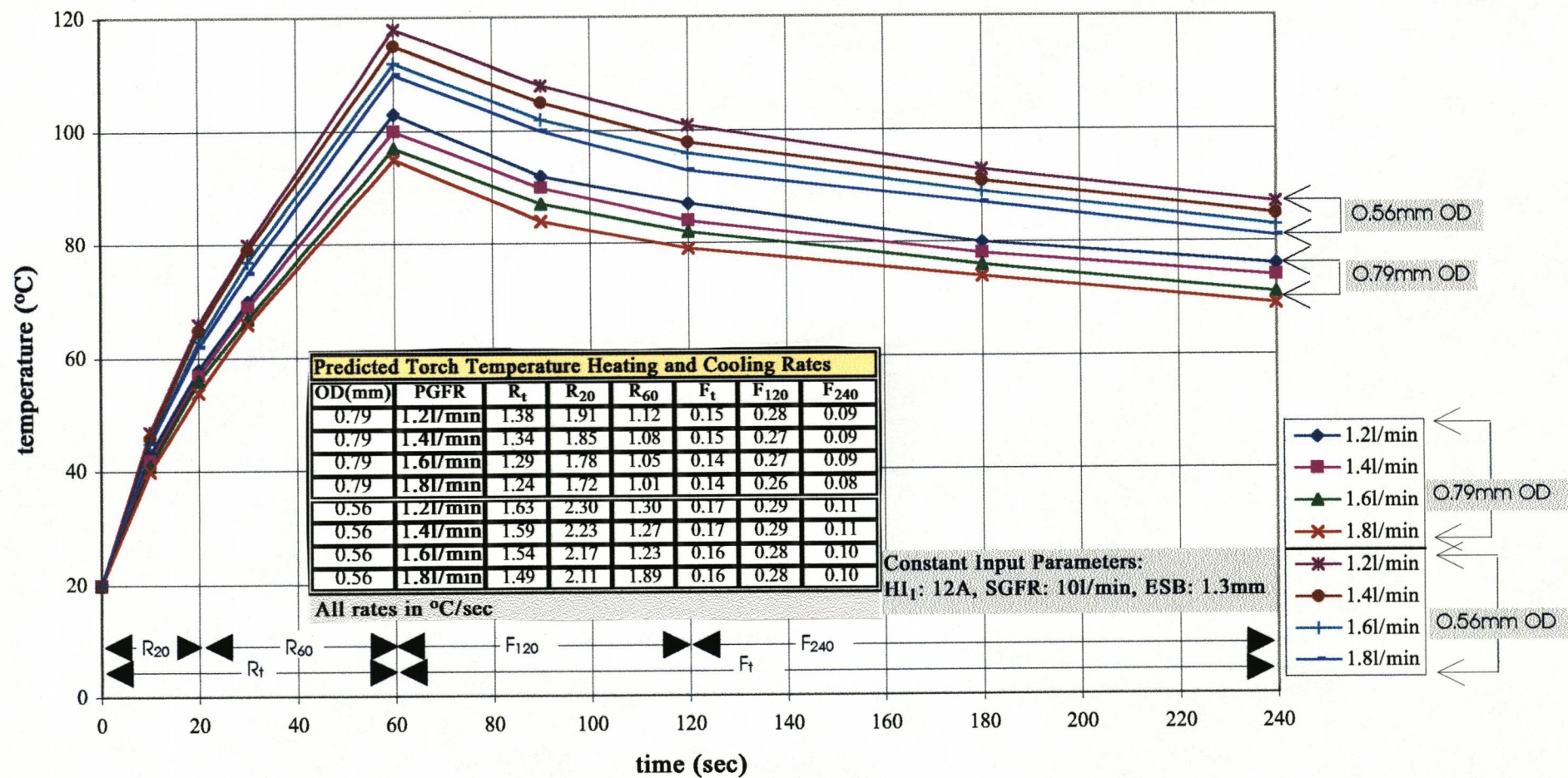


Figure 69b: Plasma Gas Flow Rate (PGFR) Influence on Torch Temperature Based on Predicted Temperatures for Four Different PGFR (1.2l/min, 1.4l/min, 1.6l/min, 1.8l/min).

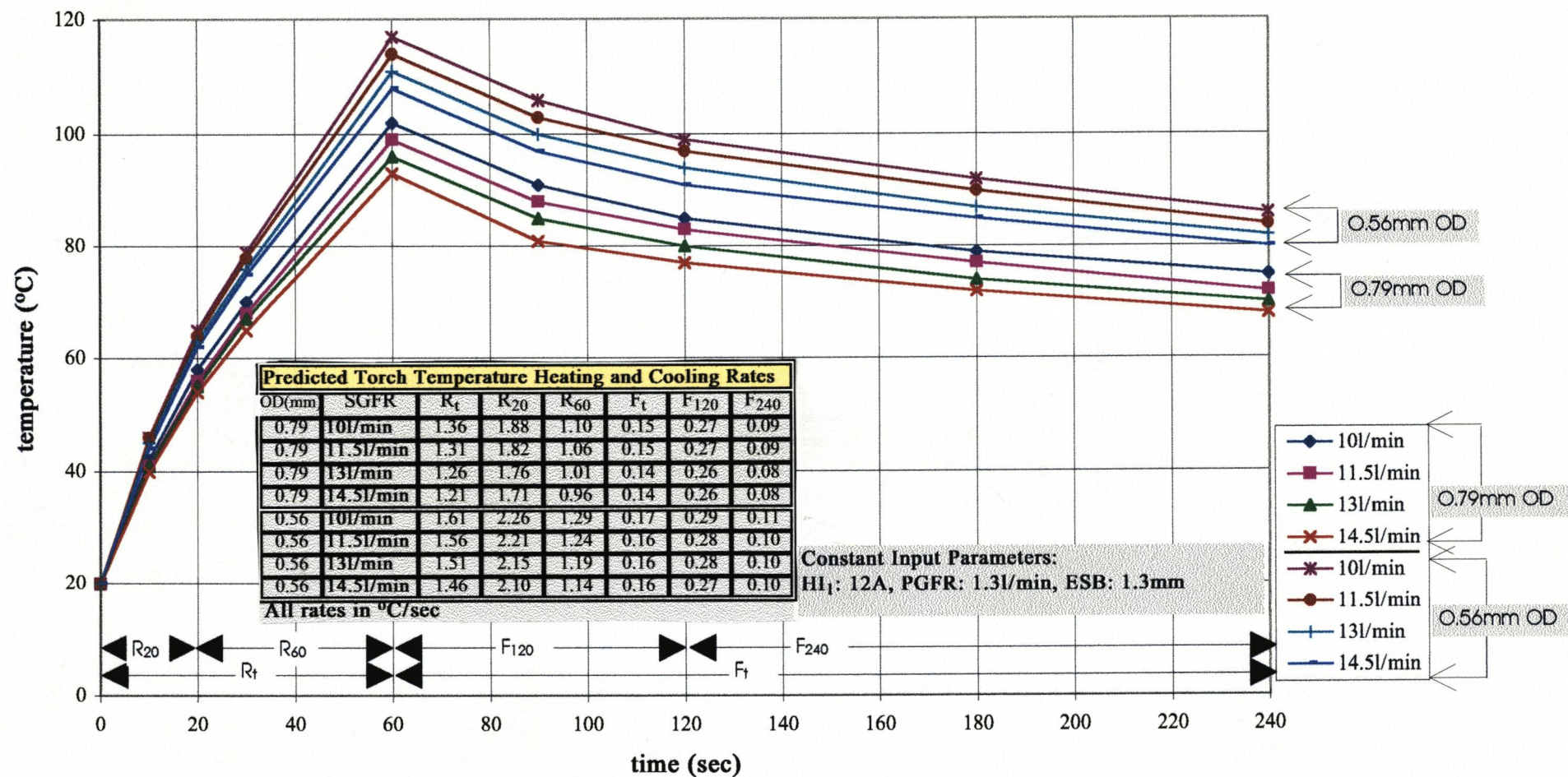


Figure 69c: Shielding Gas Flow Rate (SGFR) Influence on Torch Temperature Based on Predicted Temperatures for Four Different SGFR (10l/min, 11.5l/min, 13l/min, 14.5l/min).

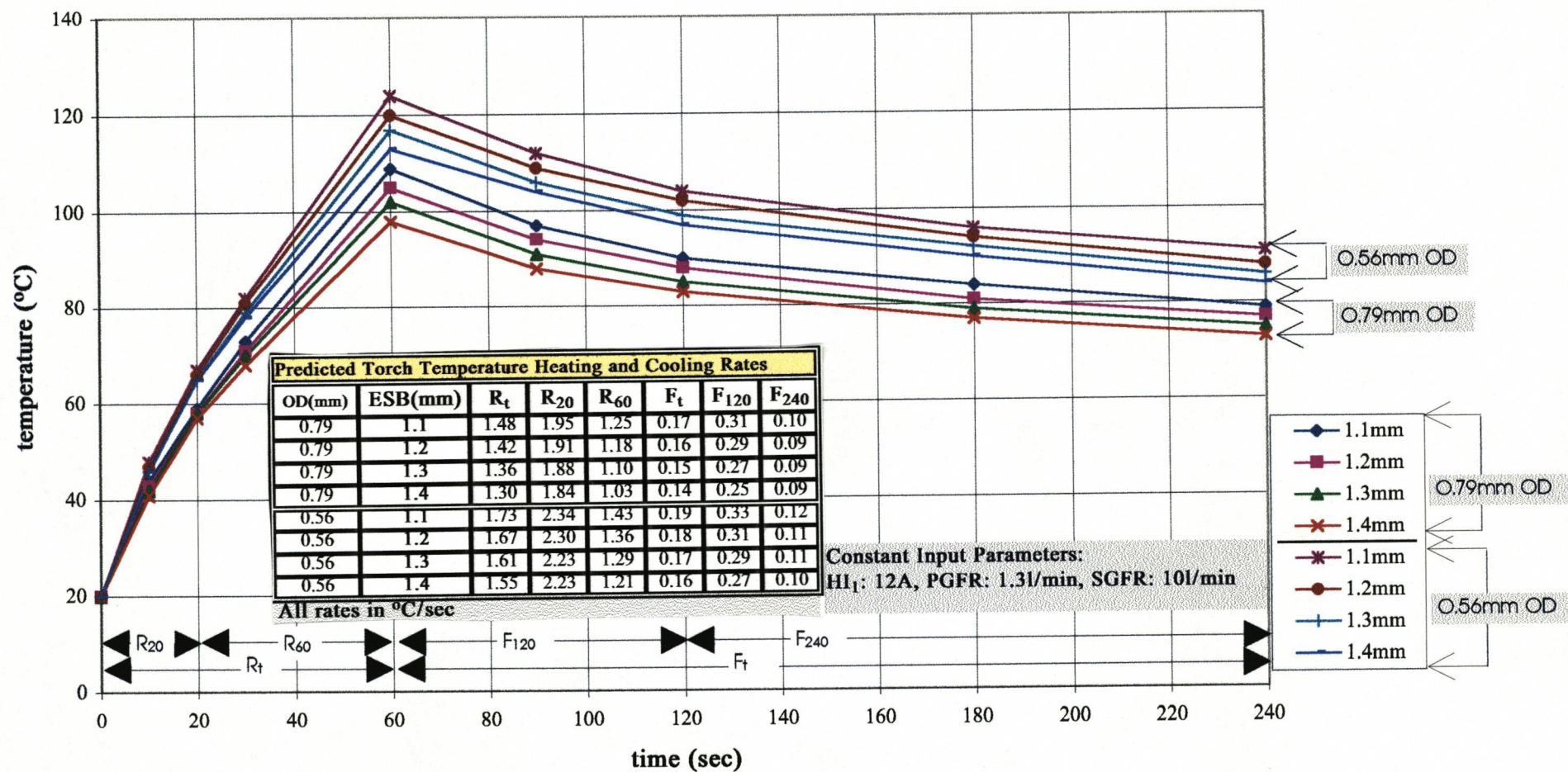


Figure 69d: Electrode Set Back Distance (ESB) Influence on Torch Temperature Based on Predicted Temperatures for Four Different ESB (1.1mm, 1.2mm, 1.3mm, 1.4mm).

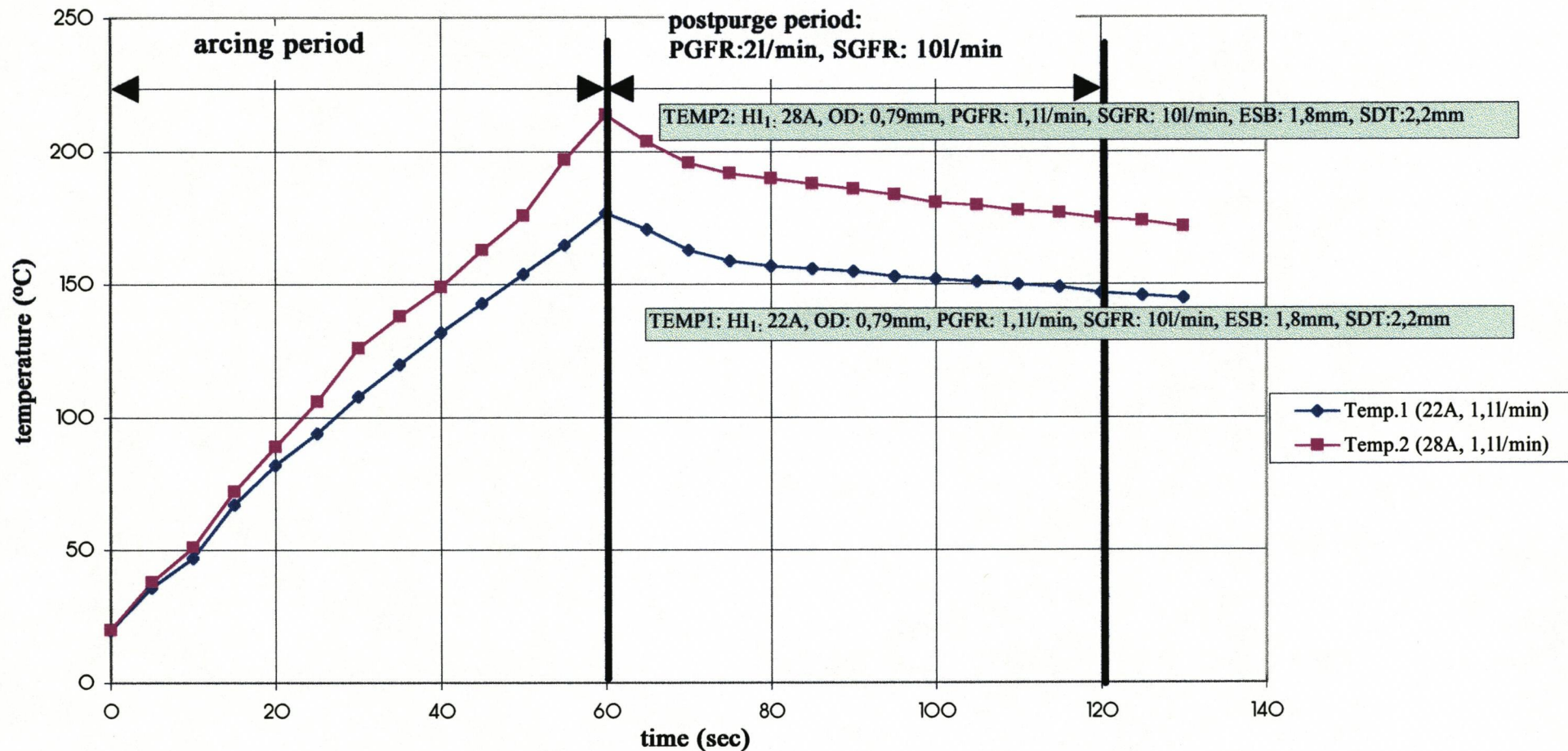


Figure 70: Torch Temperature Cycles for Two Different Welding Conditions Using Ar-5% H_2 as Shielding Gas (see Table B2, Appendix B for Results).

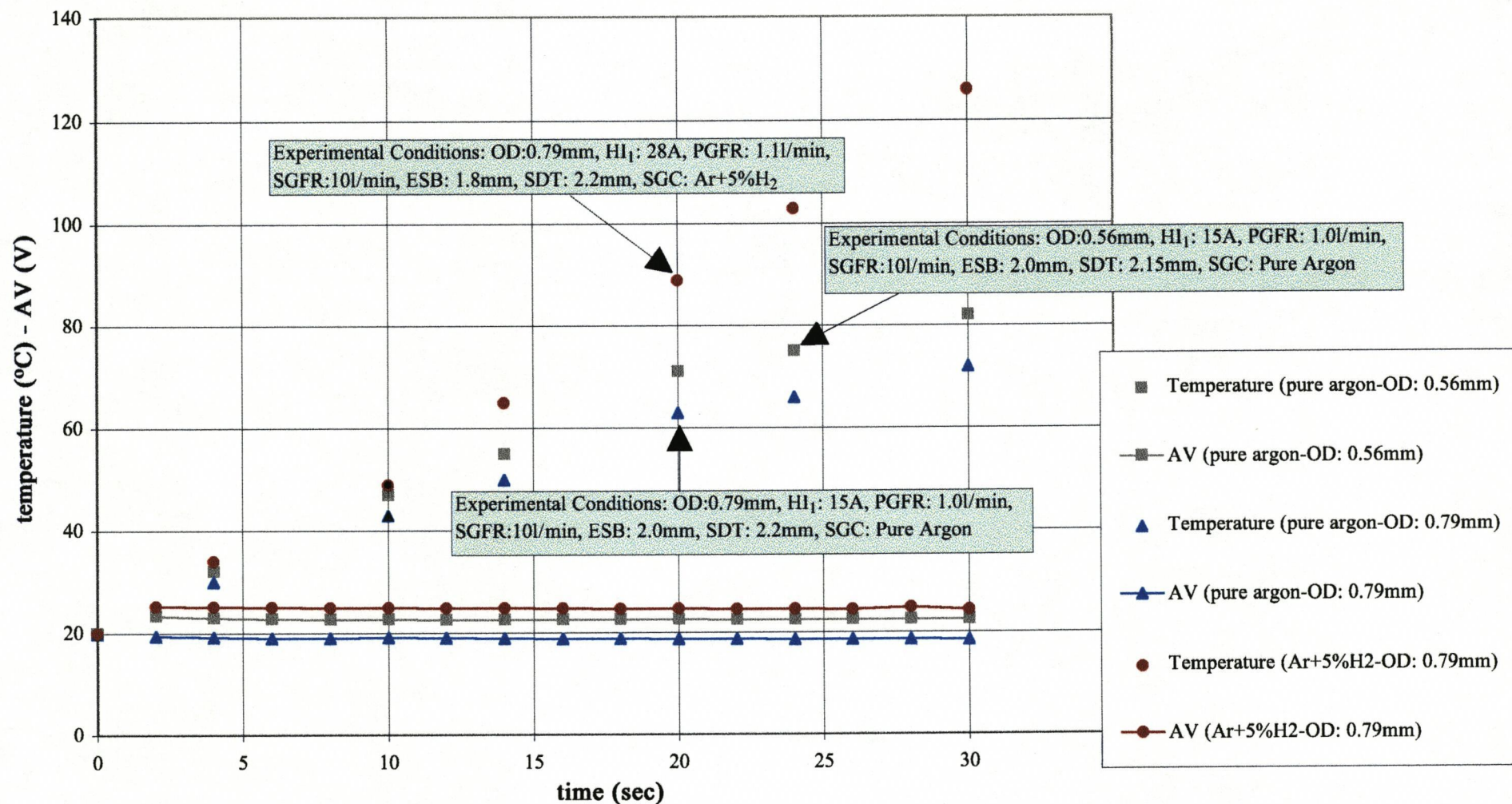


Figure 71: Influence of Torch Heating Up on Arc Voltage for Two Orifice Diameters (0.56mm, 0.79mm) and Two Shielding Gas Compositions (Pure Argon, Ar+5%H₂) (see Table C1, Appendix C for Results)

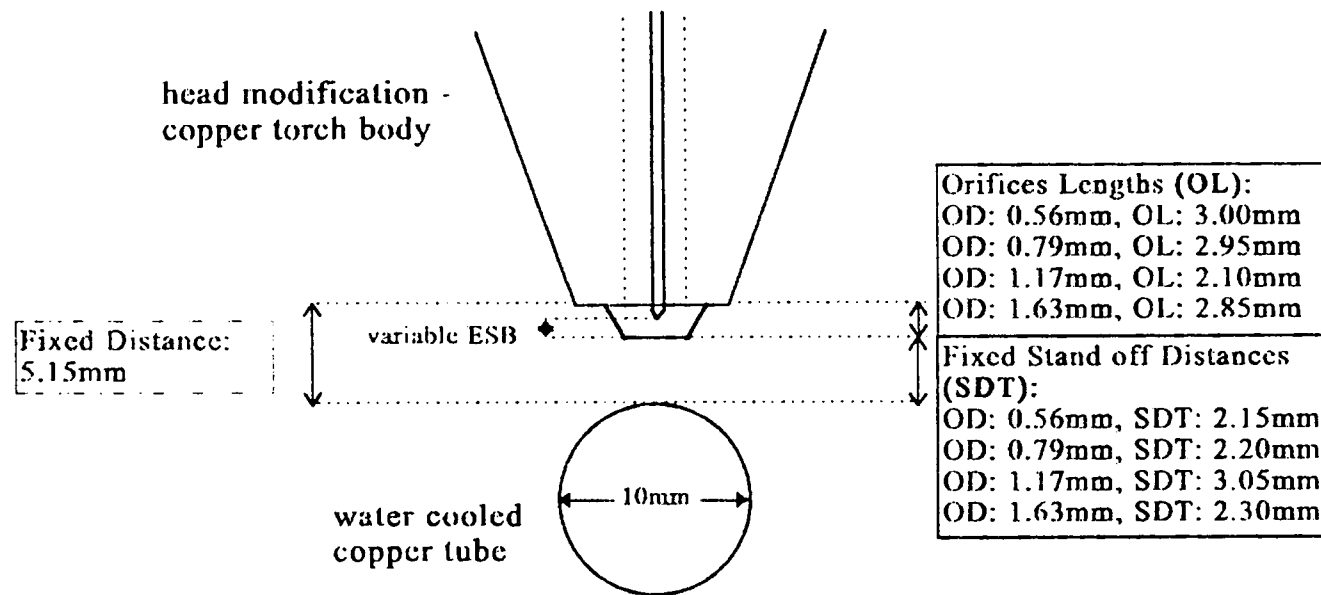


Figure 72: Experimental Set-up for the Investigation of the Orifice Diameter-Arc Voltage Relationship. Note the Fixed Stand off Distances (SDT) due to the Fixed Distance Between the Copper Torch Body and the Water Cooled Copper Tube

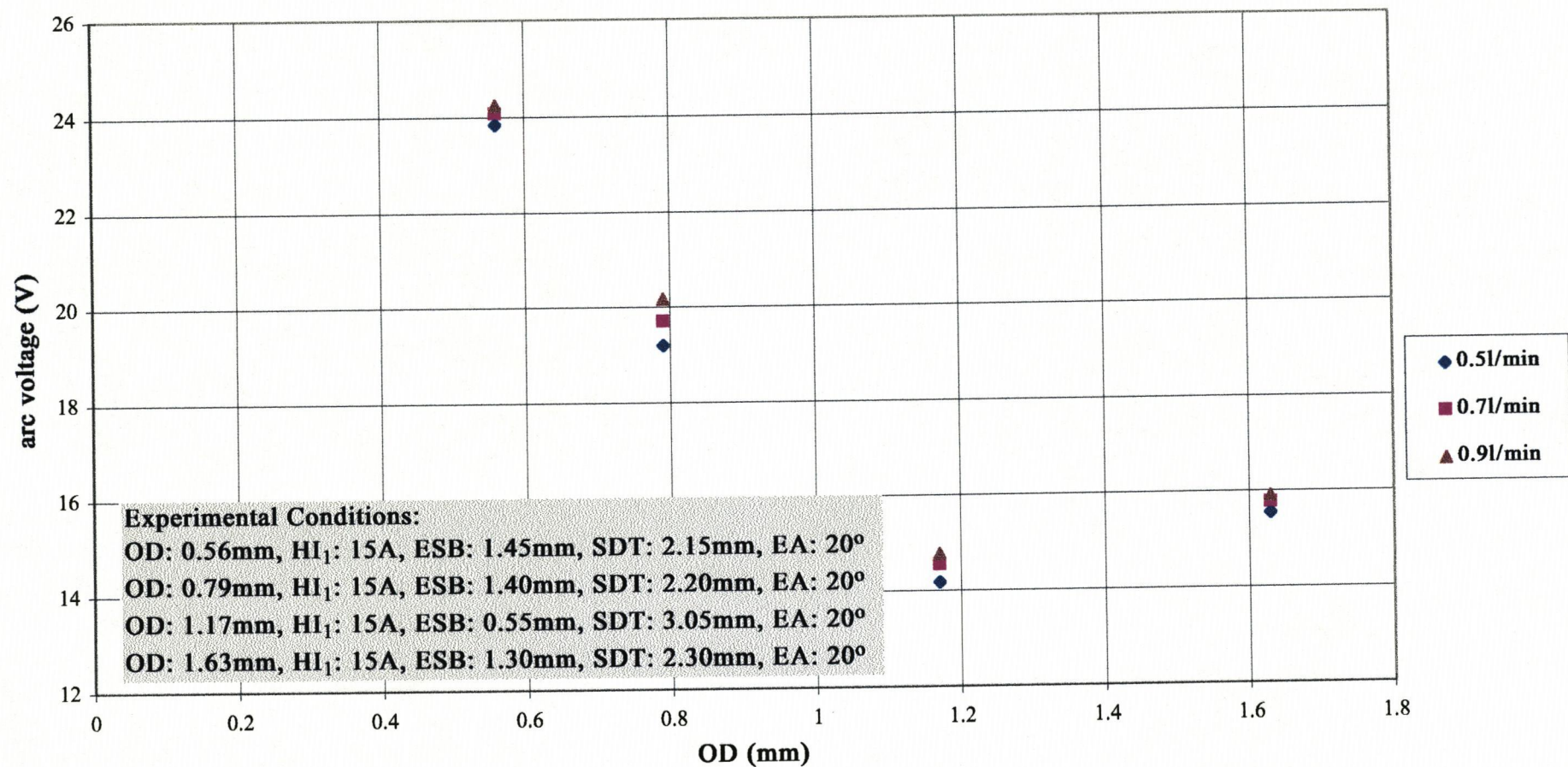


Figure 73: Influence of Orifice Diameter on Arc Voltage for Three Different Plasma Gas Flow Rates (0.5l/min, 0.7l/min, 0.9l/min) (see Table D1, Appendix D for Results).

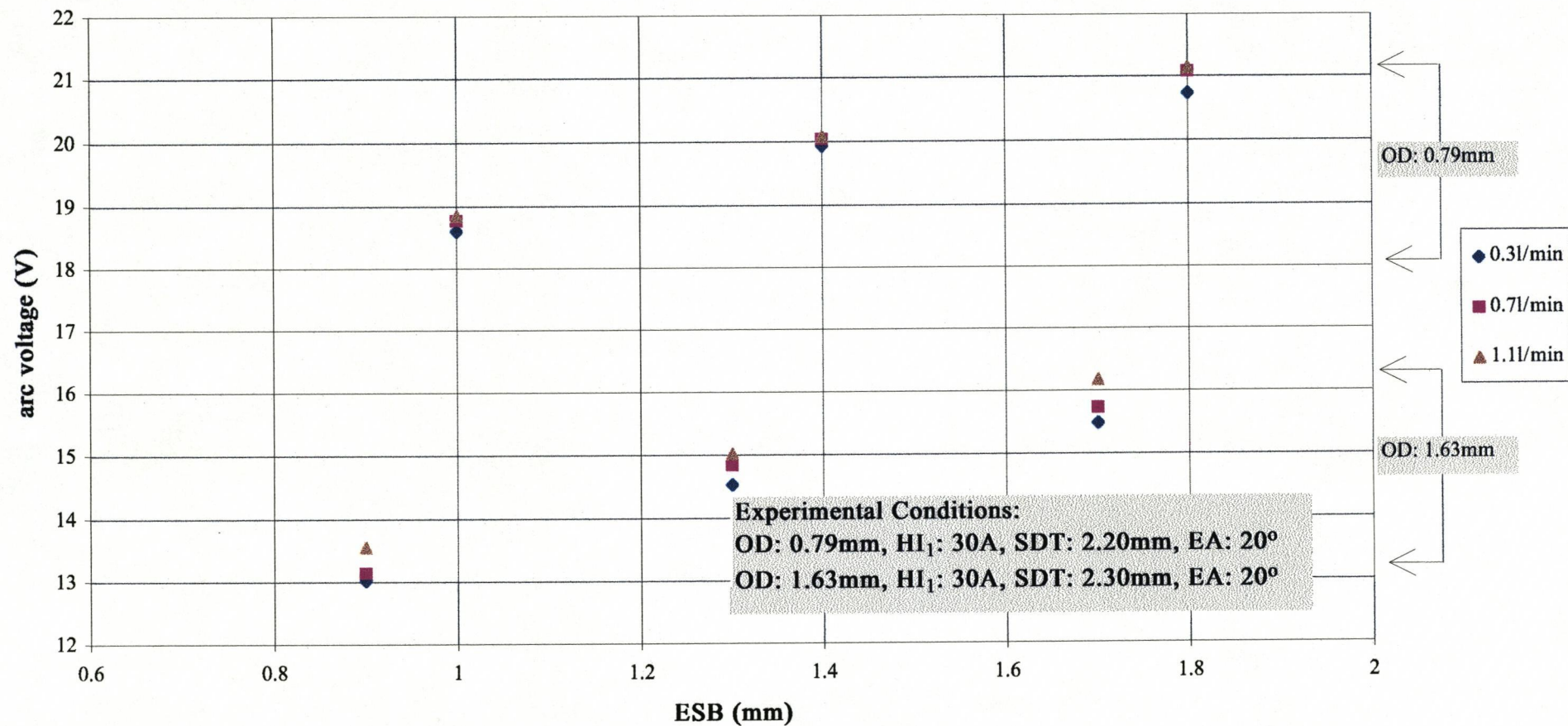


Figure 74: Influence of Electrode Set Back Distance (ESB) on Arc Voltage for Three Different Plasma Gas Flow Rates (0.3l/min, 0.7l/min, 1.1l/min) and for Two Different Orifice Diameters (0.79mm and 1.63mm) (see Table D2, Appendix D for Results).

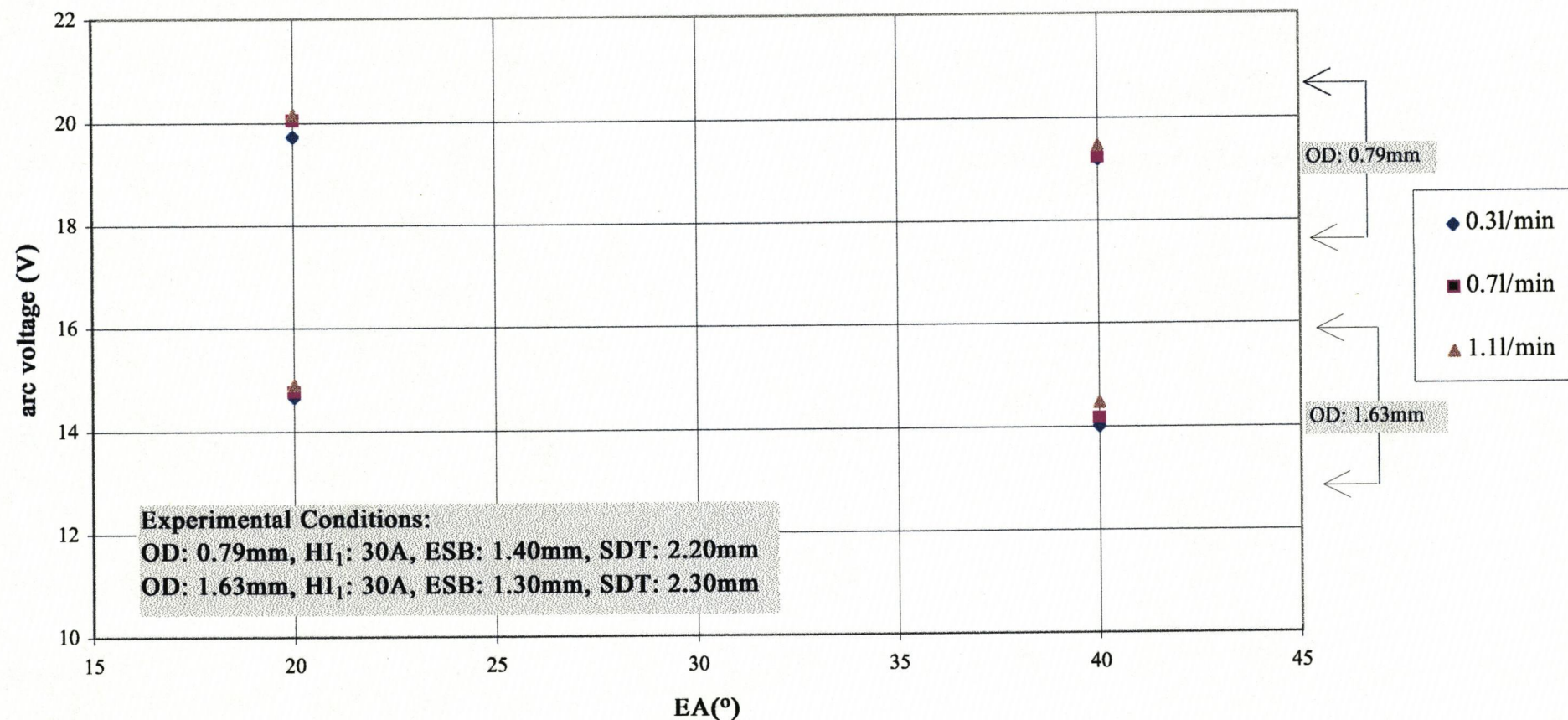


Figure 75: Influence of Electrode Angle (EA) on Arc Voltage for Three Different Plasma Gas Flow Rates (0.3l/min, 0.7l/min, 1.1l/min) and for Two Different Orifice Diameters (0.79mm and 1.63mm) (see Table D3, Appendix D for Results).

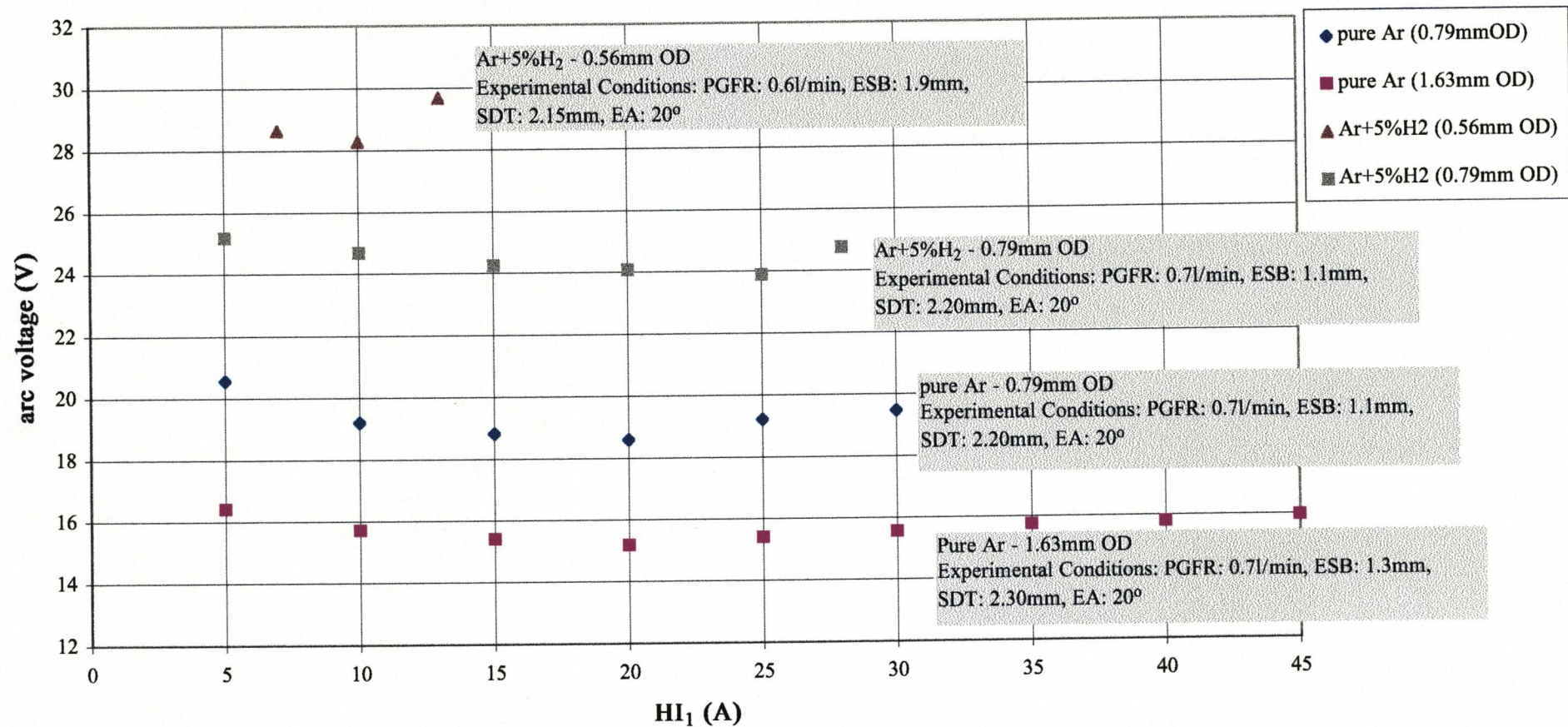


Figure 76: Influence of Welding Current (HI₁) on Arc Voltage for Two Different Shielding Gases (Pure Argon, Ar+5%H₂) and for Various Orifice Diameters (see Table D4, Appendix D for Results).

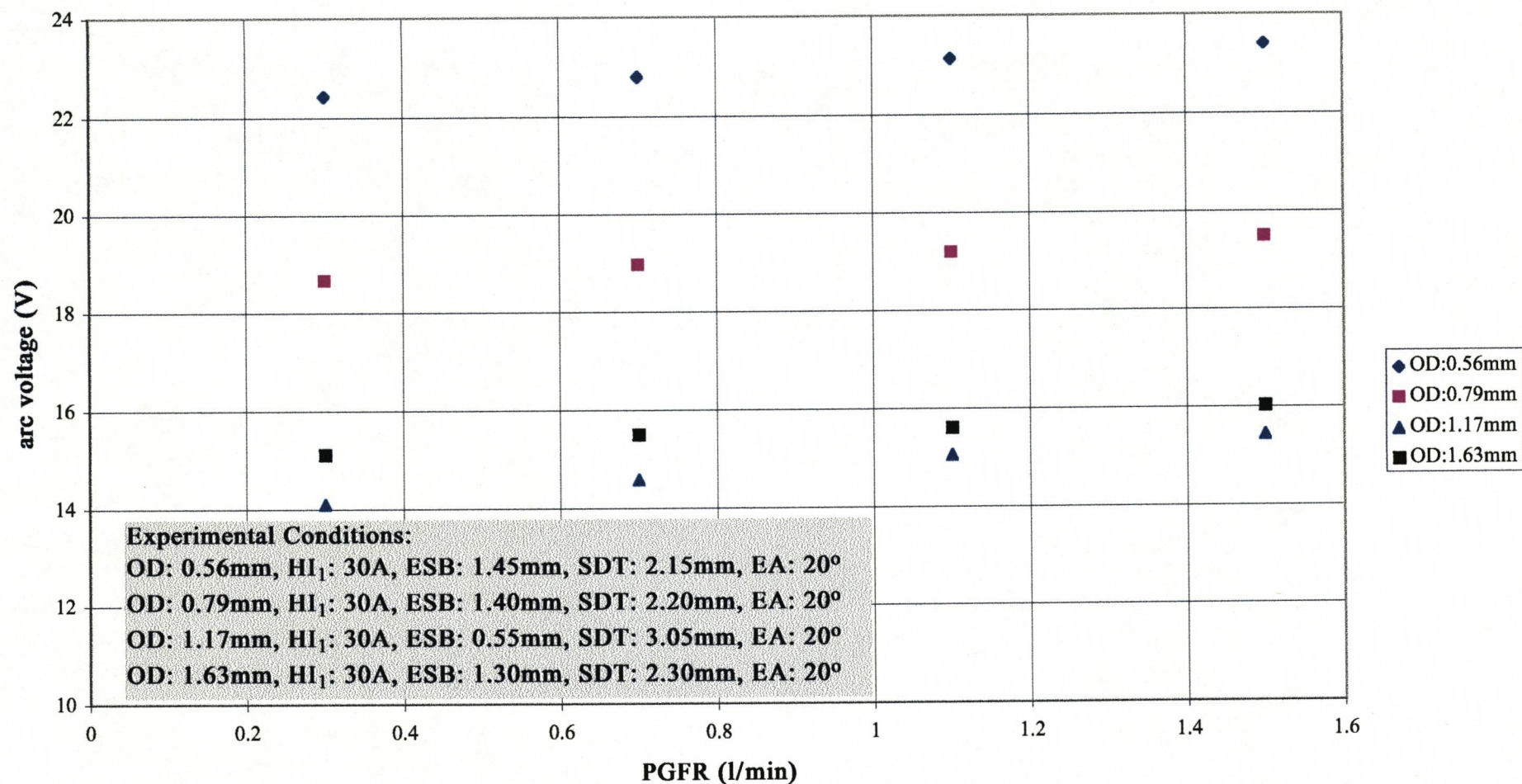


Figure 77: Influence of PGFR on Arc Voltage for Four Different Orifice Diameters (0.56mm, 0.79mm, 1.17mm, 1.63mm) (see Table D5, Appendix D for Results).

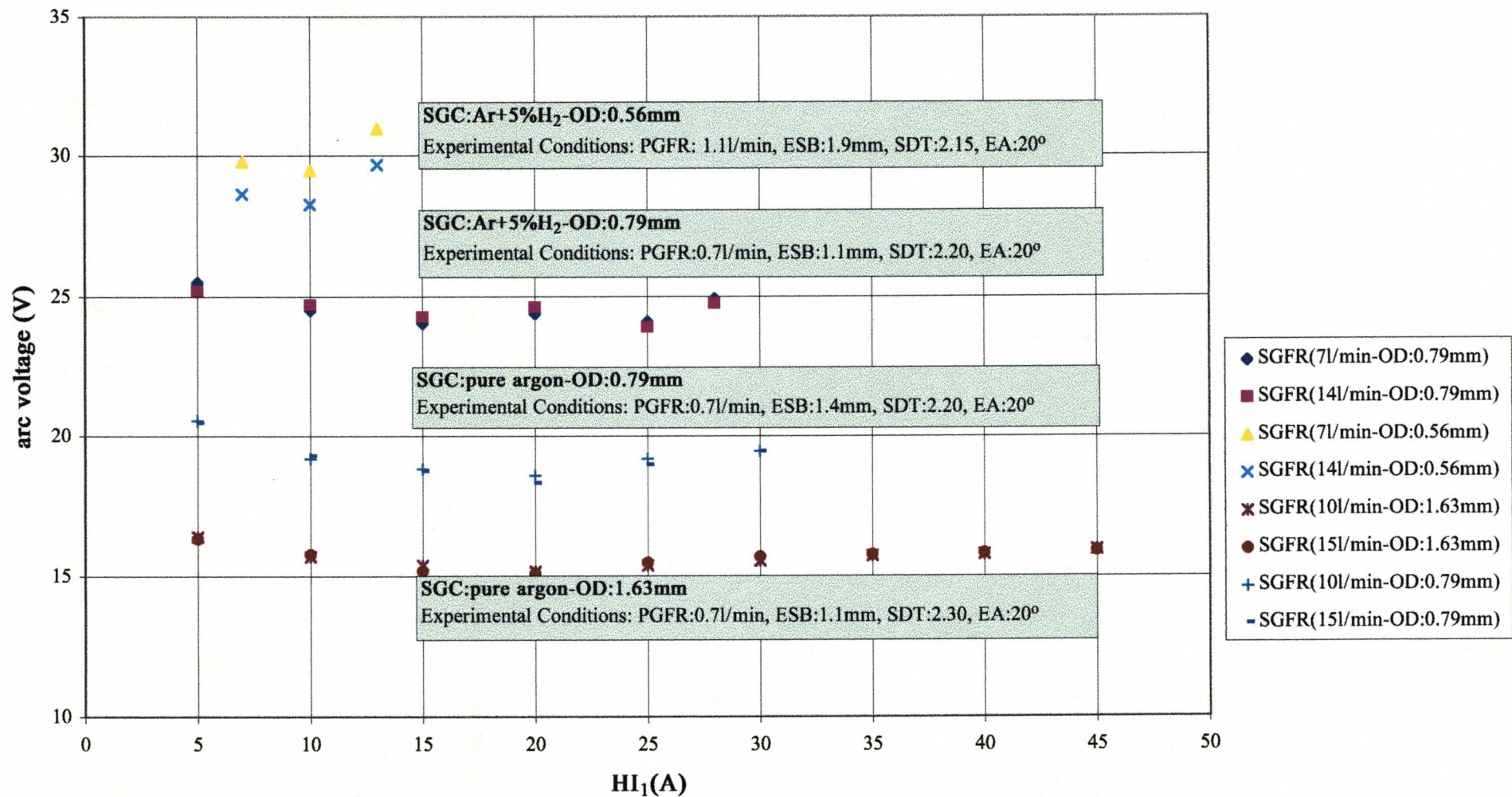


Figure 78: Influence of Shielding Gas Flow Rate (SGFR) on Arc Voltage for Two Different Shielding Gases (Pure Argon, Ar+5%H₂) and for Various Welding Currents (HI₁) (see Table D6, Appendix D for Results).

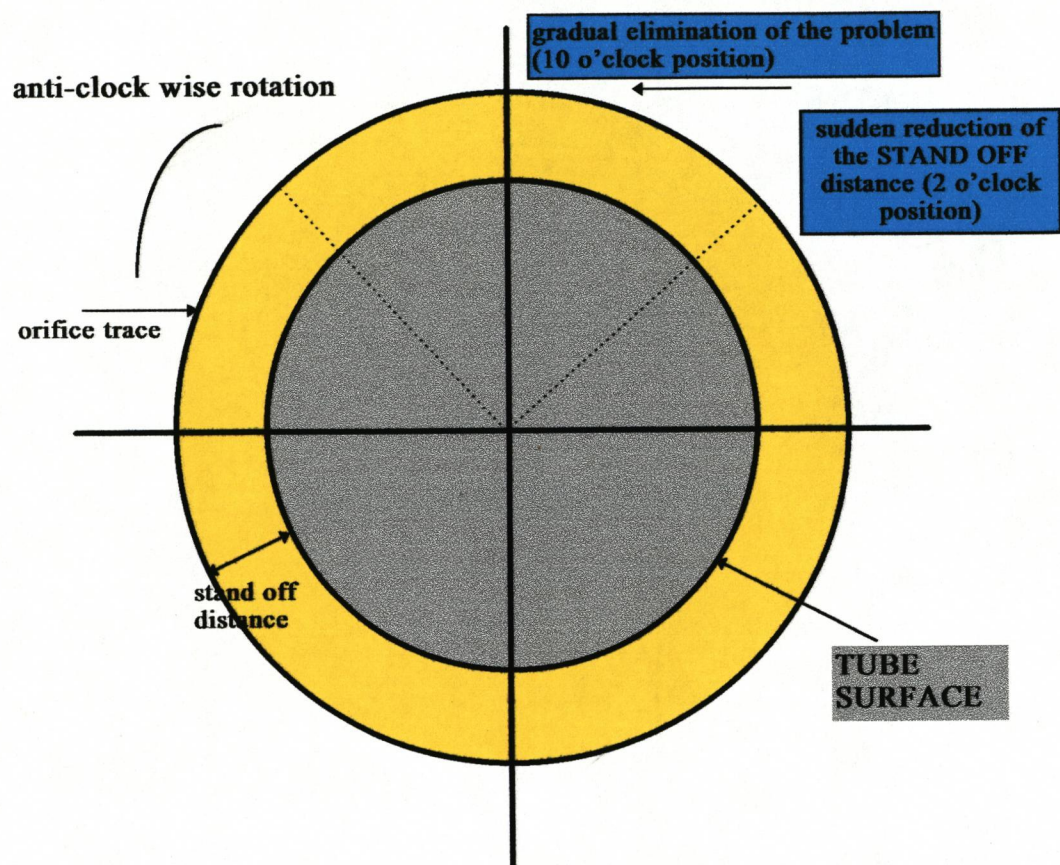


Figure 79: Sudden Reduction of the Stand Off Distance (SDT) at 2 o'clock Position and Gradual Recovery to its Original Value (10 o'clock position).

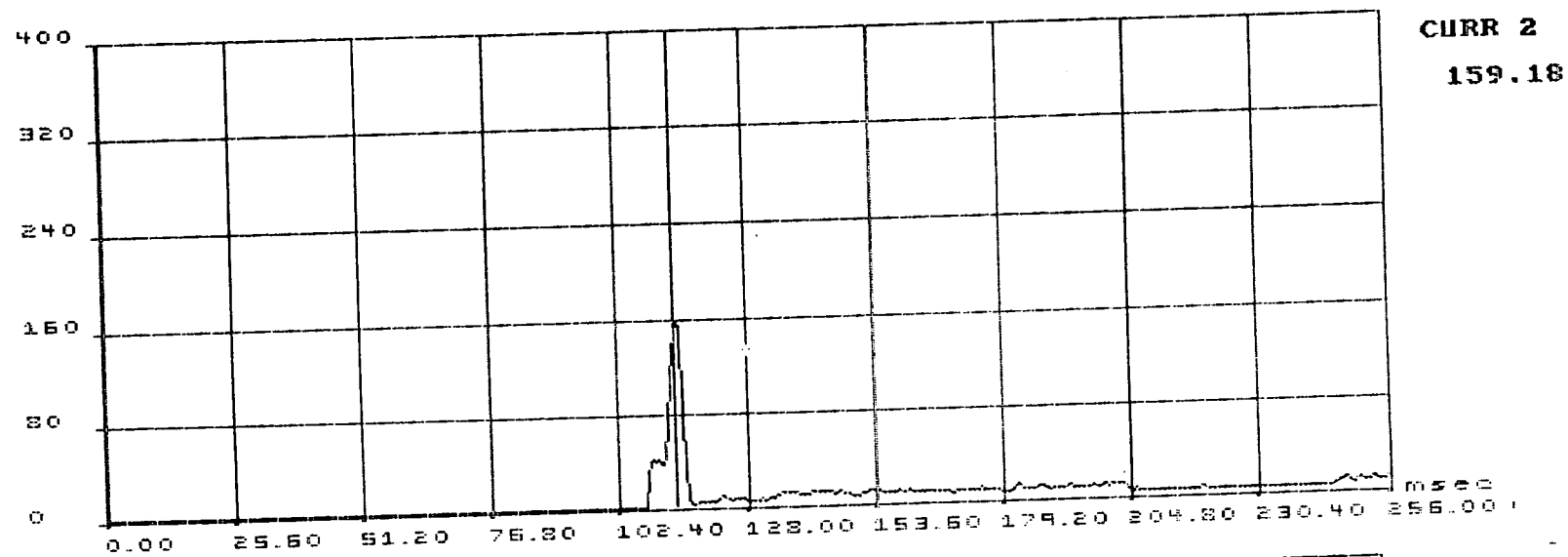
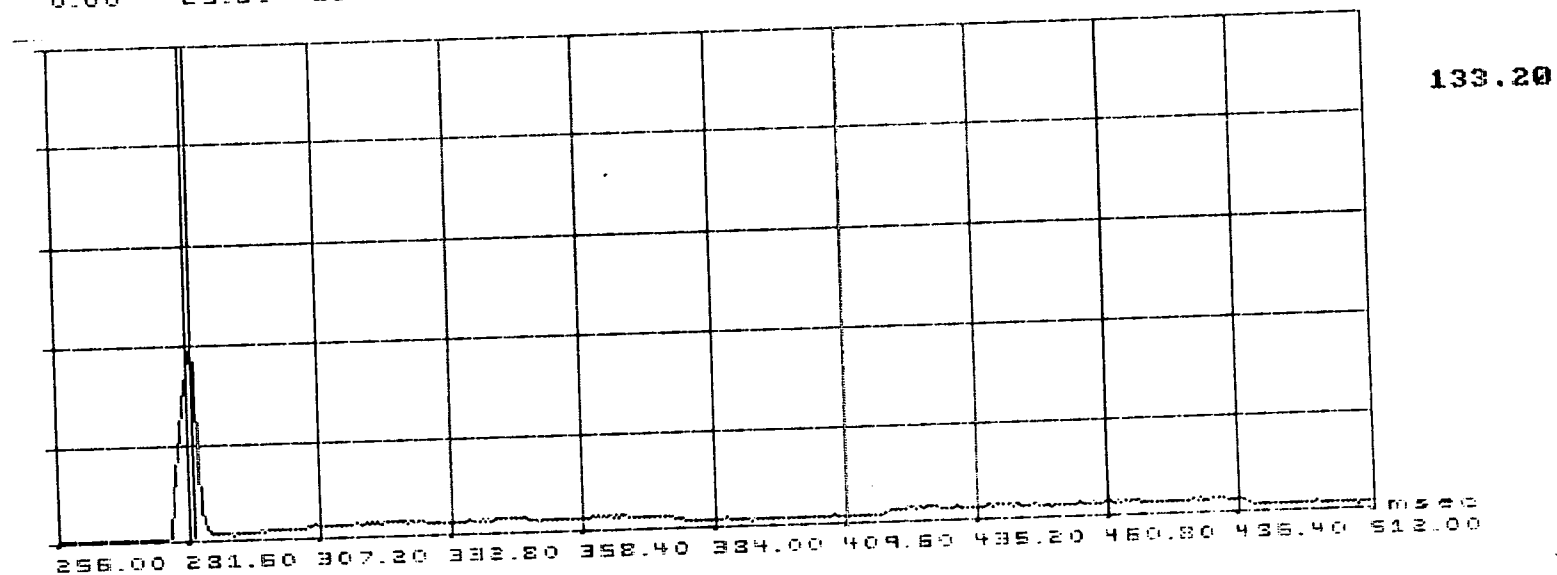


Figure 80: Welding Current malfunction identified during arc initiation in a number of trials.

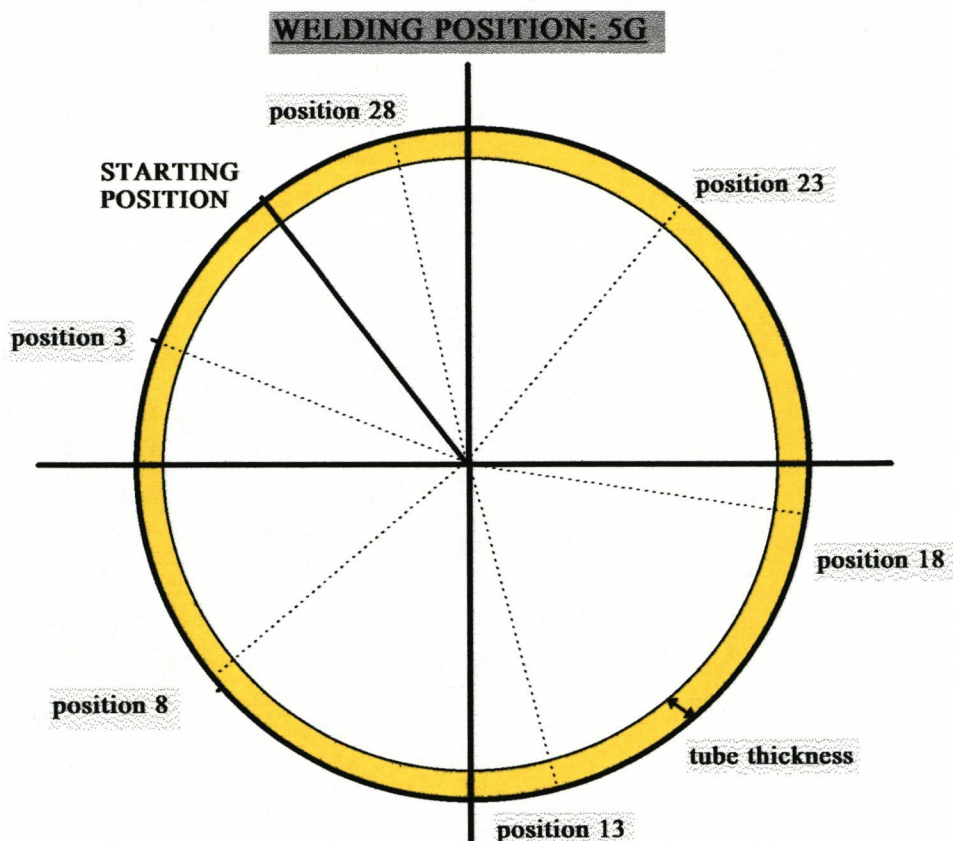


Figure 81a: Measurement Positions for Model Development of the Ti-3Al-2.5V Tubes (10mmX0.6mm).

[position 3: 3mm (0.19π) from starting position, position 8: 8mm (0.51π) from starting position, position 13: 13mm (0.83π) from starting position, position 18: 18mm (0.15π) from starting position, position 23: 23mm (1.47π) from starting position, position 28: 28mm (1.79π) from starting position].

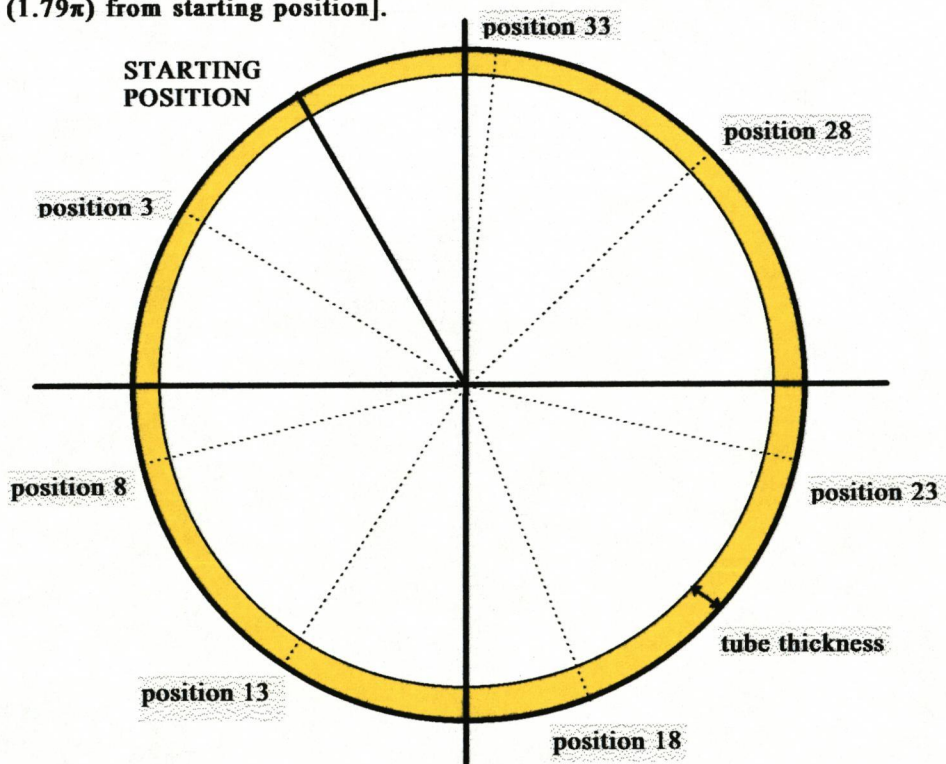


Figure 81b: Measurement Positions for Model Development of the 316L Tubes (a: 12.7mmX0.7mm, b: 12.7mmX1.25mm).

[position 3: 3mm (0.15π) from starting position, position 8: 8mm (0.40π) from starting position, position 13: 13mm (0.65π) from starting position, position 18: 18mm (0.90π) from starting position, position 23: 23mm (1.15π) from starting position, position 28: 28mm (1.40π) from starting position, position 33: 33mm (1.65π) from starting position].

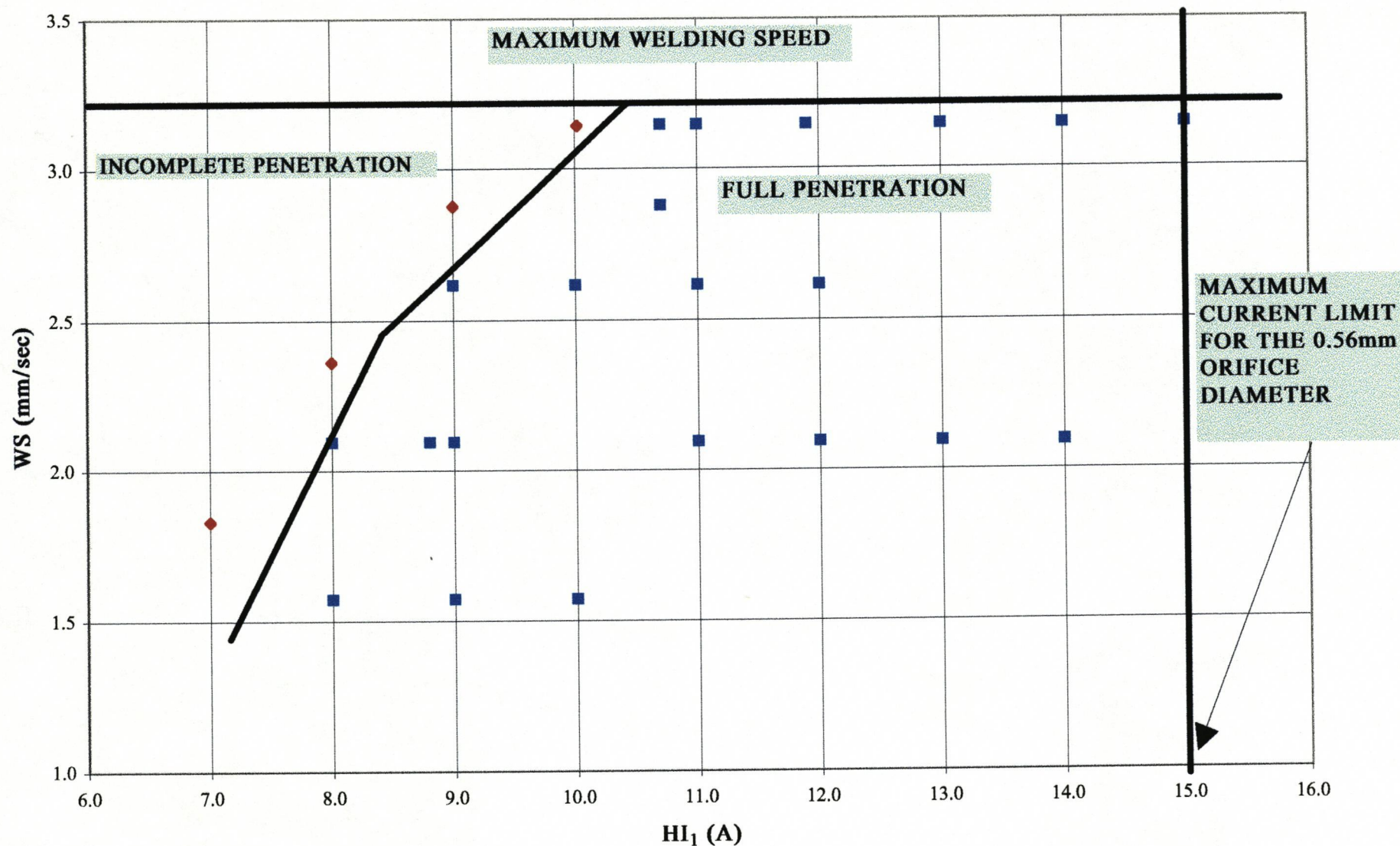


Figure 82: General Experimental Grid and Operational Envelope for the Melt-in Mode Plasma Welding of Ti-3Al-2.5V Tubes, Constructed Based on the Welding Current-Welding Speed Combinations Utilised (Orifice Diameter: 0.56mm).

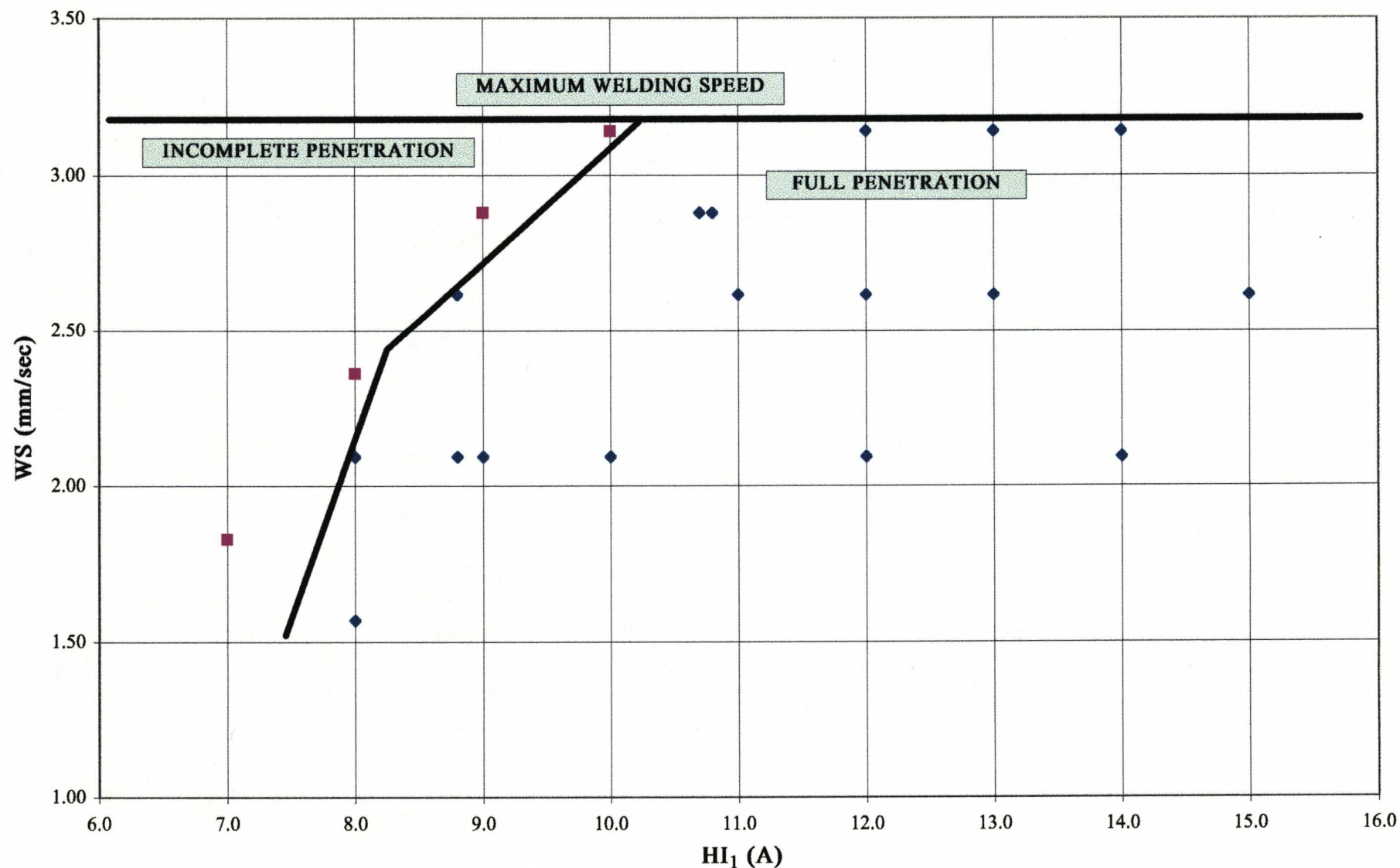


Figure 83: General Experimental Grid and Operational Envelope for Melt-In Mode Plasma Welding of Ti-3Al-2.5V Tubes, Constructed Based on the Welding Current-Welding Speed Combinations Utilised (Orifice Diameter: 0.79mm).

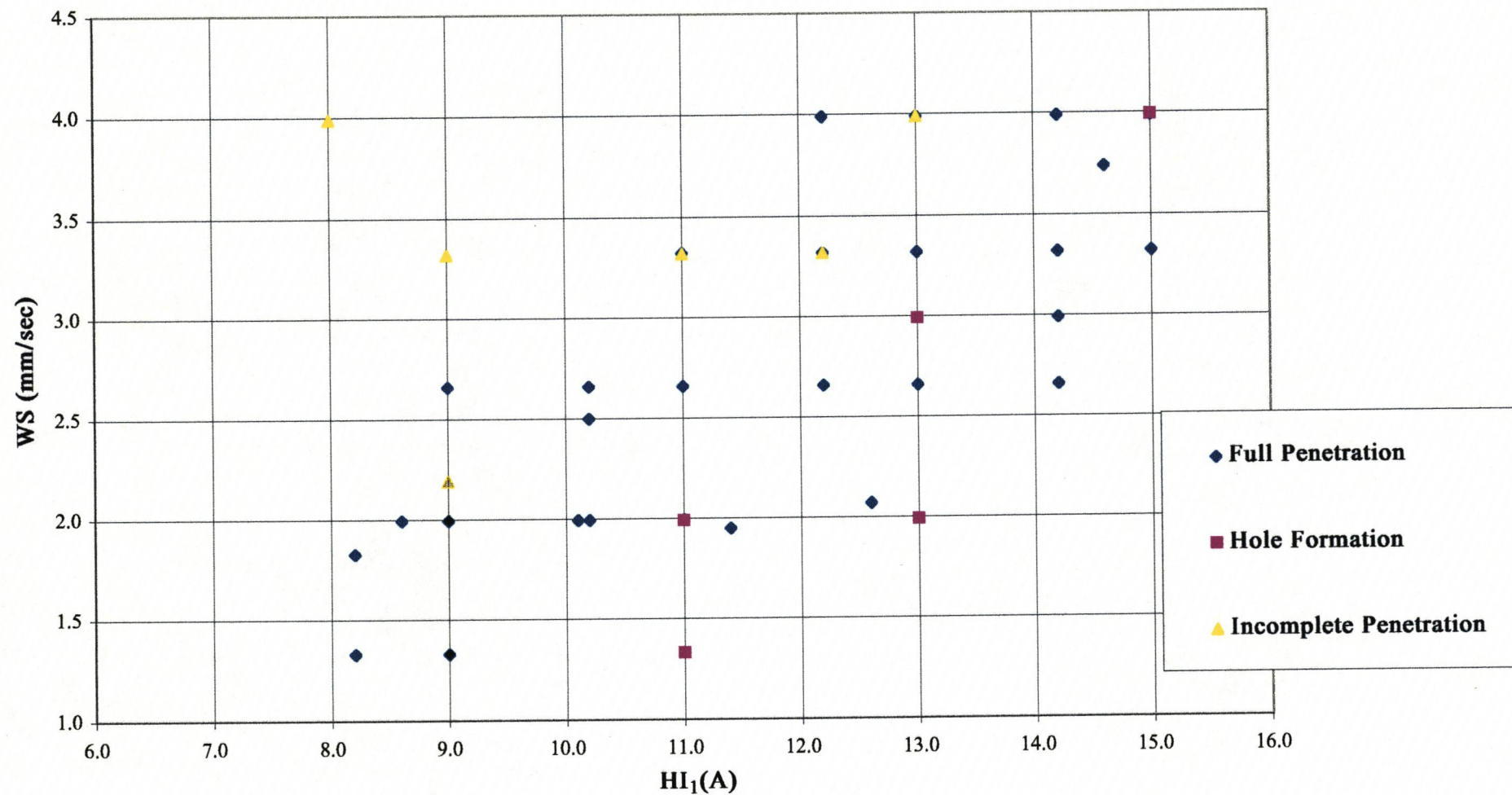


Figure 84: General Experimental Grid for Melt-In Mode Plasma Welding of 316L Tubes, Constructed Based on the Welding Current-Welding Speed Combinations Utilised.

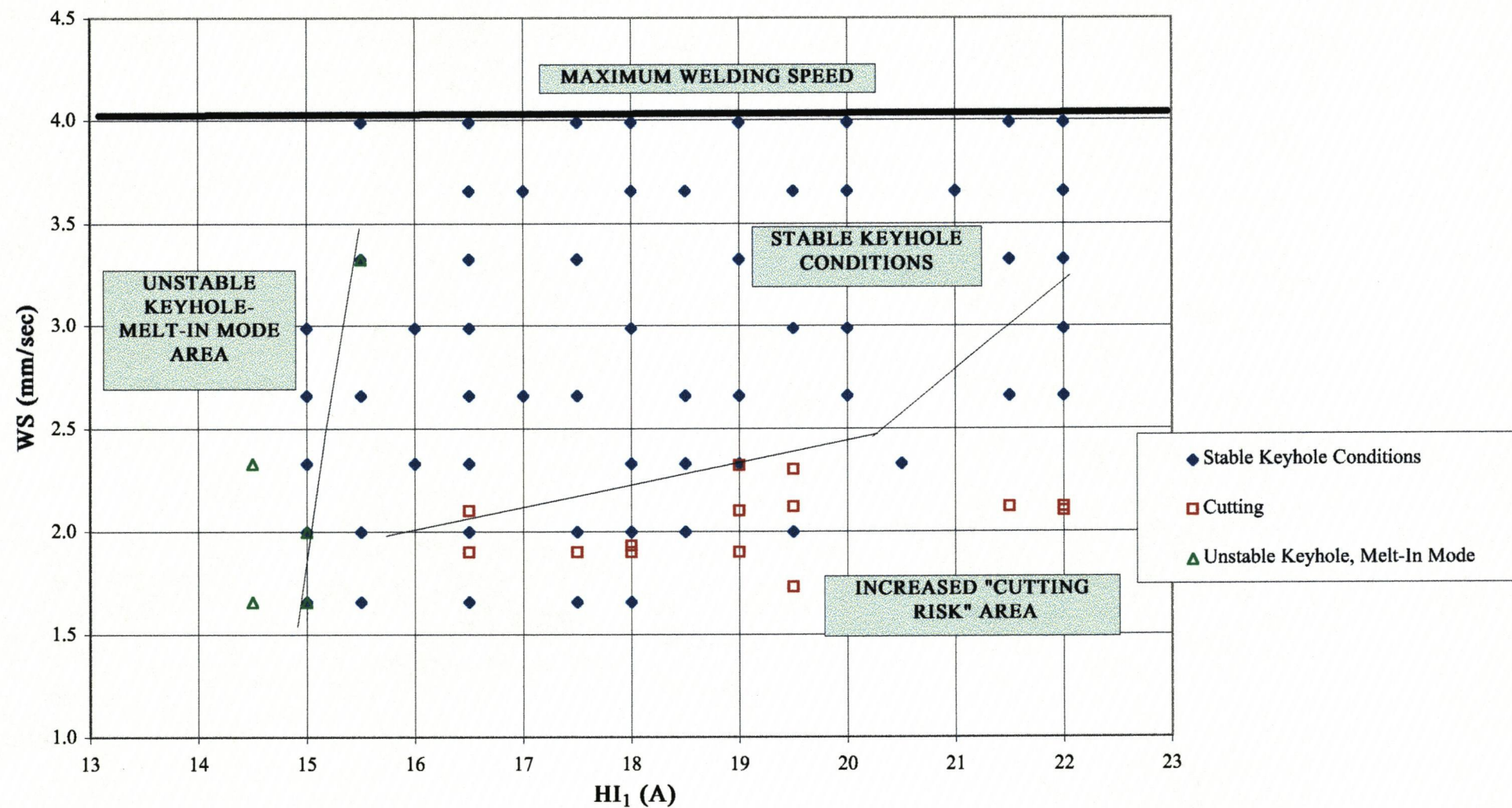
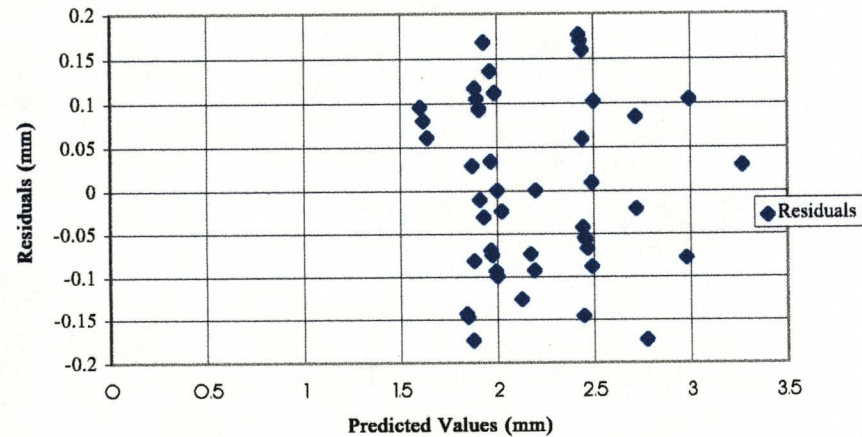
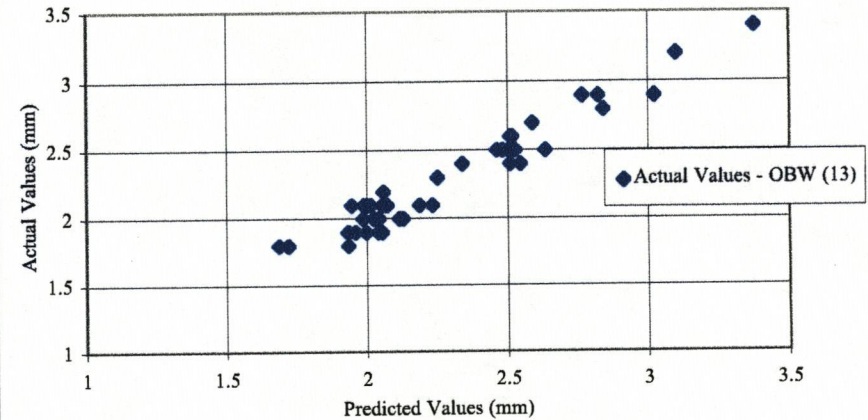


Figure 85: General Experimental Grid and Operational Envelope for Plasma Keyhole Welding of 316L Tubes, Constructed Based on the Welding Current-Welding Speed Combinations Utilised.

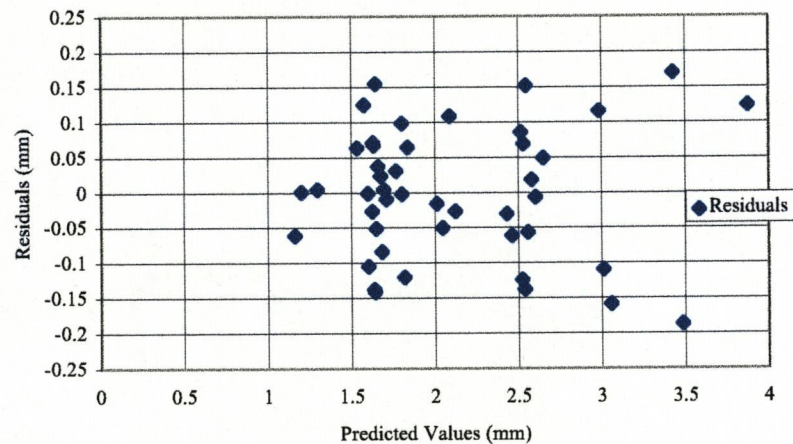
Predicted Values Versus Residuals for the Outer Bead Width at Position 8 (OD: 0.56mm)



Predicted Versus Actual Values for the Outer Bead Width at Position 13 (OD: 0.56mm)



Predicted Versus Residuals for the Inner Bead Width at Position 23 (OD: 0.56mm)



Predicted Versus Actual Values for the Inner Bead Width at Position 28 (OD: 0.56mm)

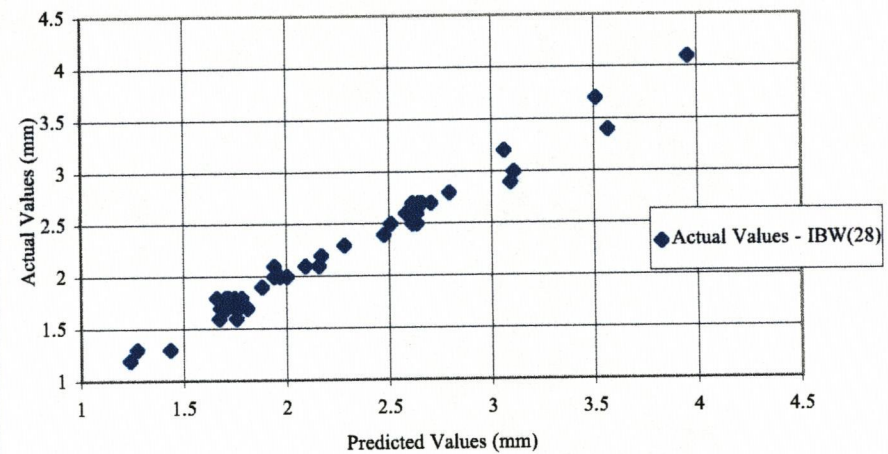
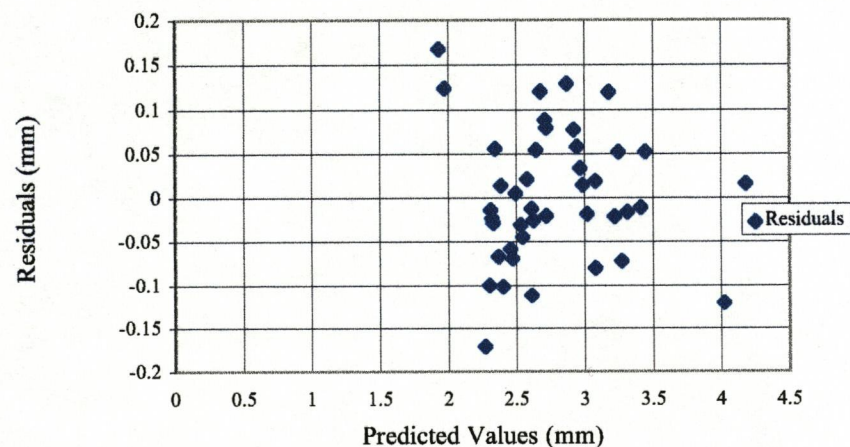
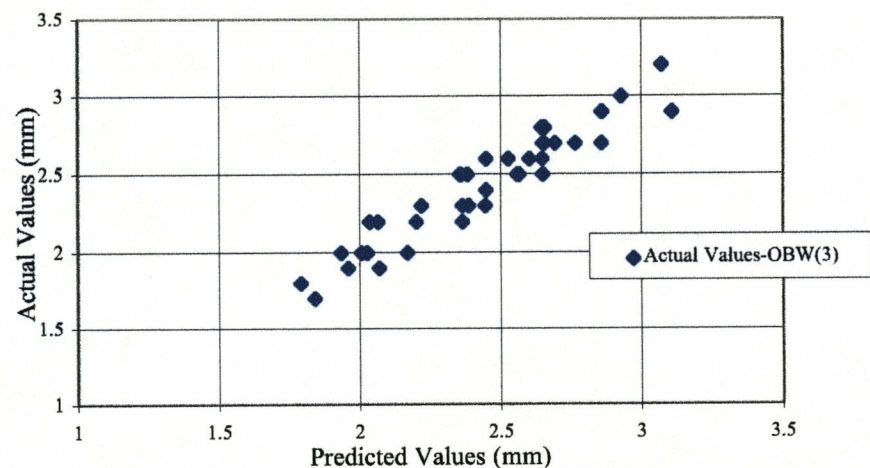


Figure 86a: Sample Plots of Predicted Versus Obtained Values and Residual Versus Predicted Values Used for Examination of Models Adequacy (Orifice Diameter: 0.56mm)

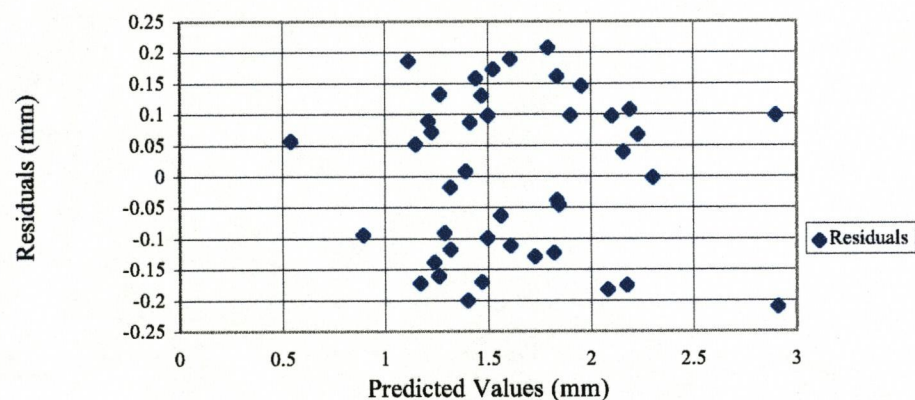
Predicted Versus Residuals for the Outer Bead Width at Position 23 (OD: 0.79mm)



Predicted Versus Actual Values for the Outer Bead Width at Position 3 (OD: 0.79mm)



Predicted Versus Residuals for the Inner Bead Width at Position 8 (OD: 0.79mm)



Predicted Versus Actual Values for the Inner Bead Width at Position 18 (OD: 0.79mm)

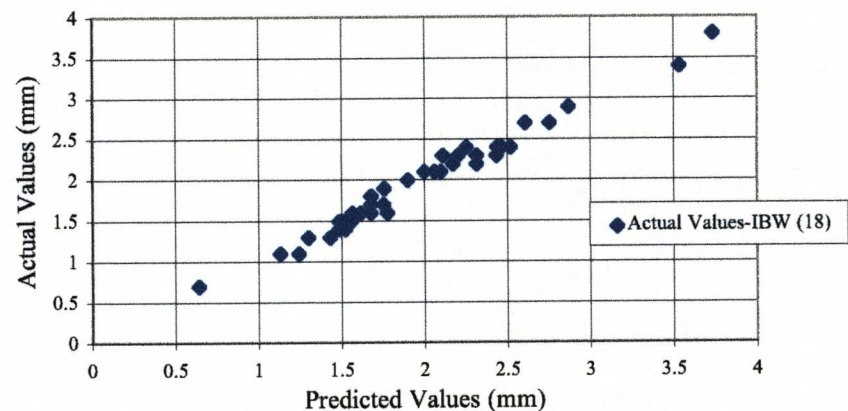
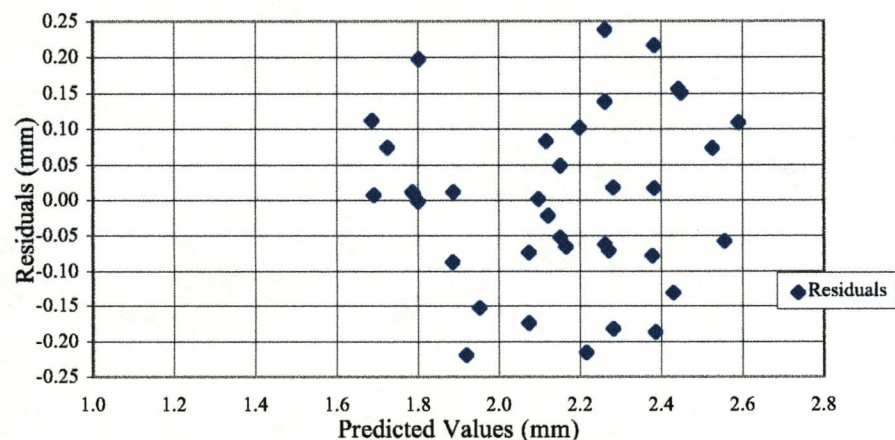
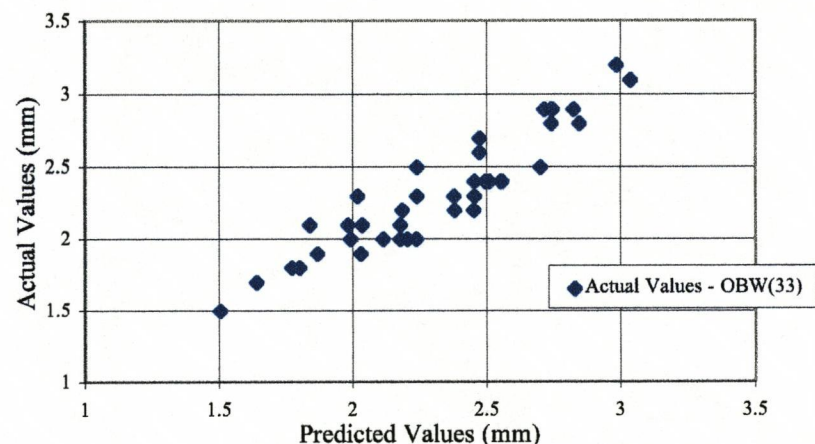


Figure 86b: Sample Plots of Predicted Versus Obtained Values and Residual Versus Predicted Values Used for Examination of Models Adequacy (Orifice Diameter: 0.79mm).

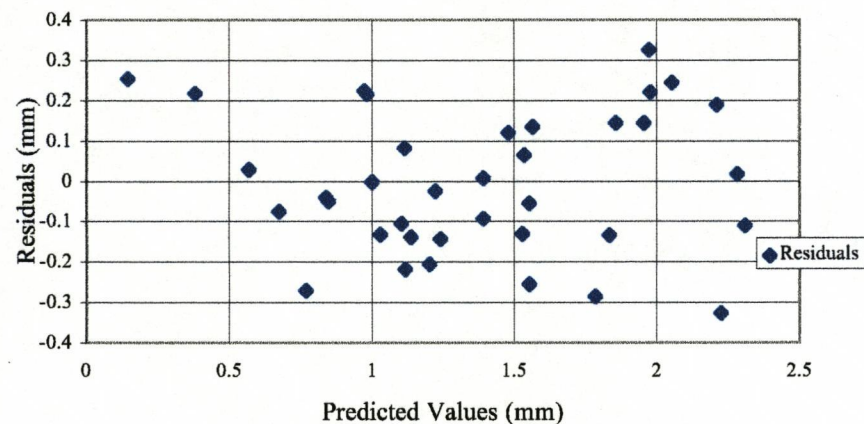
**Predicted Values Versus Residuals for the Outer
Bead Width at Position 3 (Melt-in Mode Welding of
A.S.S)**



**Predicted Values Versus Residuals for the Outer
Bead Width at Position 33 (Melt-In Mode Welding
of A.S.S)**



**Predicted Versus Residuals for the Inner Bead Width
at Position 13 (Melt-in Mode Welding of A.S.S)**



**Predicted Versus Actual Values for the Inner Bead
Width at Position 23 (Melt-in Mode Welding of
A.S.S)**

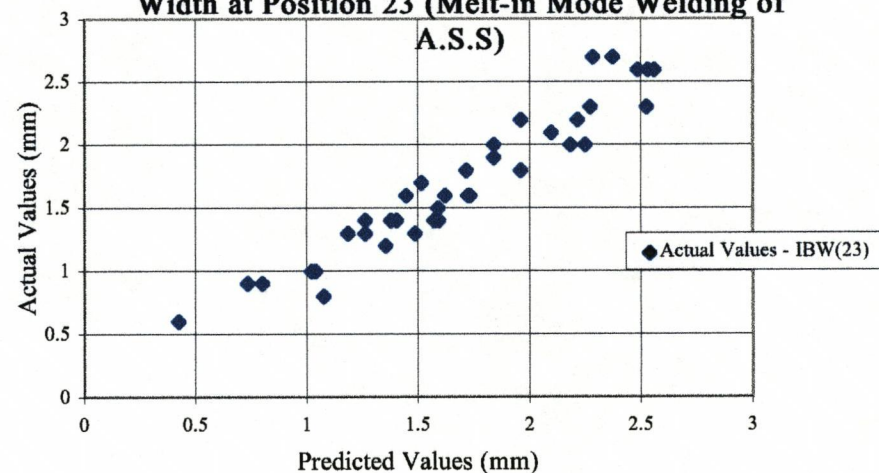
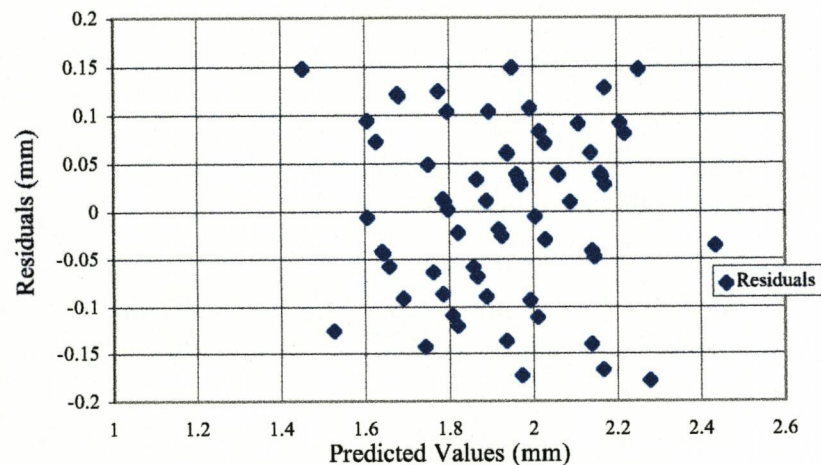
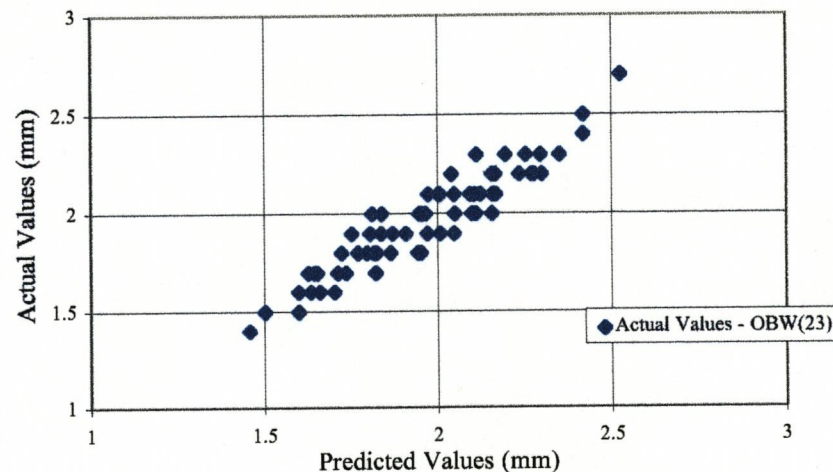


**Figure 87: Sample Plots of Predicted Versus Obtained Values and Residual Versus Predicted Values
Used for Examination of Models Adequacy in Plasma Welding of 316L Tubes (Melt-In Mode).**

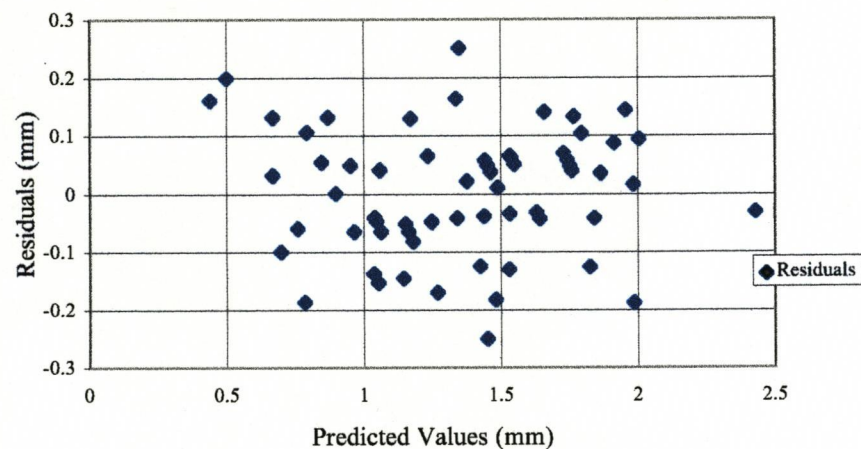
Predicted Versus Residuals for the Outer Bead Width at Position 8 (Keyhole Welding of A.S.S)



Predicted Versus Actual Values for the Outer Bead Width at Position 23 (Keyhole Welding Of A.S.S)



Predicted Versus Residuals for the Inner Bead Width at Position 13 (Keyhole Welding of A.S.S)



Predicted Versus Actual Values for the Inner Bead Width at Position 28 (Keyhole Welding of A.S.S)

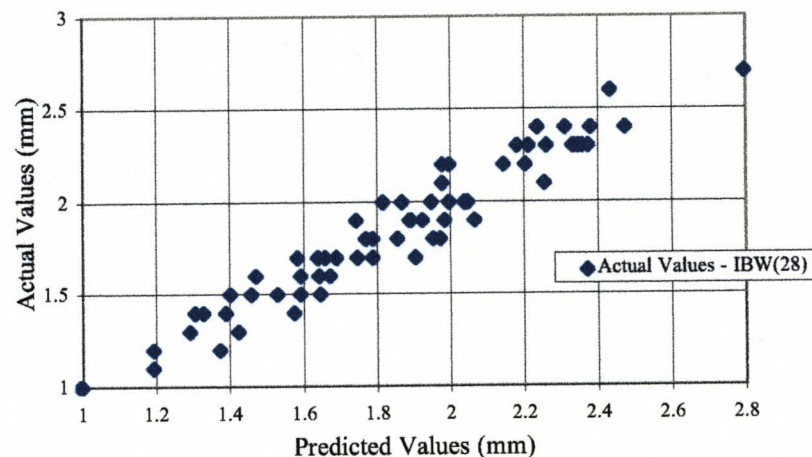
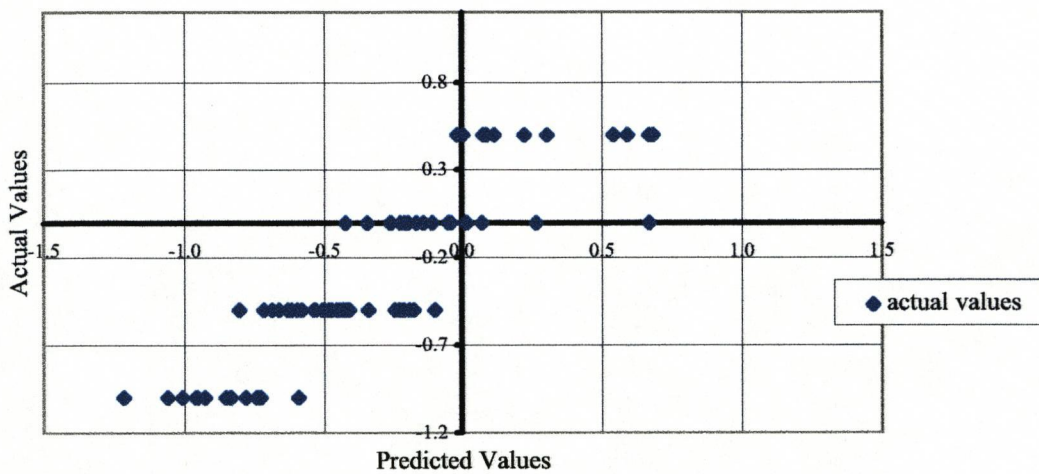
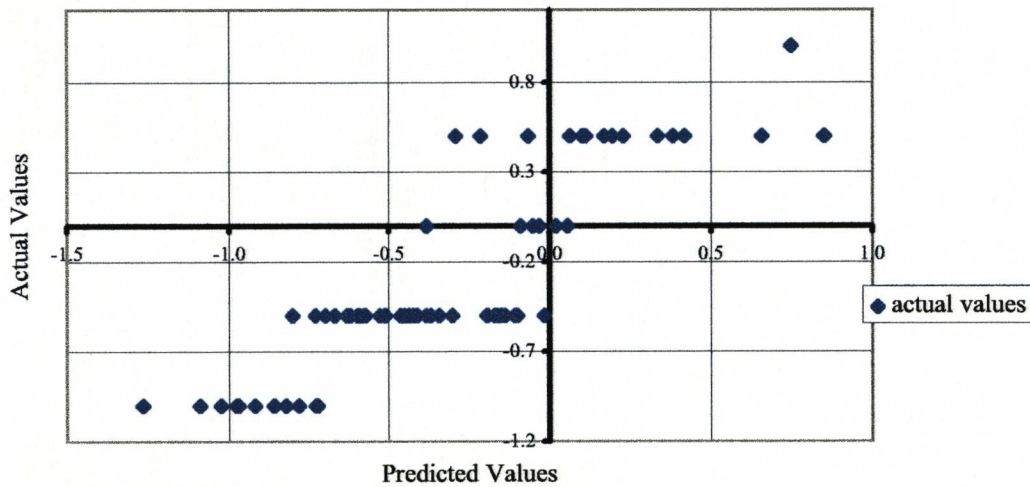


Figure 88: Sample Plots of Predicted Versus Obtained Values and Residual Versus Predicted Values Used for Examination of Models Adequacy in Plasma Welding of 316L Tubes (Keyhole Mode).

Predicted Versus Actual Values of the Outer Bead Width Undercut Probability at Position 8 (Keyhole Welding of A.S.S)



Predicted Versus Actual Values of the Outer Bead Width Undercut Probability at Position 18 (Keyhole Welding of A.S.S)



Predicted Versus Actual Values of the Outer Bead Width Undercut Probability at Position 28 (Keyhole Welding of A.S.S)

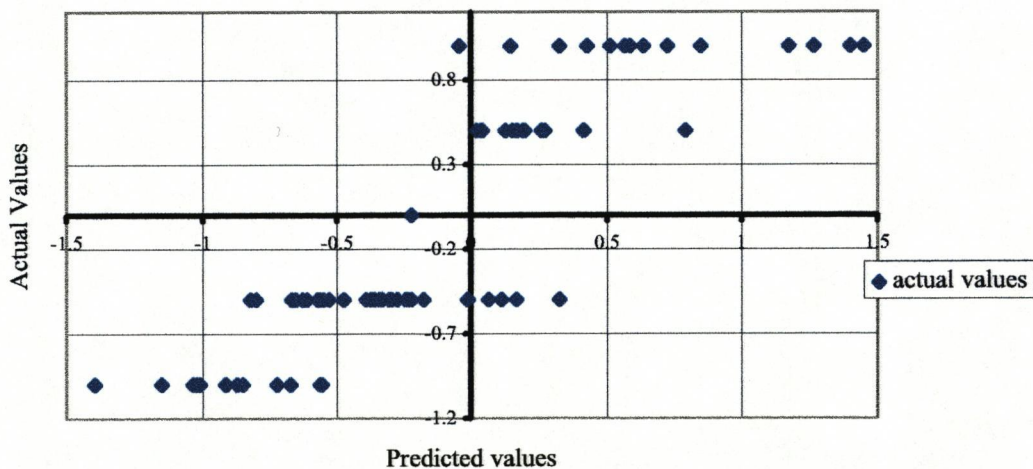


Figure 89: Sample Plots of Predicted Versus Obtained Values Used for Examination of Undercut Models Adequacy in Plasma Keyhole Welding of 316L Tubes.

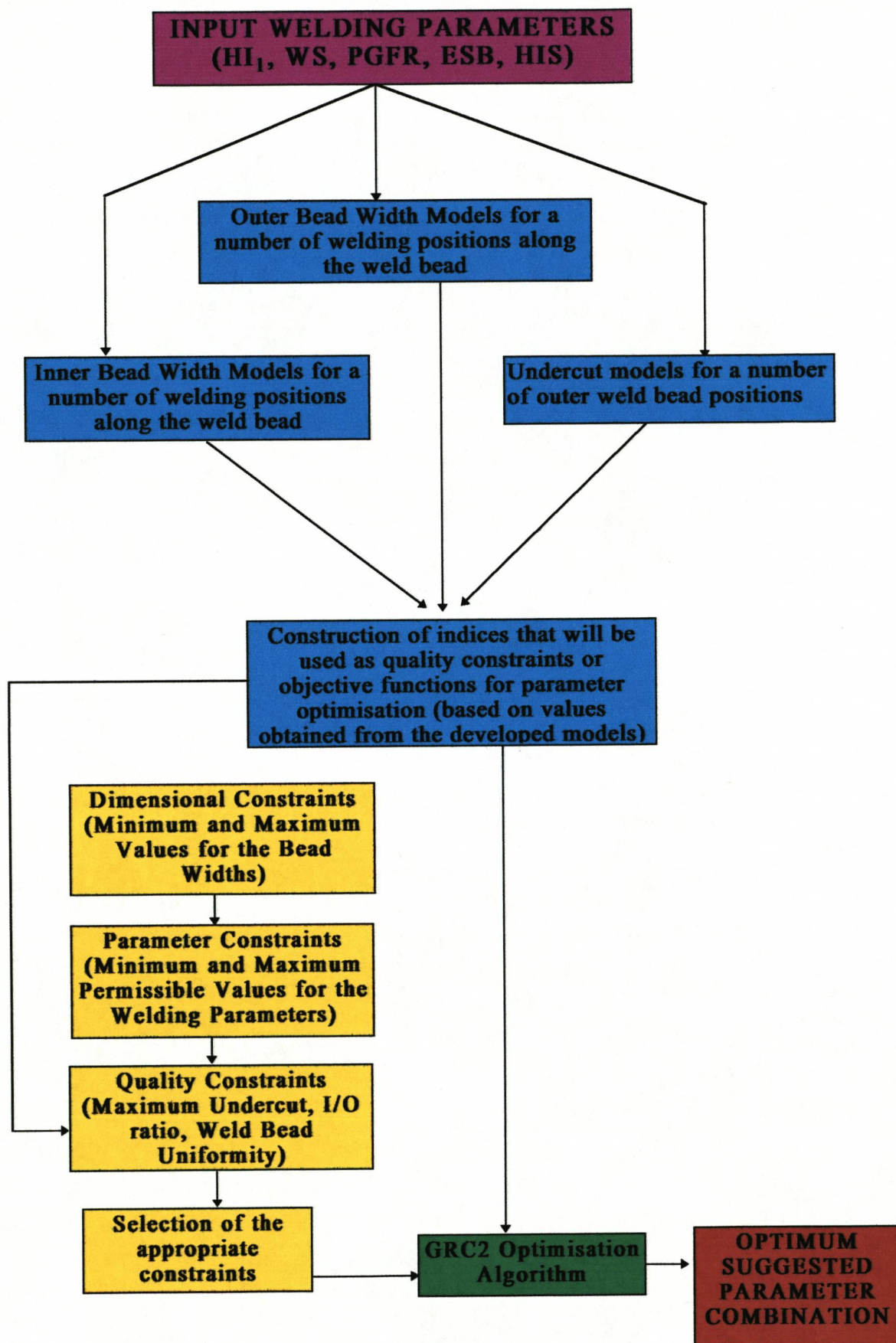
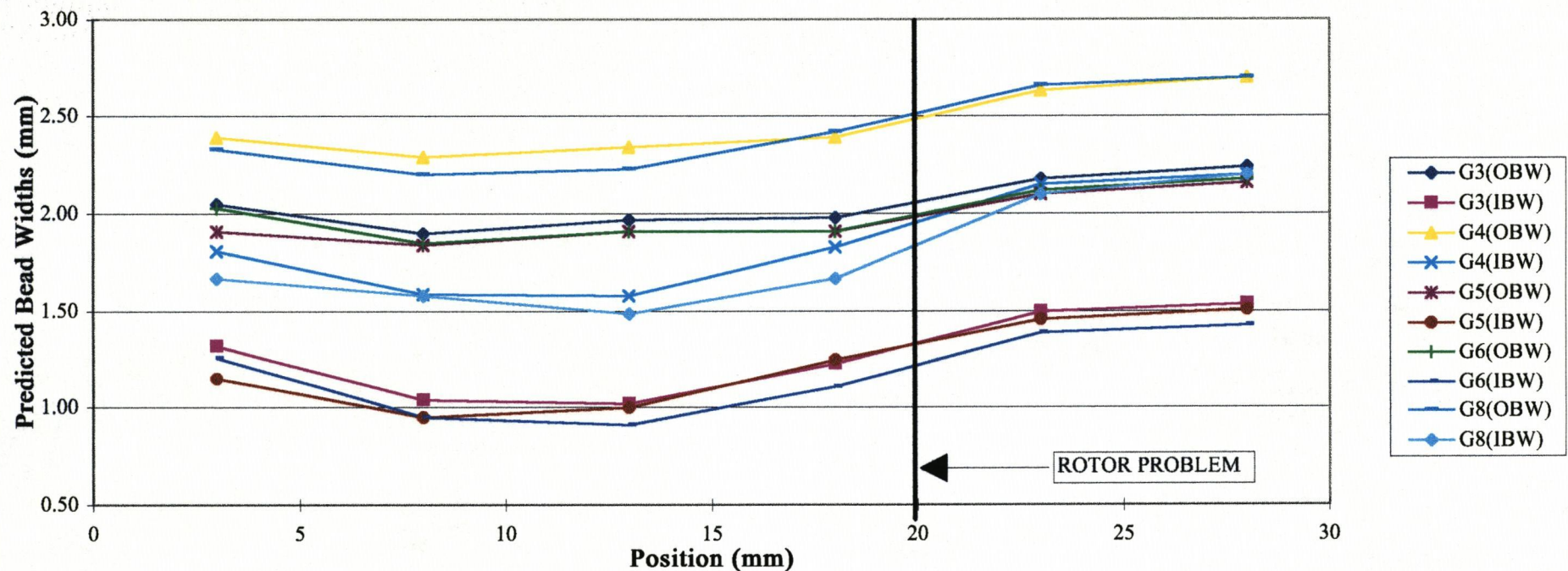
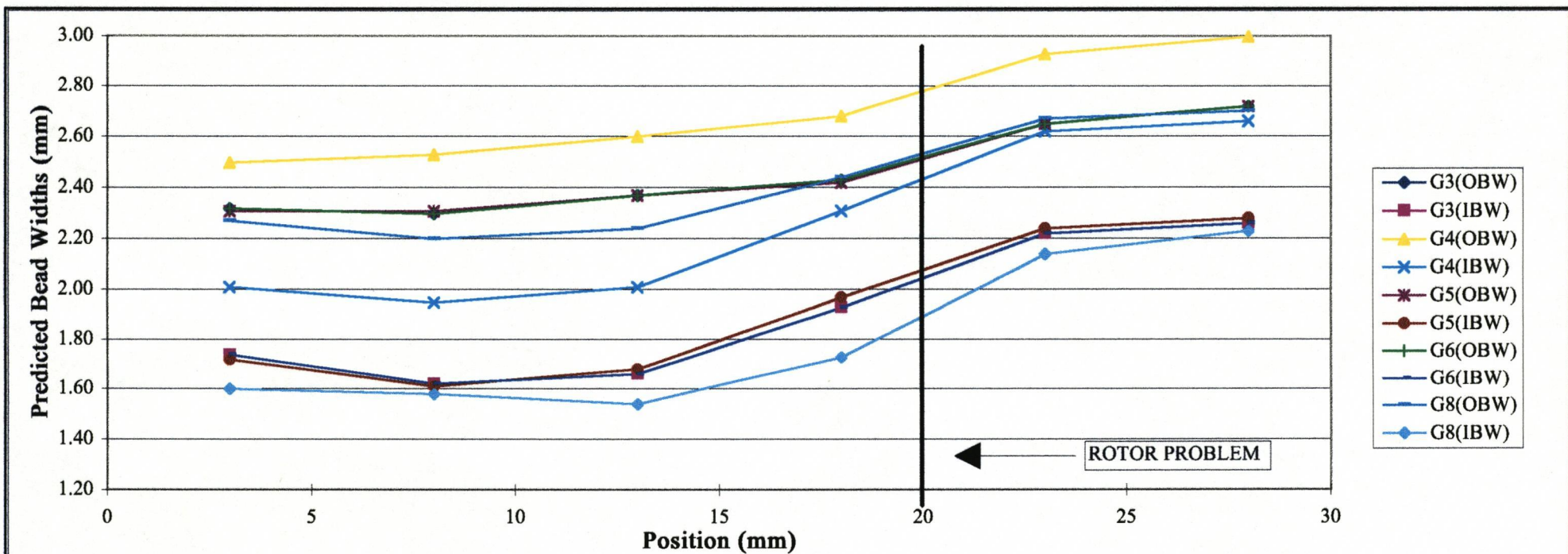


Figure 90: General Description of the Procedure Utilised for Optimisation of the Orbital Plasma Welding Process.



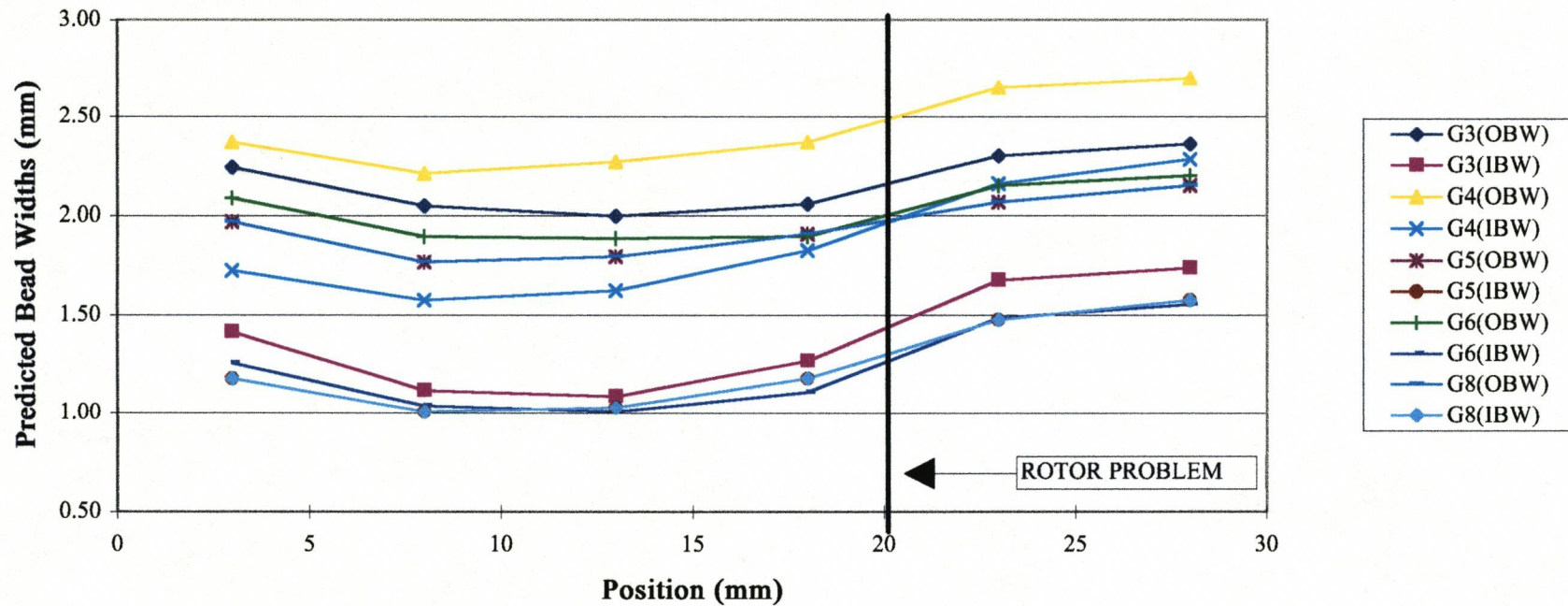
PARAMETRIC CONSTRAINTS (1st Set)						DIMENSIONAL CONSTRAINTS (1st Set)								
HI ₁ (8-14)	WS(1.57-3.14)	PGFR(0.3-1.3)	ESB(1.0-2.0)	DT*1st(20-40)		Outer Bead Width (OBW): 0.9mm-2.7mm Inner Bead Width (IBW): 0.9mm-2.7mm								
Optimum Recommended Parameter Combimations						Predicted Bead Widths for the Various Positions							RESULTS	
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	DT*1st(secA)	Position	3	8	13	18	23	28		
G3(OBW)	10.0	2.8	0.3	2.0	20	OBW	2.05	1.90	1.97	1.98	2.18	2.24	G3	6.40%
G3(IBW)						IBW	1.32	1.04	1.02	1.23	1.50	1.54		
G4(OBW)	11.8	3.0	0.3	2.0	20	OBW	2.39	2.29	2.34	2.39	2.63	2.70	G4	14.20%
G4(IBW)						IBW	1.81	1.59	1.58	1.83	2.15	2.20		
G5(OBW)	9.0	2.4	0.6	2.0	20	OBW	1.91	1.84	1.91	1.91	2.10	2.16	G5	0.31mm
G5(IBW)						IBW	1.15	0.95	1.00	1.25	1.46	1.51		
G6(OBW)	10.0	2.9	0.3	2.0	20	OBW	2.03	1.85	1.91	1.91	2.12	2.18	G6	0.52mm
G6(IBW)						IBW	1.26	0.95	0.91	1.11	1.39	1.43		
G8(OBW)	11.7	2.9	0.3	1.0	20	OBW	2.33	2.20	2.23	2.42	2.66	2.70	G8	0.18mm
G8(IBW)						IBW	1.67	1.58	1.49	1.67	2.10	2.20		

Figure 91: Optimum Recommended Parameter Combinations and Predicted Results for the First Set of Constraints (0.56mm Orifice Diameter).



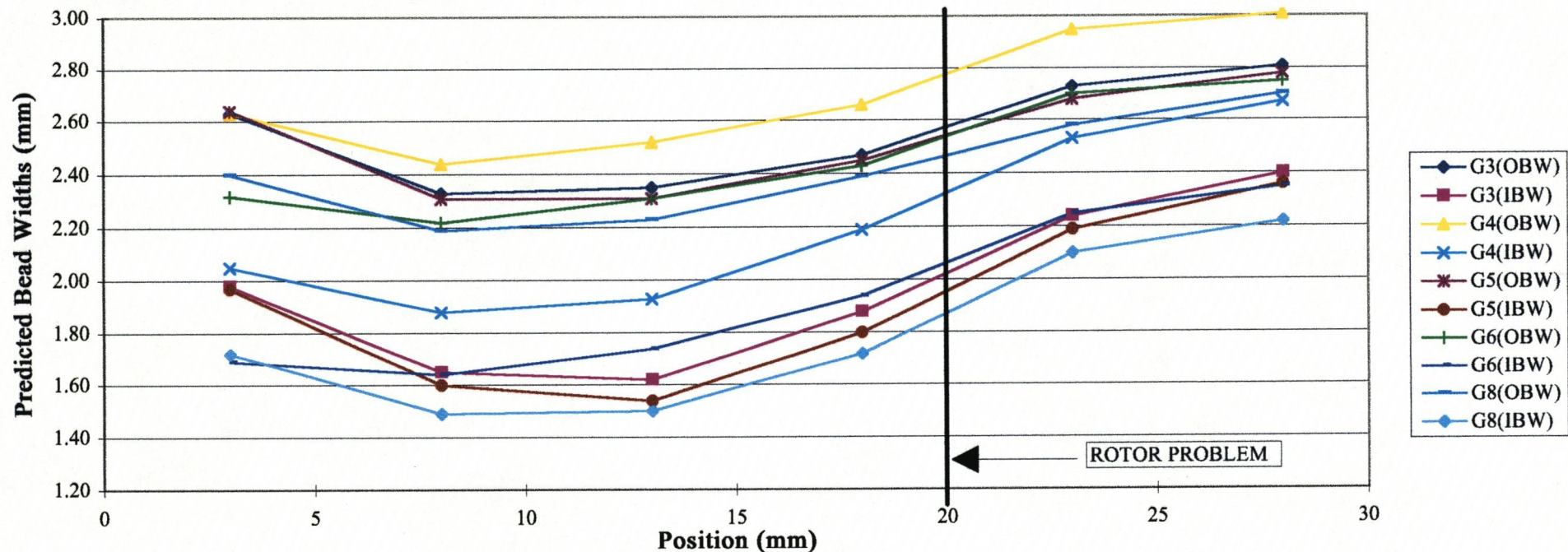
PARAMETRIC CONSTRAINTS (2nd Set)						DIMENSIONAL CONSTRAINTS (2nd Set)								
HI ₁ (11-14)	WS(1.57-2.50)	PGFR(0.3-1.3)	ESB(1.0-2.0)	DT*1st(20-40)		Outer Bead Width (OBW): 0.9mm-3.0mm Inner Bead Width (IBW): 0.9mm-3.0mm								
Optimum Recommended Parameter Combinations						Predicted Bead Widths for the Various Positions						RESULTS		
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	DT*1st(sec*A)	Position	3	8	13	18	23			28
G3(OBW)	11.0	2.5	0.3	2.0	20	OBW	2.32	2.30	2.37	2.43	2.65	2.72	G3	7.30%
G3(IBW)						IBW	1.74	1.62	1.66	1.93	2.22	2.26		
G4(OBW)	11.9	2.5	0.3	2.0	20	OBW	2.50	2.53	2.60	2.68	2.93	3.00	G4	14.20%
G4(IBW)						IBW	2.01	1.95	2.01	2.31	2.62	2.66		
G5(OBW)	11.0	2.5	0.5	2.0	20	OBW	2.31	2.31	2.37	2.42	2.65	2.72	G5	0.41mm
G5(IBW)						IBW	1.72	1.61	1.68	1.97	2.24	2.28		
G6(OBW)	11.0	2.5	0.3	2.0	20	OBW	2.32	2.30	2.37	2.43	2.65	2.72	G6	0.64mm
G6(IBW)						IBW	1.74	1.62	1.66	1.93	2.22	2.26		
G8(OBW)	11.0	2.5	0.3	1.0	20	OBW	2.27	2.20	2.24	2.44	2.67	2.70	G8	0.20mm
G8(IBW)						IBW	1.60	1.58	1.54	1.73	2.14	2.23		

Figure 92: Optimum Recommended Parameter Combinations and Predicted Results for the Second Set of Constraints (0.56mm Orifice Diameter)



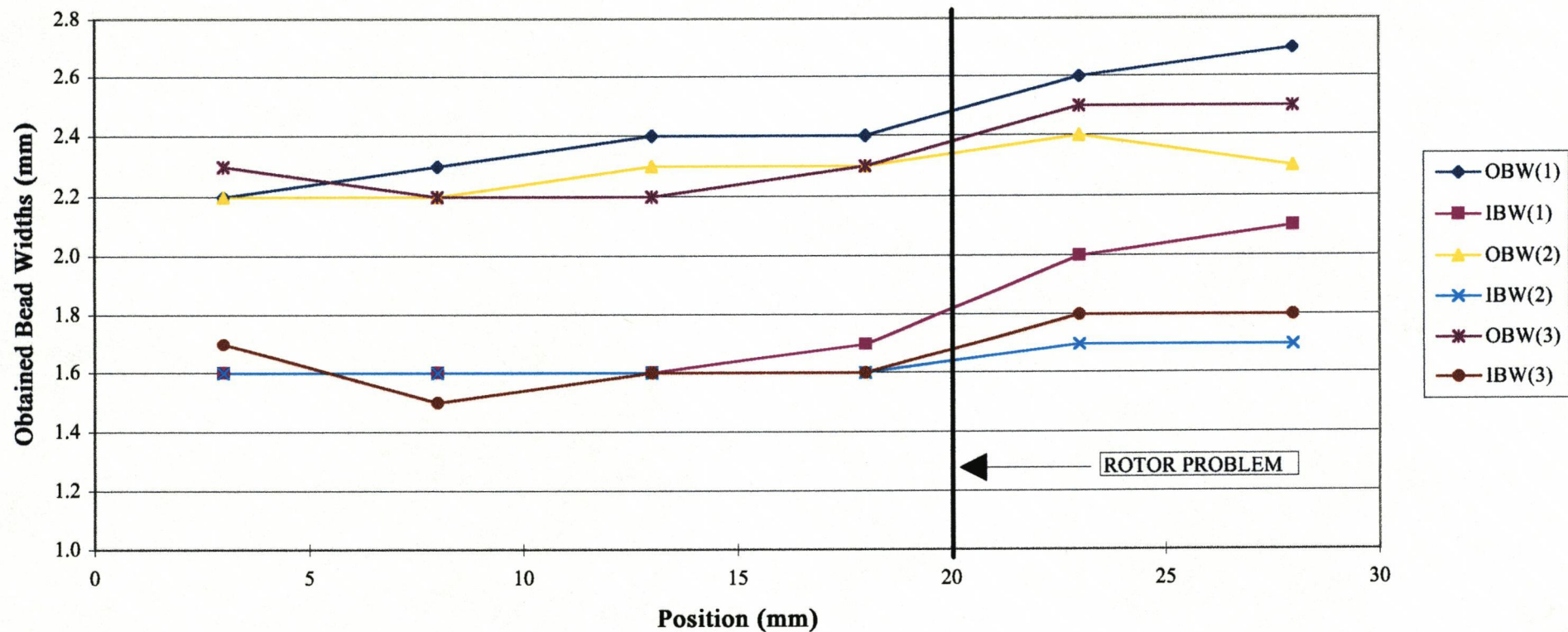
PARAMETRIC CONSTRAINTS (1st Set)						DIMENSIONAL CONSTRAINTS (1st Set)								
HI ₁ (8-14)	WS(1.57-3.14)	PGFR(0.3-0.9)	ESB(1.4-2.2)	DT*1st(20-40)		Outer Bead Width (OBW): 0.9mm-2.7mm Inner Bead Width (IBW): 0.9mm-2.7mm								
Optimum Recommended Parameter Combimations						Predicted Bead Widths for the Various Positions						RESULTS		
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	DT*1st(secA)	Positions	3	8	13	18	23	28		
G3(OBW)	11.0	3.1	0.3	1.9	24	OBW	2.24	2.05	2.00	2.06	2.30	2.36	G3	7.00%
G3(IBW)						IBW	1.42	1.12	1.09	1.27	1.68	1.74		
G4(OBW)	11.4	2.6	0.3	2.2	25	OBW	2.37	2.21	2.27	2.37	2.65	2.70	G4	15.30%
G4(IBW)						IBW	1.73	1.58	1.63	1.83	2.16	2.28		
G5(OBW)	9.0	2.3	0.7	2.2	21	OBW	1.97	1.77	1.80	1.91	2.07	2.15	G5	0.38mm
G5(IBW)						IBW	1.18	1.01	1.03	1.18	1.48	1.58		
G6(OBW)	11.0	3.1	0.3	2.2	20	OBW	2.09	1.90	1.89	1.90	2.15	2.20	G6	0.55mm
G6(IBW)						IBW	1.26	1.04	1.01	1.11	1.49	1.56		
G8(OBW)	9.0	2.3	0.7	2.2	21	OBW	1.97	1.77	1.80	1.91	2.07	2.15	G8	0.31mm
G8(IBW)						IBW	1.18	1.01	1.03	1.18	1.48	1.58		

Figure 93: Optimum Recommended Parameter Combinations and Predicted Results for the First Set of Constraints (0.79mm Orifice Diameter)



PARAMETRIC CONSTRAINTS (2nd Set)						DIMENSIONAL CONSTRAINTS (2nd Set)								
HI ₁ (11-14)	WS(1.57-2.50)	PGFR(0.3-0.9)	ESB(1.4-2.2)	DT*1st(20-40)		Outer Bead Width (OBW): 0.9mm-3.0mm Inner Bead Width (IBW): 0.9mm-3.0mm								
Optimum Recommended Parameter Combimations						Predicted Bead Widths for the Various Positions						RESULTS		
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	DT*1st(sec*A)	Position	3	8	13	18	23	28		
G3(OBW)	11.0	2.5	0.5	2.2	39	OBW	2.63	2.33	2.35	2.47	2.73	2.81	G3	7.80%
G3(IBW)						IBW	1.98	1.65	1.62	1.88	2.24	2.40		
G4(OBW)	11.6	2.5	0.3	2.2	32	OBW	2.63	2.44	2.52	2.66	2.95	3.01	G4	14.80%
G4(IBW)						IBW	2.05	1.88	1.93	2.19	2.53	2.67		
G5(OBW)	11.0	2.5	0.7	2.2	40	OBW	2.64	2.31	2.31	2.45	2.68	2.78	G5	0.47mm
G5(IBW)						IBW	1.97	1.60	1.54	1.80	2.19	2.36		
G6(OBW)	11.0	2.5	0.3	2.2	20	OBW	2.32	2.22	2.31	2.43	2.70	2.75	G6	0.71mm
G6(IBW)						IBW	1.69	1.64	1.74	1.94	2.25	2.35		
G8(OBW)	11.0	2.5	0.9	2.2	25	OBW	2.40	2.19	2.23	2.39	2.58	2.70	G8	0.23mm
G8(IBW)						IBW	1.72	1.49	1.50	1.72	2.10	2.22		

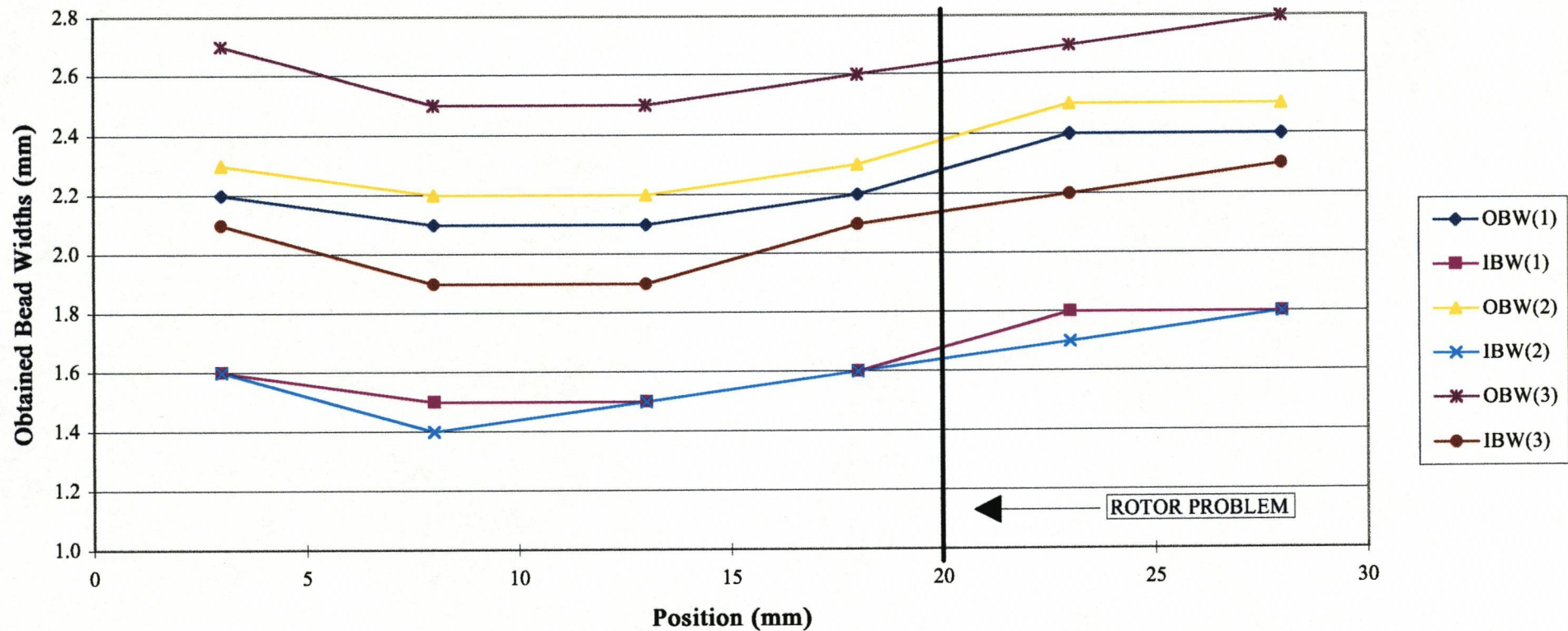
Figure 94: Optimum Recommended Parameter Combinations and Predicted Results for the Second Set of Constraints (0.79mm Orifice Diameter)



No	Starting Segment					1st Segment					2nd Segment					Obtained Bead Widths						
	Ist	WS	PGFR	ESB	DT	HI ₁	WS	PGFR	ESB	DUR	HI ₁	WS	PGFR	ESB	DUR	Trial	3	8	13	18	23	28
1	11.0	0.00	0.3	2.0	2.0	11.0	2.50	0.3	1.0	6.0	10.0	2.50	0.3	1.0	6.0	OBW(1	2.2	2.3	2.4	2.4	2.6	2.7
																IBW(1)	1.6	1.6	1.6	1.7	2.0	2.1
2	10.0	0.00	0.3	2.0	2.0	10.5	2.50	0.3	2.0	6.0	9.5	2.50	0.2	2.0	6.0	OBW(2	2.2	2.2	2.3	2.3	2.4	2.3
																IBW(2)	1.6	1.6	1.6	1.6	1.7	1.7
3	10.0	0.00	0.5	1.7	2.0	12.0	3.00	0.5	1.7	5.5	10.5	3.00	0.5	1.7	5.5	OBW(3	2.3	2.2	2.2	2.3	2.5	2.5
																IBW(3)	1.7	1.5	1.6	1.6	1.8	1.8

where: Ist: Average Welding Current Before the Initiation of Torch Rotation (in Amps)
HI₁: Average Welding Current During the Torch Rotation (in Amps)
WS: Welding Speed (in mm/sec) PGFR : Plasma Gas Flow Rate (in l/min) DUR: Duration of Segment (in sec)
DT: Time Period Between Arc Initiation and Initiation of Torch Rotation (in sec) ESB: Electrode Set Back Distance (in mm)
OBW: Outer Bead Width (in mm) IBW: Inner Bead Width (in mm)

Figure 95: Three Segments Optimisation Procedures and Obtained Results for the 0.56mm Orifice Diameter (Ti-3Al-2.5V Tube Welding).



No	Starting Segment					1st Segment					2nd Segment					Obtained Bead Widths						
	Ist	WS	PGFR	ESB	DT	HI ₁	WS	PGFR	ESB	DUR	HI ₁	WS	PGFR	ESB	DUR	Trial	3	8	13	18	23	28
1	10.0	0.00	0.3	2.0	2.4	10.5	2.50	0.3	2.0	6.0	9.5	2.50	0.3	2.0	6.0	OBW(1)	2.2	2.1	2.1	2.2	2.4	2.4
																IBW(1)	1.6	1.5	1.5	1.6	1.8	1.8
2	10.0	0.00	0.3	2.0	2.9	10.0	2.20	0.3	2.0	7.0	9.0	2.20	0.3	2.0	7.0	OBW(2)	2.3	2.2	2.2	2.3	2.5	2.5
																IBW(2)	1.6	1.4	1.5	1.6	1.7	1.8
3	10.0	0.00	0.3	2.2	3.9	11.5	2.50	0.3	2.2	6.0	10.0	2.50	0.3	2.2	6.0	OBW(3)	2.7	2.5	2.5	2.6	2.7	2.8
																IBW(3)	2.1	1.9	1.9	2.1	2.2	2.3

where: Ist: Average Welding Current Before the Initiation of Torch Rotation (in Amps)

HI₁: Average Welding Current During the Torch Rotation (in Amps)

WS: Welding Speed (in mm/sec)

PGFR : Plasma Gas Flow Rate (in l/min)

DT: Time Period Between Arc Initiation and Initiation of Torch Rotation (in sec)

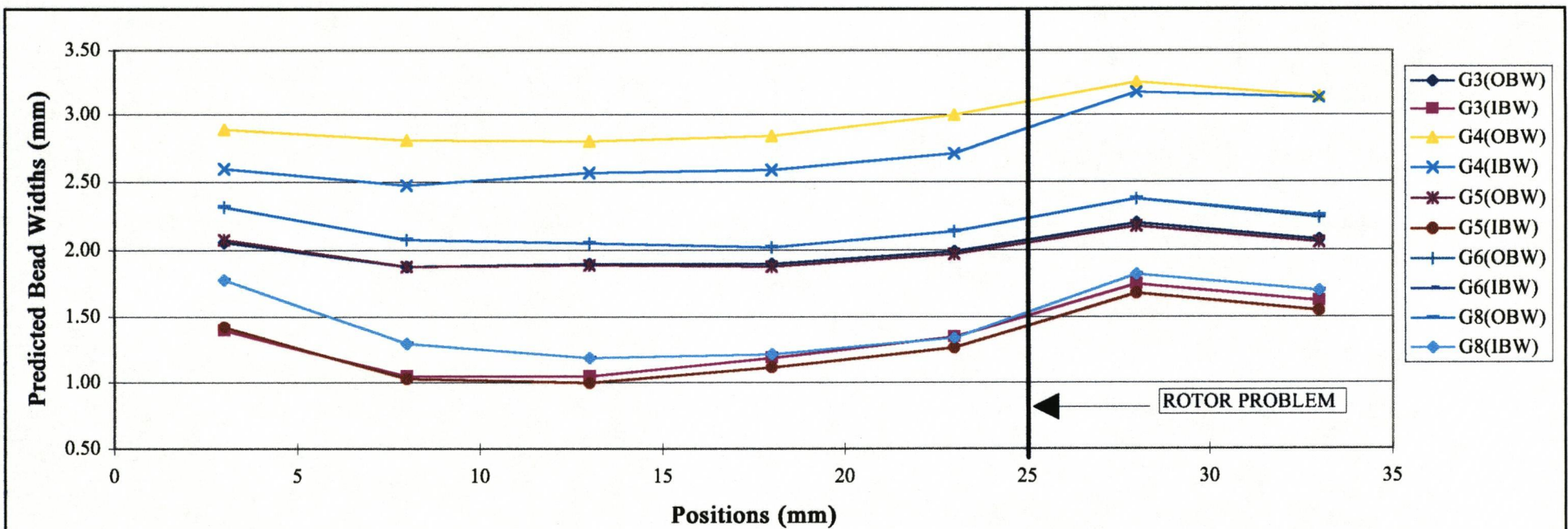
DUR: Duration of Segment (in sec)

ESB: Electrode Set Back Distance (in mm)

OBW: Outer Bead Width (in mm)

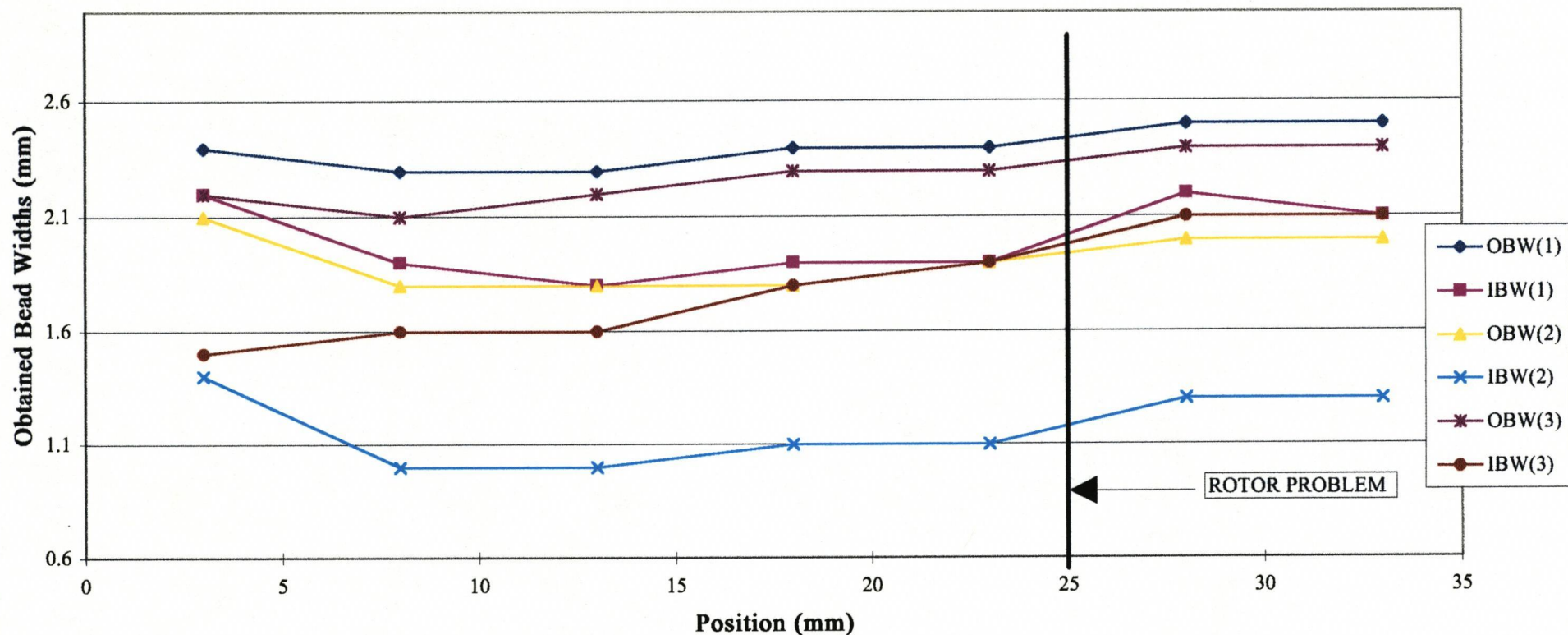
IBW: Inner Bead Width (in mm)

Figure 96: Three Segments Optimisation Procedures and Obtained Results for the 0.79mm Orifice Diameter (Ti-3Al-2.5V Tube Welding).



PARAMETRIC CONSTRAINTS					DIMENSIONAL AND QUALITY CONSTRAINTS									
HI ₁ (9-14)	WS(2.00-3.99)	PGFR(0.3-0.6)	ESB(1.5-1.9)		Outer Bead Width (OBW): 1.2mm-4.8mm Inner Bead Width (IBW): 1.2mm-4.8mm Maximum Inner Bead Width Range (3-33): 0.7mm									
Optimum Recommended Parameter Combinations					Predicted Bead Widths for the Various Positions								RESULTS	
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	Position	3	8	13	18	23	28	33		
G3(OBW)	11.1	3.13	0.6	1.9	OBW	2.06	1.88	1.90	1.90	1.99	2.20	2.08	G3	5.80%
G3(IBW)					IBW	1.40	1.05	1.05	1.19	1.35	1.75	1.62		
G4(OBW)	14.0	2.73	0.6	1.9	OBW	2.89	2.81	2.80	2.84	3.00	3.26	3.15	G4	10.40%
G4(IBW)					IBW	2.60	2.48	2.57	2.59	2.71	3.18	3.14		
G5(OBW)	11.6	3.36	0.6	1.9	OBW	2.08	1.88	1.89	1.88	1.97	2.18	2.06	G5	0.30mm
G5(IBW)					IBW	1.42	1.03	1.00	1.12	1.27	1.68	1.55		
G6(OBW)	14.0	3.99	0.6	1.9	OBW	2.32	2.08	2.05	2.02	2.14	2.38	2.24	G6	0.63mm
G6(IBW)					IBW	1.78	1.30	1.19	1.22	1.34	1.82	1.70		
G8(OBW)	14.0	3.99	0.6	1.5	OBW	2.32	2.08	2.05	2.02	2.14	2.38	2.25	G8	0.14mm
G8(IBW)					IBW	1.78	1.30	1.19	1.22	1.34	1.82	1.70		

Figure 97: Optimum Recommended Parameter Combinations and Predicted Results for Melt-in Mode Welding of the A.S.S (316L) Tubes.



No	Starting Segment					1st Segment					2nd Segment					Obtained Bead Widths							
	Ist	WS	PGFR	ESB	DT	HI ₁	WS	PGFR	ESB	DUR	HI ₁	WS	PGFR	ESB	DUR	Position	3	8	13	18	23	28	33
1	15.0	0.00	0.6	1.9	1.0	14.2	3.50	0.6	1.9	6.0	13.0	3.50	0.6	1.9	5.0	OBW(1)	2.4	2.3	2.3	2.4	2.4	2.5	2.5
																IBW(1)	2.2	1.9	1.8	1.9	1.9	2.2	2.1
2	15.0	0.00	0.4	1.9	1.0	12.2	3.30	0.4	1.9	6.0	11.0	3.30	0.4	1.9	6.0	OBW(2)	2.1	1.8	1.8	1.8	1.9	2.0	2.0
																IBW(2)	1.4	1.0	1.0	1.1	1.1	1.3	1.3
3	15.0	0.00	0.4	1.5	1.0	10.2	2.00	0.4	1.5	10.0	9.0	2.00	0.4	1.5	9.0	OBW(3)	2.2	2.1	2.2	2.3	2.3	2.4	2.4
																IBW(3)	1.5	1.6	1.6	1.8	1.9	2.1	2.1

where: Ist: Average Welding Current Before the Initiation of Torch Rotation (in Amps)

HI₁: Average Welding Current During the Torch Rotation (in Amps)

WS: Welding Speed (in mm/sec)

PGFR : Plasma Gas Flow Rate (in l/min)

DUR: Duration of Segment (in sec)

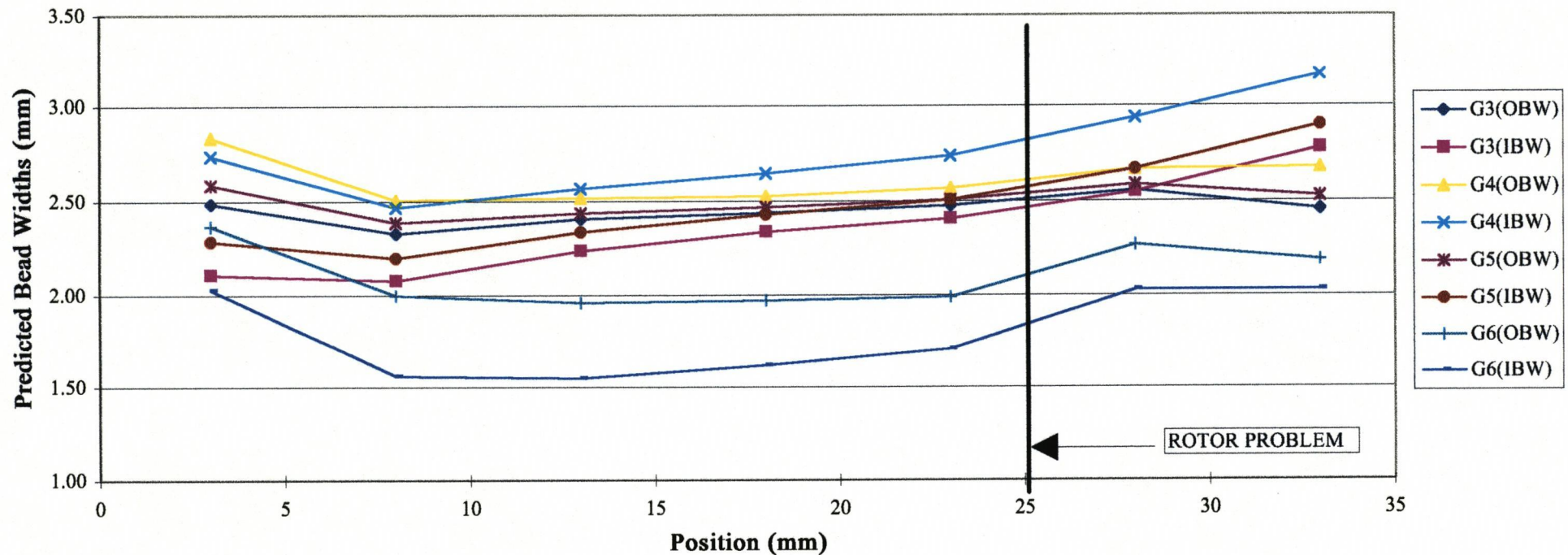
DT: Time Period Between Arc Initiation and Initiation of Torch Rotation (in sec)

ESB: Electrode Set Back Distance (in mm)

OBW: Outer Bead Width (in mm)

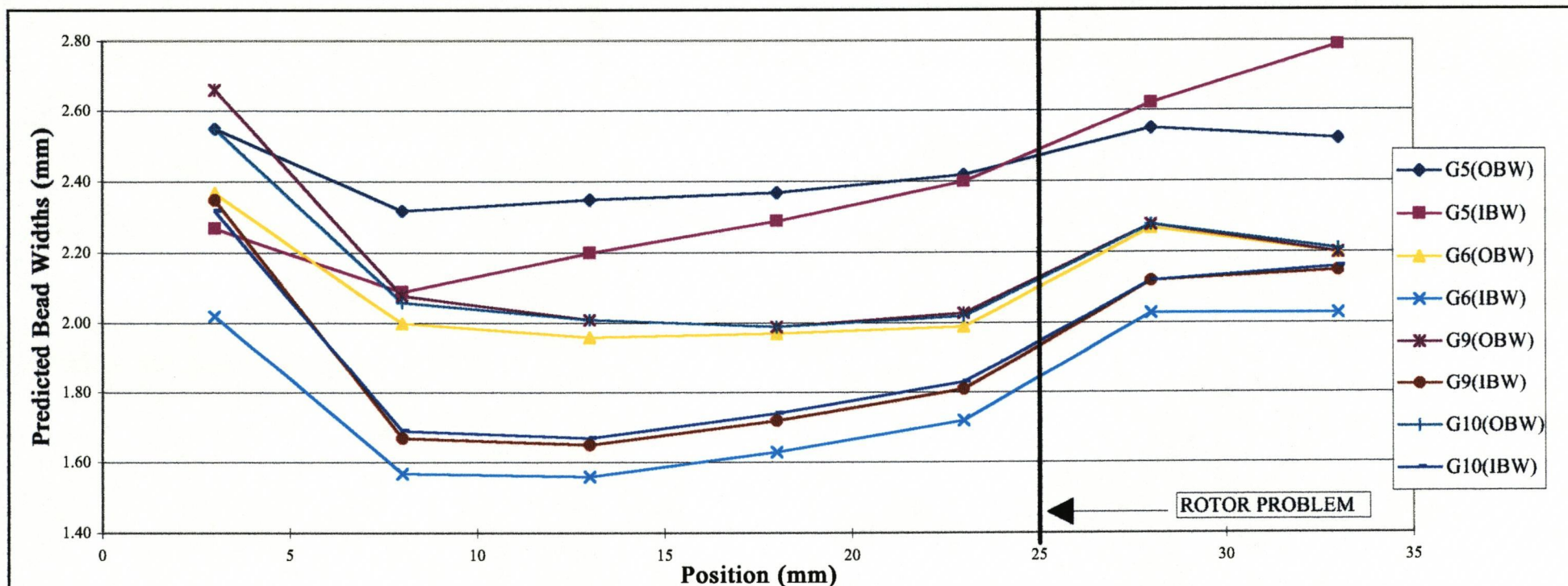
IBW: Inner Bead Width (in mm)

Figure 98: Three Segments Optimisation Procedures and Obtained Results for Melt-in Mode Welding of A.S.S (316L) Tubes.



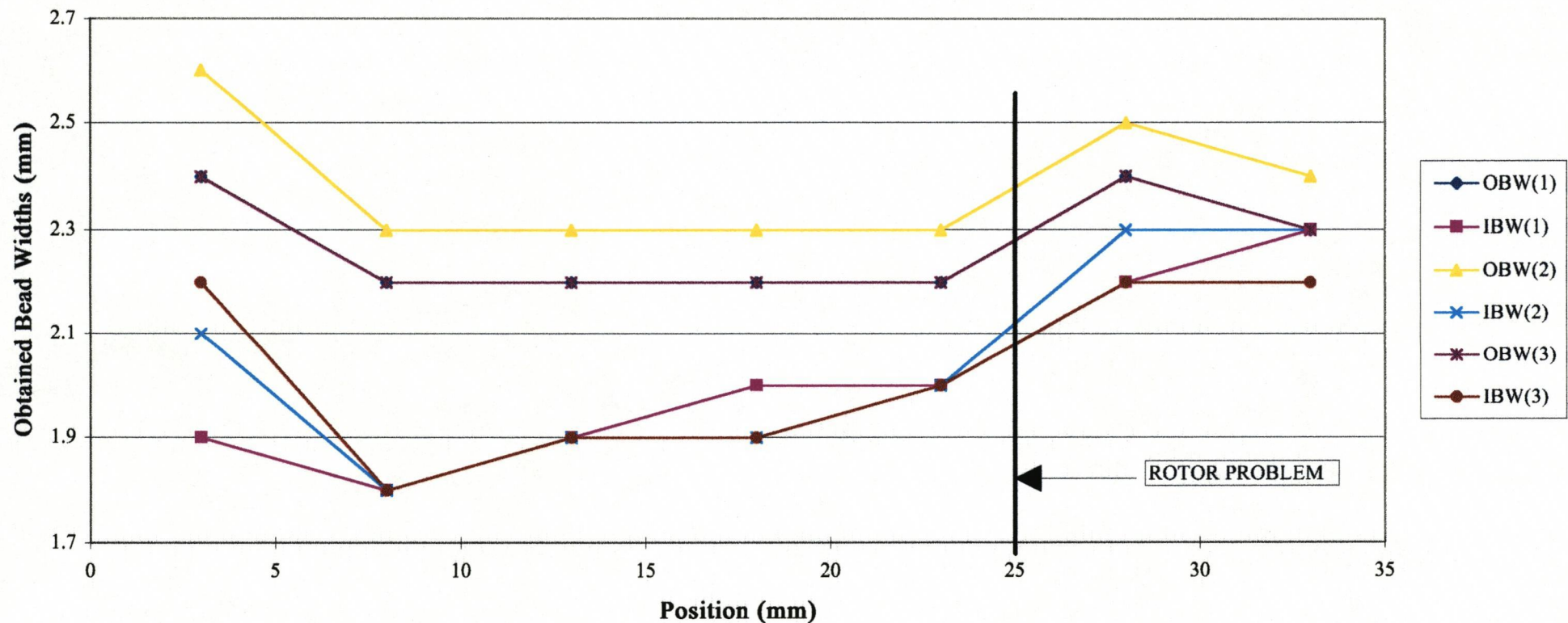
PARAMETRIC CONSTRAINTS					DIMENSIONAL AND QUALITY CONSTRAINTS									
HI ₁ (15-22)	WS(1.66-3.99)	PGFR(1.9-2.5)	ESB(1.3-2.0)		Outer Bead Width (OBW): 1.2mm-4.8mm					Maximum IBW/OBW (I/O) Ratio: 1.2				
					Inner Bead Width (IBW): 1.2mm-4.8mm					Maximum Inner Bead Width Range (3-33): 0.7mm				
Optimum Recommended Parameter Combinations					Predicted Bead Widths for the Various Positions								RESULTS	
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	Position	3	8	13	18	23	28	33		
G3(OBW)	17.9	1.93	1.9	1.3	OBW	2.49	2.33	2.41	2.44	2.48	2.56	2.46	G3	2.82%
G3(IBW)					IBW	2.11	2.08	2.24	2.34	2.41	2.55	2.78		
G4(OBW)	22.0	2.53	1.9	1.3	OBW	2.84	2.51	2.52	2.53	2.57	2.67	2.68	G4	8.60%
G4(IBW)					IBW	2.74	2.47	2.57	2.65	2.74	2.94	3.17		
G5(OBW)	19.1	2.09	1.9	1.3	OBW	2.59	2.39	2.44	2.47	2.51	2.59	2.53	G5	0.20mm
G5(IBW)					IBW	2.29	2.20	2.34	2.43	2.51	2.67	2.90		
G6(OBW)	19.9	3.42	1.9	1.3	OBW	2.37	2.00	1.96	1.97	1.99	2.27	2.19	G6	0.47mm
G6(IBW)					IBW	2.03	1.56	1.55	1.62	1.71	2.03	2.03		

Figure 99: Optimum Recommended Parameter Combinations and Predicted Results for Keyhole Welding of the A.S.S (316L) Tubes.



PARAMETRIC CONSTRAINTS					DIMENSIONAL AND QUALITY CONSTRAINTS									
HI ₁ (15-22)	WS(1.66-3.99)	PGFR(1.9-2.5)	ESB(1.3-2.0)		Outer Bead Width (OBW): 1.2mm-4.8mm					Maximum IBW/OBW (I/O) Ratio: 1.2				
					Inner Bead Width (IBW): 1.2mm-4.8mm					Maximum Inner Bead Width Range (3-33): 0.7mm				
					Maximum Absolute Undercut Index: 0.5									
Optimum Recommended Parameter Combinations					Predicted Bead Widths for the Various Positions								RESULTS	
OBJ. FUNCT.	HI ₁ (A)	WS(mm/sec)	PGFR (l/min)	ESB (mm)	Position	3	8	13	18	23	28	33		
G5(OBW)	19.3	2.32	2	1.3	OBW	2.55	2.32	2.35	2.37	2.42	2.55	2.52	G5	0.22mm
G5(IBW)					IBW	2.27	2.09	2.20	2.29	2.40	2.62	2.79		
G6(OBW)	19.8	3.39	1.9	1.3	OBW	2.37	2.00	1.96	1.97	1.99	2.27	2.20	G6	0.47mm
G6(IBW)					IBW	2.02	1.57	1.56	1.63	1.72	2.03	2.03		
G9(OBW)	22.0	3.88	1.9	1.6	OBW	2.66	2.08	2.01	1.99	2.03	2.28	2.20	G9	6E-10
G9(IBW)					IBW	2.35	1.67	1.65	1.72	1.81	2.12	2.15		
G10(OBW)	22.0	3.92	1.9	1.3	OBW	2.55	2.06	2.01	1.99	2.02	2.28	2.21	G10	0.14
G10(IBW)					IBW	2.32	1.69	1.67	1.74	1.83	2.12	2.16		

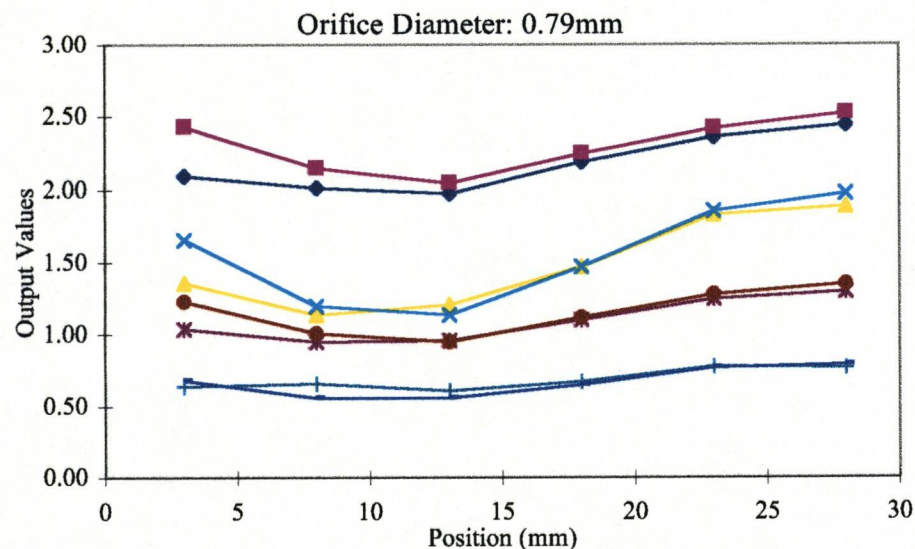
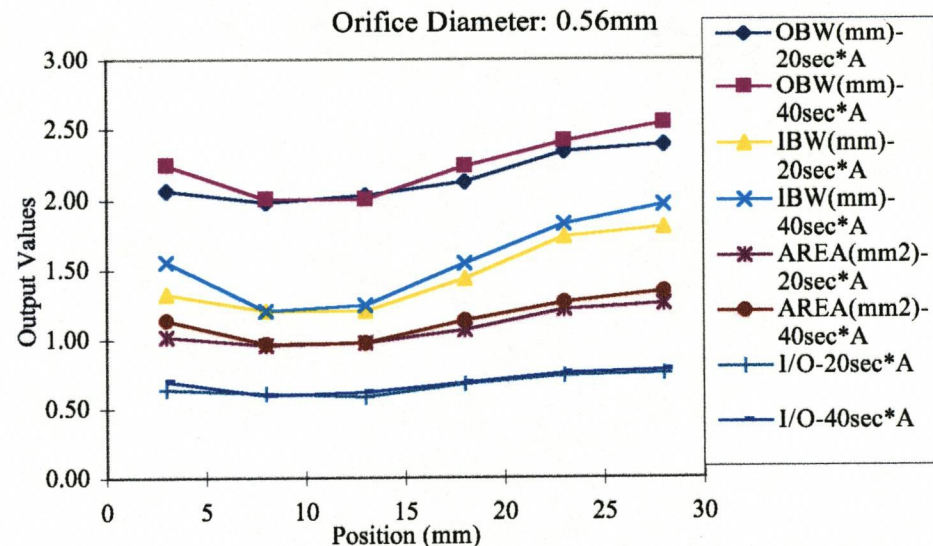
Figure 100: Optimum Recommended Parameter Combinations and Predicted Results for Keyhole Welding of the A.S.S (316L) Tubes.



No	Starting Segment					1st Segment					2nd Segment					Obtained Bead Widths							
	Ist	WS	PGFR	ESB	DT	HI ₁	WS	PGFR	ESB	DUR	HI ₁	WS	PGFR	ESB	DUR	Position	3	8	13	18	23	28	33
1	16.5	0.00	2.3	1.6	2.0	17.0	2.01	1.9	1.6	10.0	16.0	2.01	1.9	1.6	9.0	OBW(1)	2.4	2.2	2.2	2.2	2.2	2.4	2.3
																IBW(1)	1.9	1.8	1.9	2.0	2.0	2.2	2.3
2	16.5	0.00	2.3	1.6	2.0	18.0	2.24	2.1	2.0	9.0	17.0	2.24	2.1	1.6	8.0	OBW(2)	2.6	2.3	2.3	2.3	2.3	2.5	2.4
																IBW(2)	2.1	1.8	1.9	1.9	2.0	2.3	2.3
3	16.5	0.00	2.3	1.6	2.0	20.0	2.97	1.9	1.6	7.0	18.5	2.97	1.9	1.6	6.0	OBW(3)	2.4	2.2	2.2	2.2	2.2	2.4	2.3
																IBW(3)	2.2	1.8	1.9	1.9	2.0	2.2	2.2

where: Ist: Average Welding Current Before the Initiation of Torch Rotation (in Amps)
HI₁: Average Welding Current During the Torch Rotation (in Amps)
WS: Welding Speed (in mm/sec) PGFR : Plasma Gas Flow Rate (in l/min) DUR: Duration of Segment (in sec)
DT: Time Period Between Arc Initiation and Initiation of Torch Rotation (in sec) ESB: Electrode Set Back Distance (in mm)
OBW: Outer Bead Width (in mm) IBW: Inner Bead Width (in mm)

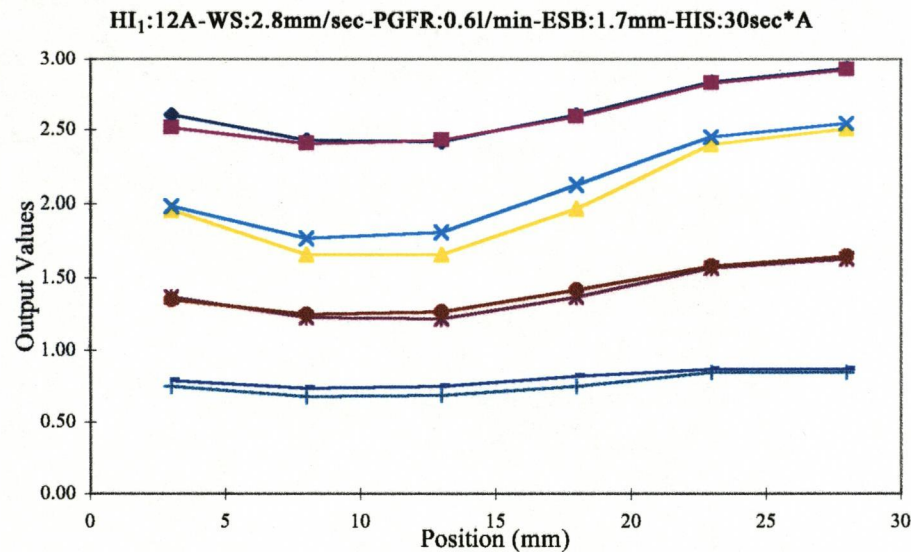
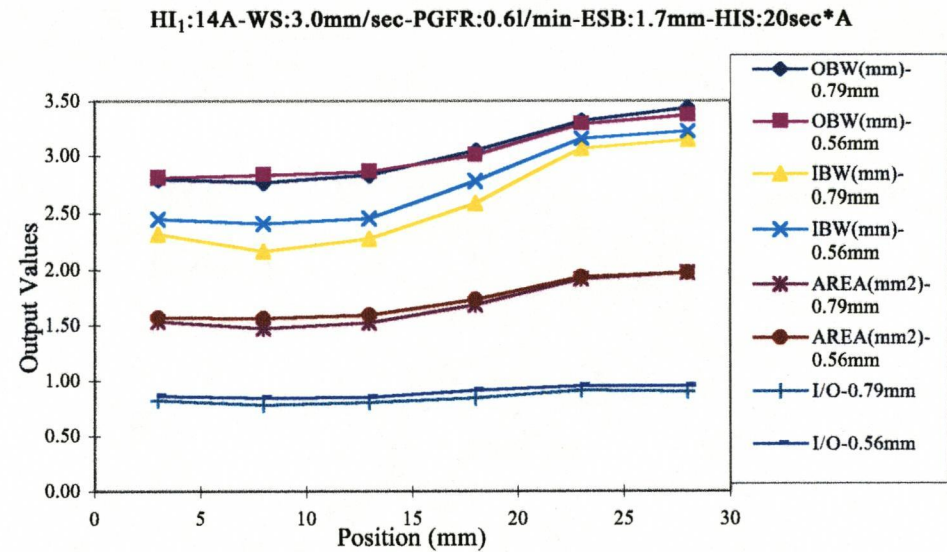
Figure 101: Three Segments Optimisation Procedures and Obtained Results for Keyhole Welding of A.S.S (316L) Tubes.



Influence of HIS on bead characteristics for Both Orifice Diameters Utilised (H₁: 14A, WS: 2.5mm/sec, PGFR: 0.6l/min, ESB: 1.5mm)

Orifice Diameter: 0.79mm							Orifice Diameter: 0.56mm					
Position	3	8	13	18	23	28	3	8	13	18	23	28
OBW(mm)-20sec*A	2.10	2.02	1.98	2.19	2.36	2.44	2.07	1.99	2.04	2.13	2.34	2.39
OBW(mm)-40sec*A	2.43	2.15	2.05	2.25	2.42	2.52	2.25	2.01	2.01	2.24	2.41	2.54
Variation	0.33	0.13	0.07	0.06	0.06	0.08	0.18	0.02	-0.03	0.11	0.07	0.15
% Variation	15.71	6.44	3.54	2.74	2.54	3.28	8.70	1.01	-1.47	5.16	2.99	6.28
IBW(mm)-20sec*A	1.36	1.14	1.21	1.47	1.83	1.89	1.33	1.21	1.21	1.44	1.74	1.81
IBW(mm)-40sec*A	1.66	1.20	1.14	1.47	1.86	1.98	1.56	1.21	1.25	1.55	1.83	1.97
Variation	0.30	0.06	-0.07	0.00	0.03	0.09	0.23	0.00	0.04	0.11	0.09	0.16
% Variation	22.06	5.26	-5.79	0.00	1.64	4.76	17.29	0.00	3.31	7.64	5.17	8.84
AREA(mm ²)-20sec*A	1.04	0.95	0.96	1.10	1.25	1.30	1.02	0.96	0.98	1.07	1.22	1.26
AREA(mm ²)-40sec*A	1.23	1.01	0.95	1.12	1.28	1.35	1.14	0.97	0.98	1.14	1.27	1.35
Variation	0.19	0.06	-0.01	0.02	0.03	0.05	0.12	0.01	0.00	0.07	0.05	0.09
% Variation	18.27	6.32	-1.04	1.82	2.40	3.85	11.76	1.04	0.00	6.54	4.10	7.14
I/O-20sec*A	0.64	0.66	0.61	0.67	0.78	0.77	0.64	0.61	0.59	0.68	0.74	0.76
I/O-40sec*A	0.68	0.56	0.56	0.65	0.77	0.79	0.70	0.60	0.62	0.69	0.76	0.78
Variation	0.04	-0.10	-0.05	-0.02	-0.01	0.02	0.06	-0.01	0.03	0.01	0.02	0.02

Figure 102: Investigation of the Influence of HIS on Weld Bead Characteristics for Both Orifice Diameters Utilised, Based on a Typical Input Parameter Combination and Two Different HIS (20sec*A and 40sec*A).

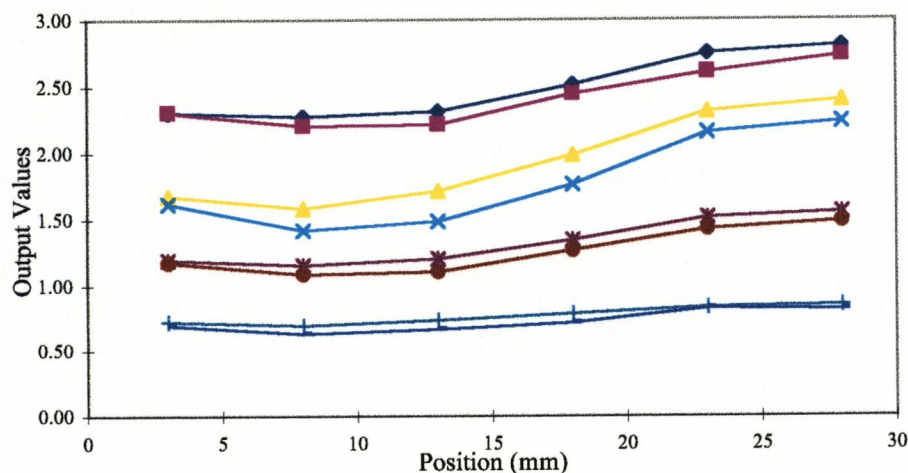


Influence of Orifice Diameter on Bead Characteristics for Two Different Orifice Diameters (0.79mm, 0.56mm)

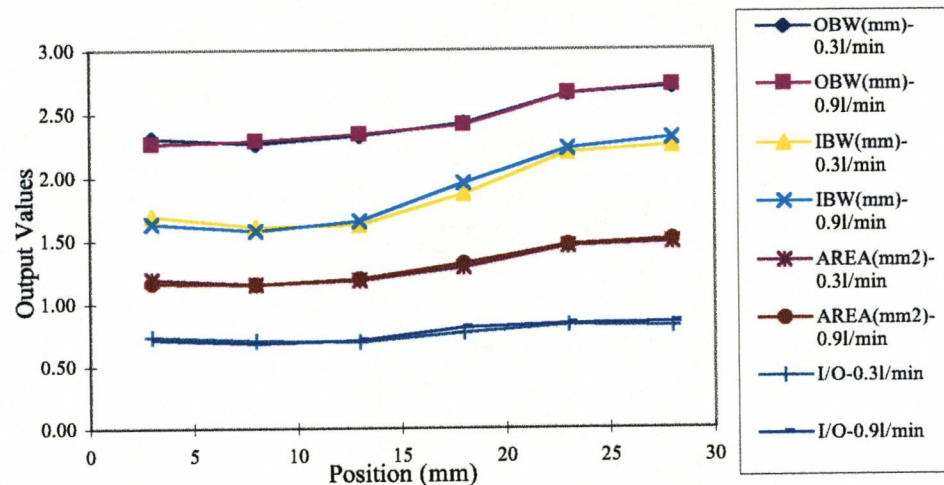
Parameter Combination	HI ₁ :12A-WS:2.8mm/sec-PGFR:0.6l/min-ESB:1.7mm-HIS:30sec*A						HI ₁ :14A-WS:3.0mm/sec-PGFR:0.6l/min-ESB:1.7mm-HIS:20sec*A					
Position	3	8	13	18	23	28	3	8	13	18	23	28
OBW(mm)-0.79mm	2.61	2.43	2.42	2.61	2.84	2.94	2.80	2.77	2.83	3.05	3.33	3.44
OBW(mm)-0.56mm	2.52	2.41	2.43	2.60	2.83	2.93	2.81	2.83	2.86	3.01	3.30	3.38
Variation	-0.09	-0.02	0.01	-0.01	-0.01	-0.01	0.01	0.06	0.03	-0.04	-0.03	-0.06
% Variation	-3.45	-0.82	0.41	-0.38	-0.35	-0.34	0.36	2.17	1.06	-1.31	-0.90	-1.74
IBW(mm)-0.79mm	1.96	1.66	1.66	1.97	2.40	2.51	2.32	2.17	2.28	2.59	3.07	3.15
IBW(mm)-0.56mm	1.99	1.77	1.81	2.13	2.45	2.55	2.45	2.41	2.46	2.78	3.16	3.23
Variation	0.03	0.11	0.15	0.16	0.05	0.04	0.13	0.24	0.18	0.19	0.09	0.08
% Variation	1.53	6.63	9.04	8.12	2.08	1.59	5.60	11.06	7.89	7.34	2.93	2.54
AREA(mm ²)-0.79mm	1.37	1.23	1.22	1.37	1.57	1.63	1.54	1.48	1.53	1.69	1.92	1.98
AREA(mm ²)-0.56mm	1.35	1.25	1.27	1.42	1.58	1.65	1.58	1.57	1.60	1.74	1.94	1.98
Variation	-0.02	0.02	0.05	0.05	0.01	0.02	0.04	0.09	0.07	0.05	0.02	0.00
% Variation	-1.46	1.63	4.10	3.65	0.64	1.23	2.60	6.08	4.58	2.96	1.04	0.00
I/O-0.79mm	0.75	0.68	0.69	0.75	0.85	0.85	0.83	0.79	0.81	0.85	0.92	0.91
I/O-0.56mm	0.79	0.74	0.75	0.82	0.87	0.87	0.87	0.85	0.86	0.92	0.96	0.96
Variation	0.04	0.06	0.06	0.07	0.02	0.02	0.04	0.06	0.05	0.07	0.04	0.05

Figure 103: Investigation of the Influence of Orifice Diameter (OD) on Weld Bead Characteristics, Based on Two Typical Input Parameter Combinations and Two OD (0.79mm-0.56mm).

Orifice Diameter: 0.79mm



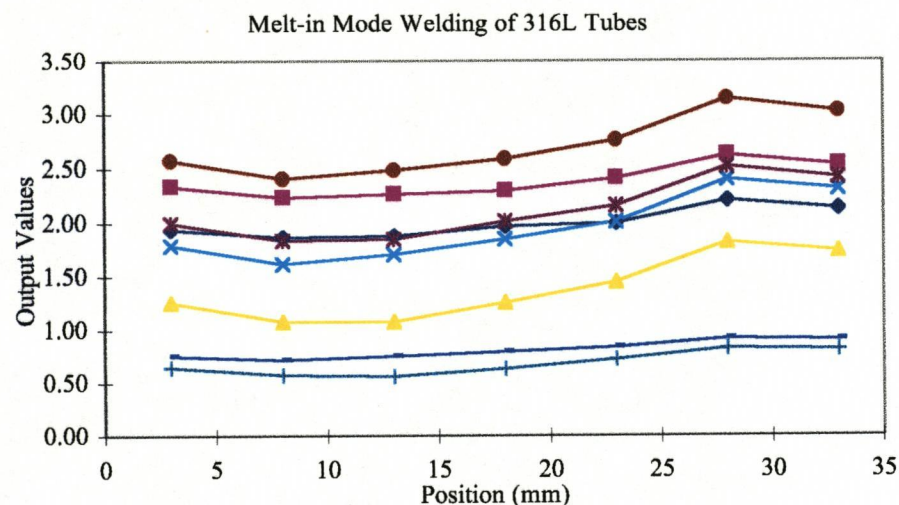
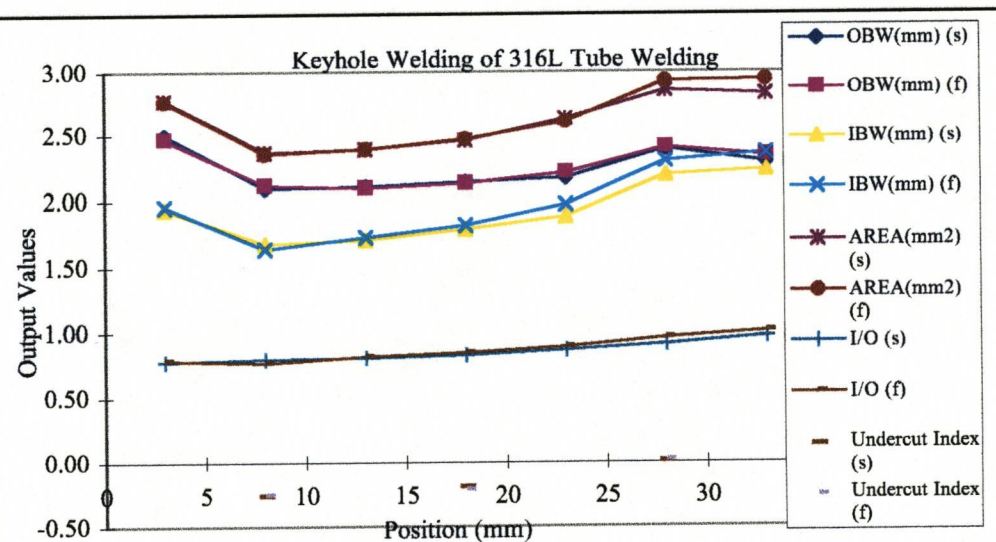
Orifice Diameter: 0.56mm



Influence of (PGFR) on Bead Characteristics for Both Orifice Diameters Utilised (H_I:11A, WS: 2.5mm/sec, ESB: 1.7mm, H_IS: 20sec*A)

	ORIFICE DIAMETER: 0.79mm						ORIFICE DIAMETER: 0.56mm					
Position	3	8	13	18	23	28	3	8	13	18	23	28
OBW(mm)-0.3l/min	2.31	2.28	2.32	2.52	2.75	2.81	2.31	2.27	2.33	2.43	2.66	2.71
OBW(mm)-0.9l/min	2.31	2.21	2.22	2.45	2.61	2.73	2.27	2.29	2.34	2.42	2.66	2.72
Variation	0.00	-0.07	-0.10	-0.07	-0.14	-0.08	-0.04	0.02	0.01	-0.01	0.00	0.01
% Variation	0.00	-3.07	-4.31	-2.78	-5.09	-2.85	-1.73	0.88	0.43	-0.41	0.00	0.37
IBW(mm)-0.3l/min	1.68	1.59	1.72	1.99	2.32	2.40	1.70	1.61	1.63	1.87	2.20	2.25
IBW(mm)-0.9l/min	1.62	1.42	1.49	1.77	2.16	2.24	1.64	1.58	1.66	1.96	2.23	2.31
Variation	-0.06	-0.17	-0.23	-0.22	-0.16	-0.16	-0.06	-0.03	0.03	0.09	0.03	0.06
% Variation	-3.57	-10.69	-13.37	-11.06	-6.90	-6.67	-3.53	-1.86	1.84	4.81	1.36	2.67
AREA(mm²)-0.3l/min	1.20	1.16	1.21	1.35	1.52	1.56	1.20	1.16	1.19	1.29	1.46	1.49
AREA(mm²)-0.9l/min	1.18	1.09	1.11	1.27	1.43	1.49	1.17	1.16	1.20	1.32	1.47	1.51
Variation	-0.02	-0.07	-0.10	-0.08	-0.09	-0.07	-0.03	0.00	0.01	0.03	0.01	0.02
% Variation	-1.67	-6.03	-8.26	-5.93	-5.92	-4.49	-2.50	0.00	0.84	2.33	0.68	1.34
I/O-0.3l/min	0.73	0.70	0.74	0.79	0.84	0.85	0.74	0.71	0.70	0.77	0.83	0.82
I/O-0.9l/min	0.70	0.64	0.67	0.72	0.83	0.82	0.72	0.69	0.71	0.81	0.84	0.85
Variation	-0.03	-0.06	-0.07	-0.07	-0.01	-0.03	-0.02	-0.02	0.01	0.04	0.01	0.03

Figure 104a: Investigation of the Influence of Plasma Gas Flow Rate on Weld Bead Characteristics for Both Orifice Diameters Utilised, Based on a Typical Input Parameter Combination and Two Different PGFR (0.3l/min and 0.9l/min).



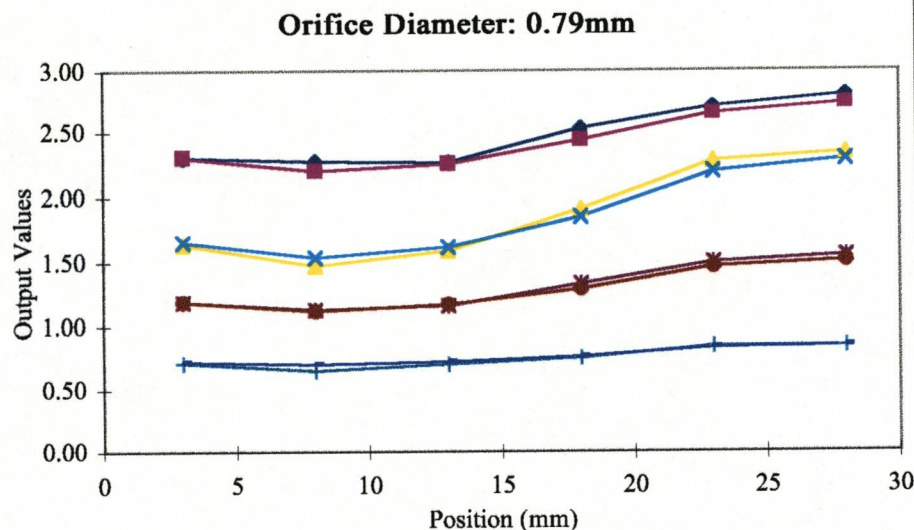
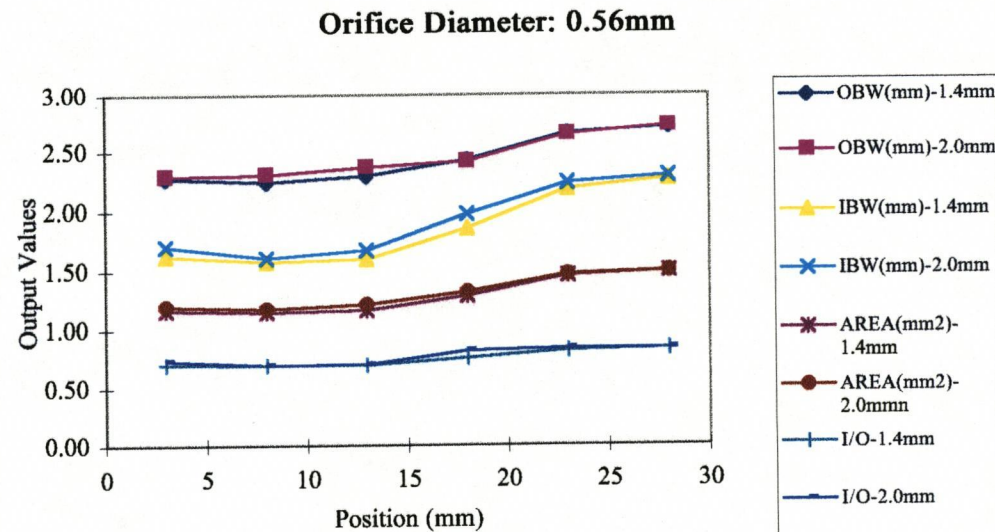
Influence of PGFR on Weld Bead Characteristics for Plasma Welding of 316L Tubes

	Melt-in Mode Welding of 316L Tubes							Keyhole Welding of 316L Tubes						
Position	3	8	13	18	23	28	33	3	8	13	18	23	28	33
OBW(mm) (s)	1.94	1.87	1.88	1.97	2.00	2.21	2.13	2.50	2.10	2.11	2.14	2.17	2.39	2.29
OBW(mm) (f)	2.34	2.24	2.27	2.30	2.41	2.62	2.53	2.47	2.12	2.10	2.13	2.21	2.40	2.34
Variation	0.40	0.37	0.39	0.33	0.41	0.41	0.40	-0.03	0.02	-0.01	-0.01	0.04	0.01	0.05
% Variation	20.62	19.79	20.74	16.75	20.50	18.55	18.78	-1.20	0.95	-0.47	-0.47	1.84	0.42	2.18
IBW(mm) (s)	1.26	1.08	1.08	1.26	1.45	1.82	1.74	1.94	1.68	1.71	1.79	1.88	2.19	2.23
IBW(mm) (f)	1.79	1.62	1.71	1.85	2.01	2.40	2.31	1.96	1.64	1.73	1.82	1.97	2.30	2.36
Variation	0.53	0.54	0.63	0.59	0.56	0.58	0.57	0.02	-0.04	0.02	0.03	0.09	0.11	0.13
% Variation	42.06	50.00	58.33	46.83	38.62	31.87	32.76	1.03	-2.38	1.17	1.68	4.79	5.02	5.83
AREA(mm²) (s)	2.00	1.84	1.85	2.02	2.16	2.52	2.42	2.78	2.37	2.39	2.46	2.63	2.86	2.83
AREA(mm²) (f)	2.58	2.41	2.49	2.59	2.76	3.14	3.02	2.77	2.36	2.39	2.47	2.61	2.93	2.94
Variation	0.58	0.57	0.64	0.57	0.60	0.62	0.60	-0.01	-0.01	0.00	0.01	-0.02	0.07	0.11
% Variation	29.00	30.98	34.59	28.22	27.78	24.60	24.79	-0.36	-0.42	0.00	0.41	-0.76	2.45	3.89
I/O (s)	0.65	0.58	0.57	0.64	0.73	0.83	0.82	0.78	0.80	0.81	0.83	0.87	0.91	0.97
I/O (f)	0.76	0.72	0.76	0.80	0.84	0.92	0.91	0.79	0.77	0.82	0.85	0.89	0.96	1.01
Variation	0.11	0.14	0.19	0.16	0.11	0.09	0.09	0.01	-0.03	0.01	0.02	0.02	0.05	0.04
Undercut Index (s)									-0.26		-0.19		0.01	
Undercut Index (f)									-0.25		-0.21		0.02	
Variation									0.01		-0.02		0.01	

Figure 104b: Influence of PGFR on Bead Characteristics for:

a) Melt-in Mode Welding of 316L Tubes (12.7mm X 1.25mm)-(HI₁:11A, WS: 2.50mm/sec, ESB: 1.7mm, PGFR(s): 0.31/min, PGFR(f): 0.61/min)

b) Keyhole Welding of 316L Tubes (12.7mm X 1.25mm)-(HI₁: 18A, WS: 2.50mm/sec, ESB: 1.7mm, PGFR(s): 1.91/min, PGFR(f): 2.31/min)

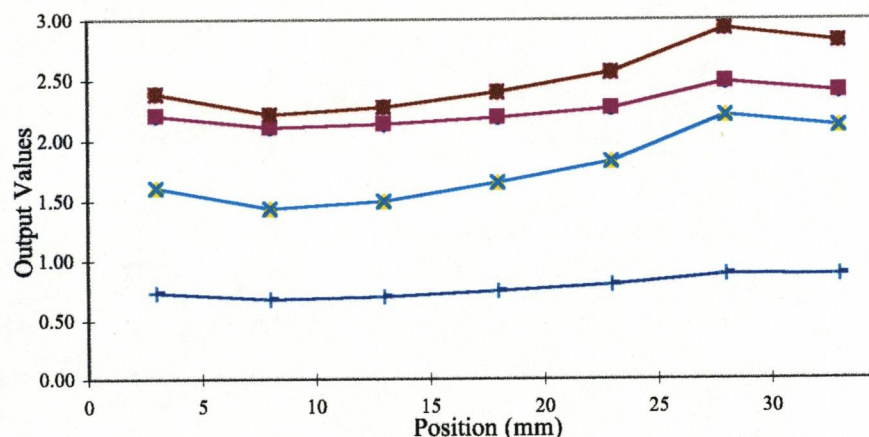


Influence of ESB on Bead Characteristics for Both Orifice Diameters Utilised (HI₁:11A, WS: 2.5mm/sec, PGFR: 0.6l/min, H₁S: 20sec*A)

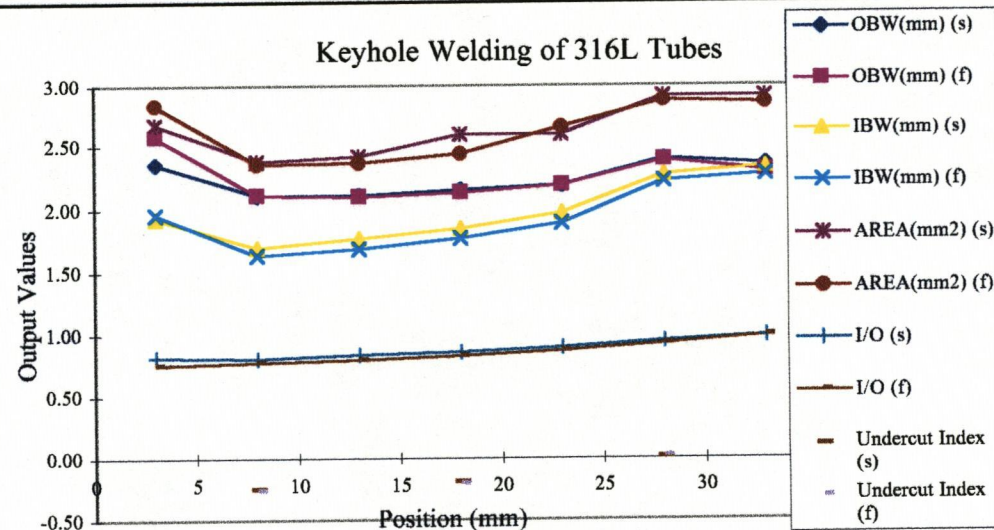
	ORIFICE DIAMETER: 0.79mm						ORIFICE DIAMETER: 0.56mm					
Position	3	8	13	18	23	28	3	8	13	18	23	28
OBW(mm)-1.4mm	2.31	2.28	2.27	2.53	2.71	2.81	2.28	2.25	2.30	2.43	2.66	2.71
OBW(mm)-2.0mm	2.31	2.21	2.26	2.44	2.65	2.74	2.30	2.31	2.37	2.42	2.65	2.72
Variation	0.00	-0.07	-0.01	-0.09	-0.06	-0.07	0.02	0.06	0.07	-0.01	-0.01	0.01
% Variation	0.00	-3.07	-0.44	-3.56	-2.21	-2.49	0.88	2.67	3.04	-0.41	-0.38	0.37
IBW(mm)-1.4mm	1.64	1.47	1.59	1.91	2.28	2.34	1.63	1.58	1.60	1.86	2.19	2.27
IBW(mm)-2.0mm	1.66	1.54	1.62	1.85	2.20	2.29	1.71	1.61	1.68	1.98	2.24	2.29
Variation	0.02	0.07	0.03	-0.06	-0.08	-0.05	0.08	0.03	0.08	0.12	0.05	0.02
% Variation	1.22	4.76	1.89	-3.14	-3.51	-2.14	4.91	1.90	5.00	6.45	2.28	0.88
AREA(mm²)-1.4mm	1.19	1.13	1.16	1.33	1.50	1.55	1.17	1.15	1.17	1.29	1.46	1.50
AREA(mm²)-2.0mm	1.19	1.12	1.17	1.29	1.46	1.51	1.20	1.18	1.22	1.32	1.47	1.50
Variation	0.00	-0.01	0.01	-0.04	-0.04	-0.04	0.03	0.03	0.05	0.03	0.01	0.00
% Variation	0.00	-0.88	0.86	-3.01	-2.67	-2.58	2.56	2.61	4.27	2.33	0.68	0.00
I/O-1.4mm	0.71	0.65	0.70	0.75	0.84	0.84	0.71	0.70	0.70	0.76	0.82	0.84
I/O-2.0mm	0.72	0.70	0.72	0.76	0.83	0.84	0.74	0.70	0.71	0.82	0.84	0.84
Variation	0.01	0.05	0.02	0.01	-0.01	0.00	0.03	0.00	0.01	0.06	0.02	0.00

Figure 105a: Investigation of the Influence of Electrode Set Back (ESB) on Weld Bead Characteristics, Based on a Typical Parameter Combination and Two Different ESB (1.4mm and 2.0mm).

Melt-in Mode Welding of 316L Tubes



Keyhole Welding of 316L Tubes



Influence of ESB on Bead Characteristics in Plasma Welding of 316L Tubes

	Melt-in Mode Welding of 316L Tubes							Keyhole Welding of 316L Tubes						
Position	3	8	13	18	23	28	33	3	8	13	18	23	28	33
OBW(mm) (s)	2.21	2.11	2.14	2.19	2.27	2.48	2.40	2.36	2.11	2.11	2.15	2.19	2.40	2.35
OBW(mm) (f)	2.21	2.11	2.14	2.19	2.27	2.48	2.40	2.58	2.11	2.10	2.13	2.19	2.39	2.30
Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.00	-0.01	-0.02	0.00	-0.01	-0.05
% Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.32	0.00	-0.47	-0.93	0.00	-0.42	-2.13
IBW(mm) (s)	1.61	1.44	1.50	1.65	1.83	2.21	2.12	1.93	1.70	1.77	1.85	1.97	2.27	2.33
IBW(mm) (f)	1.61	1.44	1.50	1.65	1.83	2.21	2.12	1.96	1.64	1.69	1.77	1.89	2.22	2.27
Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	-0.06	-0.08	-0.08	-0.08	-0.05	-0.06
% Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.55	-3.53	-4.52	-4.32	-4.06	-2.20	-2.58
AREA(mm ²) (s)	2.39	2.22	2.28	2.40	2.56	2.93	2.82	2.68	2.38	2.42	2.60	2.60	2.92	2.92
AREA(mm ²) (f)	2.39	2.22	2.28	2.40	2.56	2.93	2.82	2.84	2.36	2.37	2.44	2.66	2.88	2.86
Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	-0.02	-0.05	-0.16	0.06	-0.04	-0.06
% Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.97	-0.84	-2.07	-6.15	2.31	-1.37	-2.05
I/O (s)	0.73	0.68	0.70	0.75	0.80	0.89	0.88	0.82	0.81	0.84	0.86	0.90	0.95	0.99
I/O (f)	0.73	0.68	0.70	0.75	0.80	0.89	0.88	0.76	0.78	0.80	0.83	0.87	0.93	0.99
Variation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.06	-0.03	-0.04	-0.03	-0.03	-0.02	0.00
Undercut Index (s)									-0.25				0.01	
Undercut Index (f)									-0.26				0.02	
Variation									-0.01				0.01	

Figure 105b: Influence of ESB on Bead Characteristics for:

a) Melt-in Mode Welding of 316L Tubes (12.7mm X 1.25mm)-(HI₁:11A, WS: 2.50mm/sec, PGFR: 0.5l/min, ESB(s): 1.5mm, ESB(f): 1.9mm)

b) Keyhole Welding of 316L Tubes (12.7mm X 1.25mm)-(HI₁: 18A, WS: 2.50mm/sec, PGFR: 2.1l/min, ESB(s): 1.4mm, ESB(f): 1.9mm)

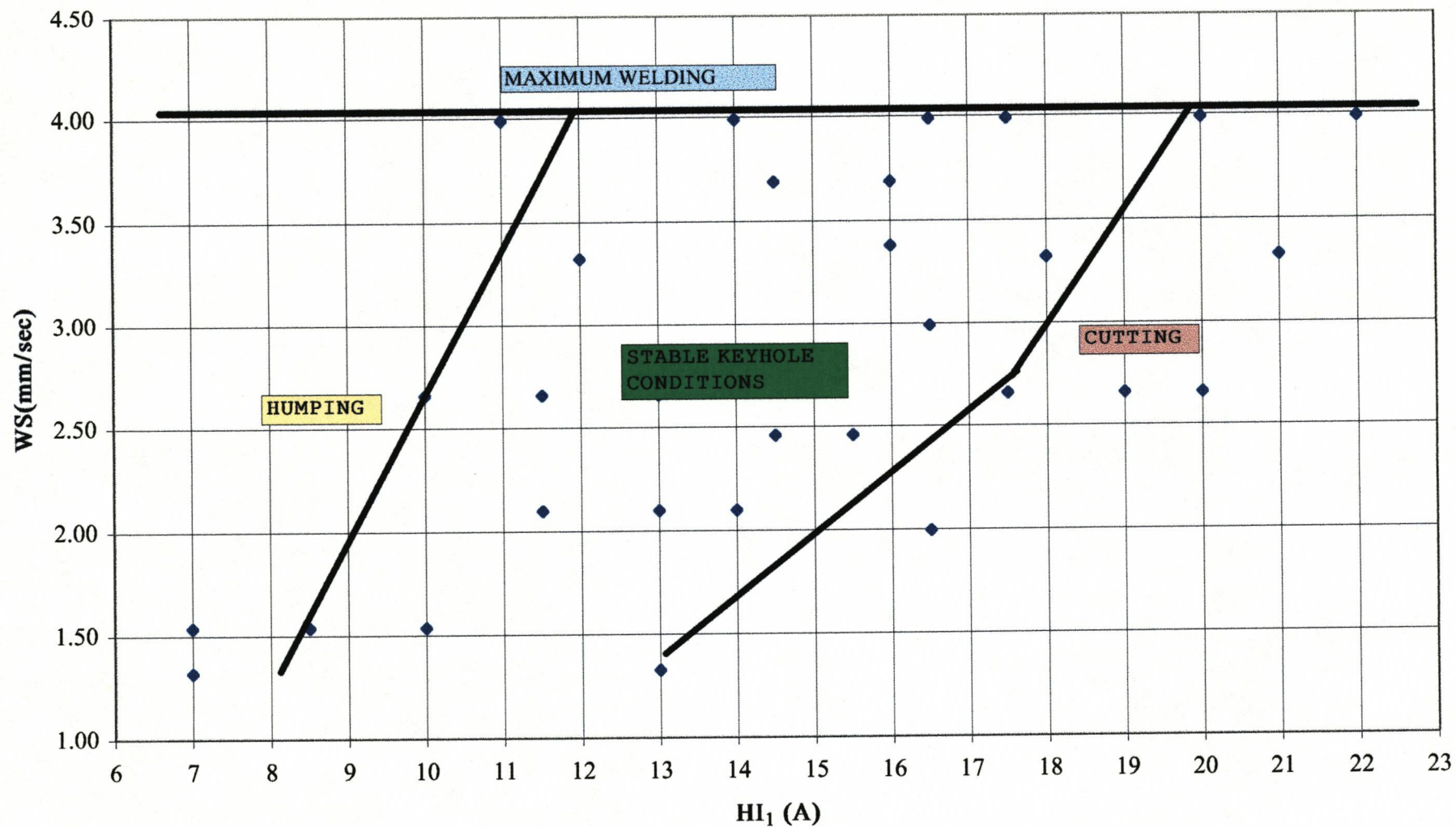
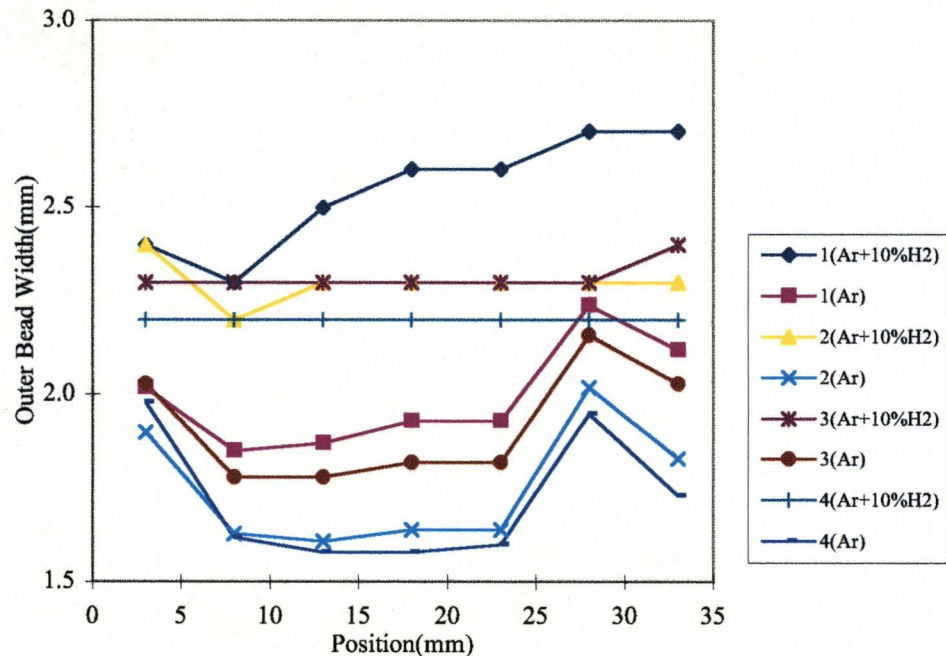
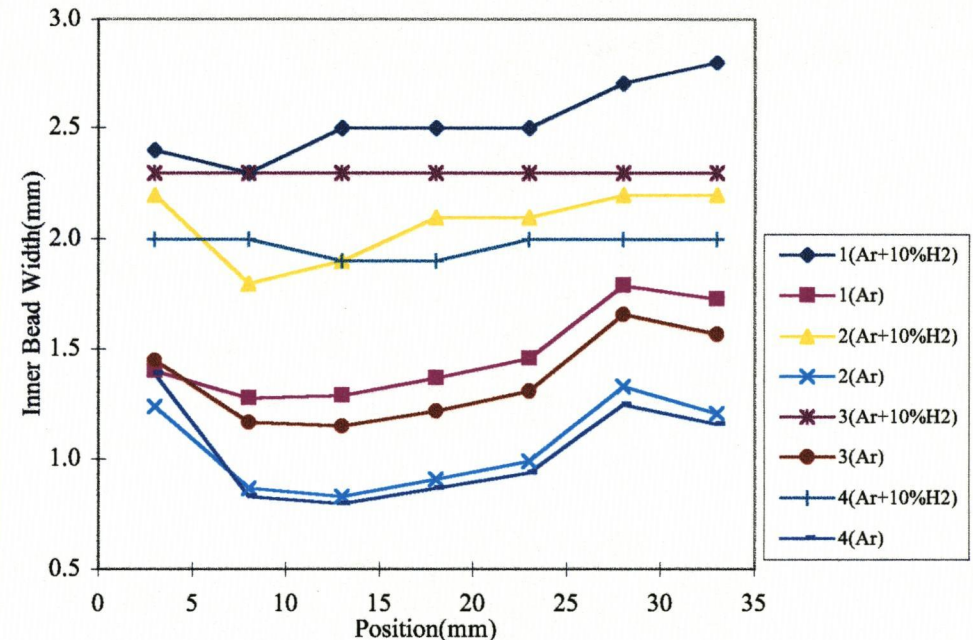


Figure 106: General Experimental Grid and Operational Envelope for Keyhole Plasma Welding of 316L Austenitic Stainless Steel Tubes Based on the Welding Current-Welding Speed Combinations Utilised (Shielding Gas: Ar+10%H₂).



SGC	Parameter Combinations				Outer Bead Width Measurements (mm)								Inner Bead Width Measurements (mm)								Weld Bead Uniformity Coefficients			
	HI ₁	WS	PGFR	ESB	3	8	13	18	23	28	33	3	8	13	18	23	28	33	COVC	COVI	RWO	RWI		
1 Ar+10%H ₂	15.5	2.46	1.4	1	2.4	2.3	2.5	2.6	2.6	2.7	2.7	2.4	2.3	2.5	2.5	2.5	2.7	2.8	6.0	6.7	0.4	0.5		
1 Ar	15.5	2.46	1.9	1.3	2.0	1.9	1.9	1.9	1.9	2.2	2.1	1.4	1.3	1.3	1.4	1.5	1.8	1.7	7.1	13.9	0.4	0.5		
2 Ar+10%H ₂	16	3.38	1.4	1	2.4	2.2	2.3	2.3	2.3	2.3	2.3	2.2	1.8	1.9	2.1	2.1	2.2	2.2	2.5	7.7	0.2	0.4		
2 Ar	16	3.38	1.9	1.9	1.9	1.6	1.6	1.6	1.6	2.0	1.8	1.2	0.9	0.8	0.9	1.0	1.3	1.2	9.2	19.2	0.4	0.5		
3 Ar+10%H ₂	16.5	2.99	1.6	1	2.3	2.3	2.3	2.3	2.3	2.3	2.4	2.3	2.3	2.3	2.3	2.3	2.3	2.3	1.6	0.0	0.1	0.0		
3 Ar	16.5	2.99	1.9	1.3	2.0	1.8	1.8	1.8	1.8	2.2	2.0	1.5	1.2	1.2	1.2	1.3	1.7	1.6	8.0	14.7	0.4	0.5		
4 Ar+10%H ₂	17.5	3.99	1.4	1	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	2.0	1.9	1.9	2.0	2.0	2.0	0.0	2.5	0.0	0.1		
4 Ar	17.5	3.99	1.9	1.3	2.0	1.6	1.6	1.6	1.6	2.0	1.7	1.4	0.8	0.8	0.9	0.9	1.3	1.2	10.2	22.4	0.4	0.6		

SGC: Shielding Gas Composition

HI₁: Average Welding Current (A)

WS: Welding Speed (mm/sec)

PGFR: Plasma Gas Flow Rate (l/min)

ESB: Electrode Set Back Distance (mm)

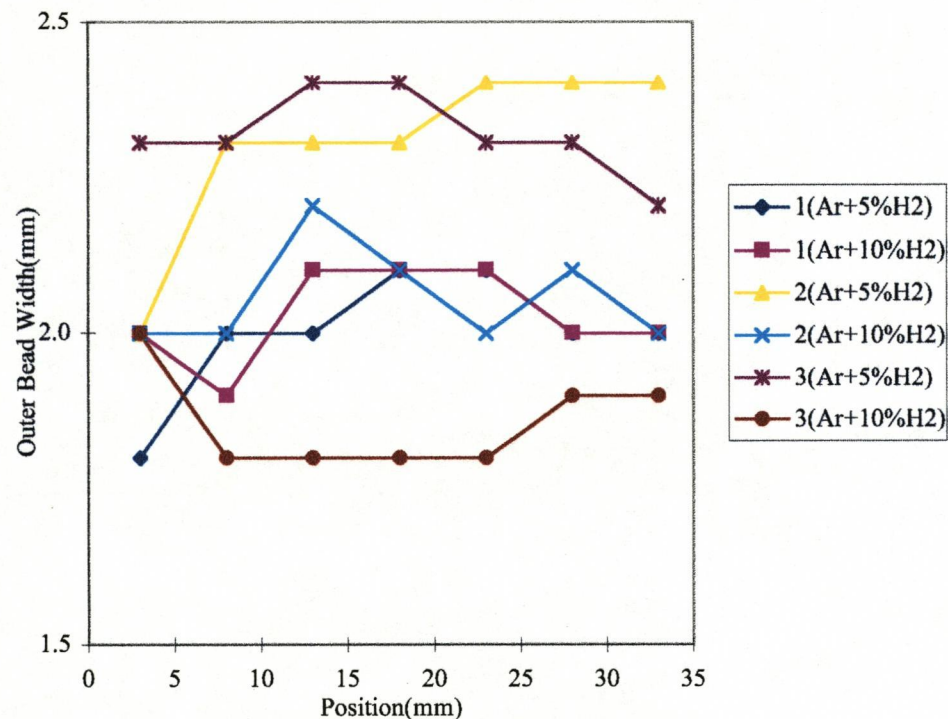
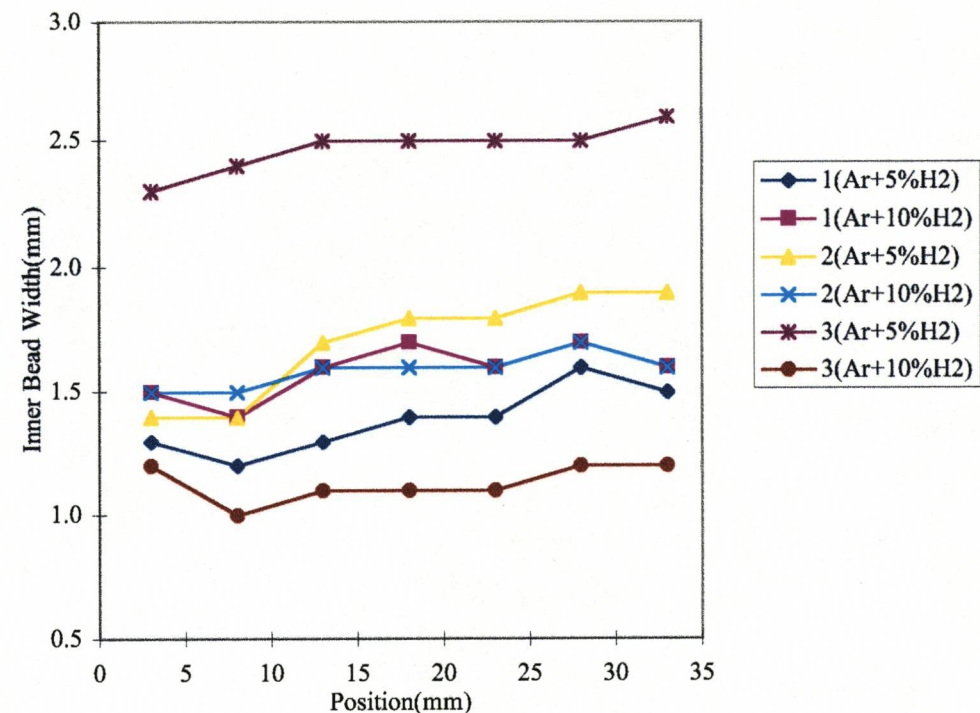
COVO: Coefficient of Variation for the Outer Bead Width (%)

COVI: Coefficient of Variation for the Inner Bead Width (%)

RWO: Width Range Between the Maximum and Minimum Outer Bead Width (mm)

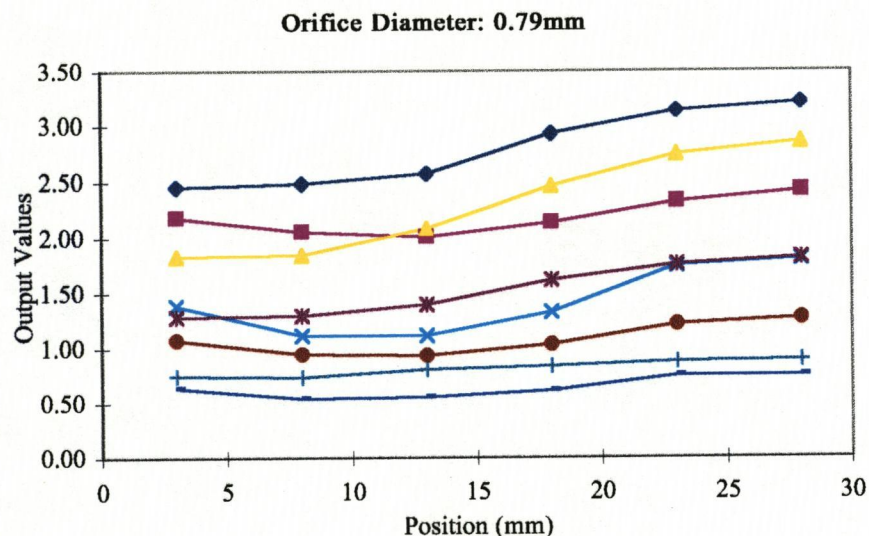
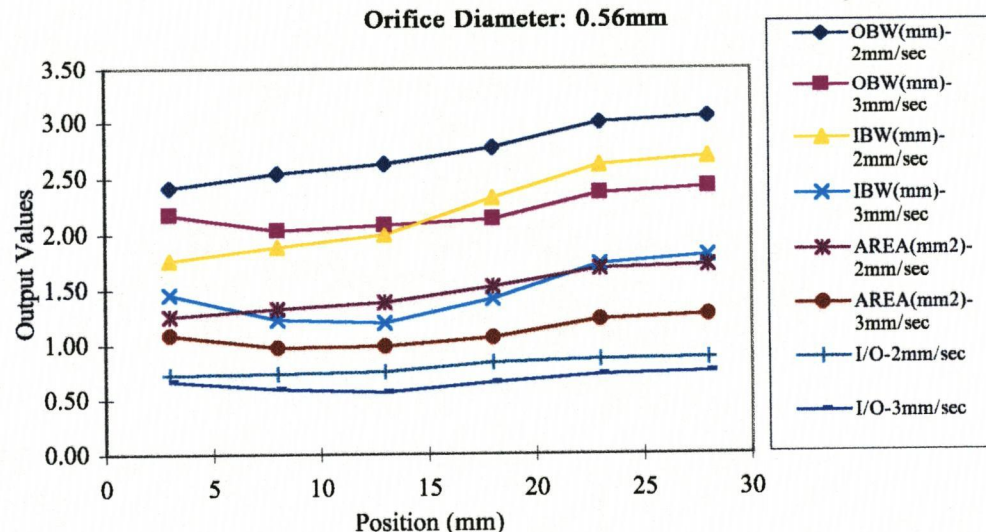
RWI: Width Range Between the Maximum and Minimum Inner Bead Width (mm)

Figure 107: Comparison of the Results Obtained With the Use of Two Different Shielding Gases (Pure Ar and Ar+10%H₂)



SGC	Parameter Combinations				Outer Bead Width Measurements (mm)							Inner Bead Width Measurements (mm)							Weld Bead Uniformity Coefficients			
	HI ₁	WS	PGFR	ESB	3	8	13	18	23	28	33	3	8	13	18	23	28	33	COVC	COVI	RWO	RWI
1 Ar+5%H ₂	11.5	2.66	1.9	1	1.8	2.0	2.0	2.1	2.1	2.0	2.0	1.3	1.2	1.3	1.4	1.4	1.6	1.5	4.8	10.6	0.3	0.4
1 Ar+10%H ₂	11.5	2.66	1.9	1	2.0	1.9	2.1	2.1	2.1	2.0	2.0	1.5	1.4	1.6	1.7	1.6	1.7	1.6	3.7	6.7	0.2	0.3
2 Ar+5%H ₂	11.5	2.10	1.6	1	2.0	2.3	2.3	2.3	2.4	2.4	2.4	1.4	1.4	1.7	1.8	1.8	1.9	1.9	6.1	13.4	0.4	0.6
2 Ar+10%H ₂	11.5	2.10	1.9	1	2.0	2.0	2.2	2.1	2.0	2.1	2.0	1.5	1.5	1.6	1.6	1.6	1.7	1.6	4.3	3.5	0.2	0.1
3 Ar+5%H ₂	14	2.10	1.6	1	2.3	2.3	2.4	2.4	2.3	2.3	2.2	2.3	2.4	2.5	2.5	2.5	2.5	2.6	2.1	3.9	0.1	0.3
3 Ar+10%H ₂	14	2.10	1.6	1	2.0	1.8	1.8	1.8	1.8	1.9	1.9	1.2	1.0	1.1	1.1	1.1	1.2	1.2	3.5	6.2	0.2	0.2
SGC: Shielding Gas Composition					COVO: Coefficient of Variation for the Outer Bead Width (%)																	
HI ₁ : Average Welding Current (A)					COVI: Coefficient of Variation for the Inner Bead Width (%)																	
WS: Welding Speed (mm/sec)					RWO: Width Range Between the Maximum and Minimum Outer Bead Width (mm)																	
PGFR: Plasma Gas Flow Rate (l/min)					RWI: Width Range Between the Maximum and Minimum Inner Bead Width (mm)																	
ESB: Electrode Set Back Distance (mm)																						

Figure 108: Comparison of the Results Obtained With the Use of Two Different Shielding Gases (Ar+5%H₂ and Ar+10%H₂) and Similar Welding Parameter Combinations.

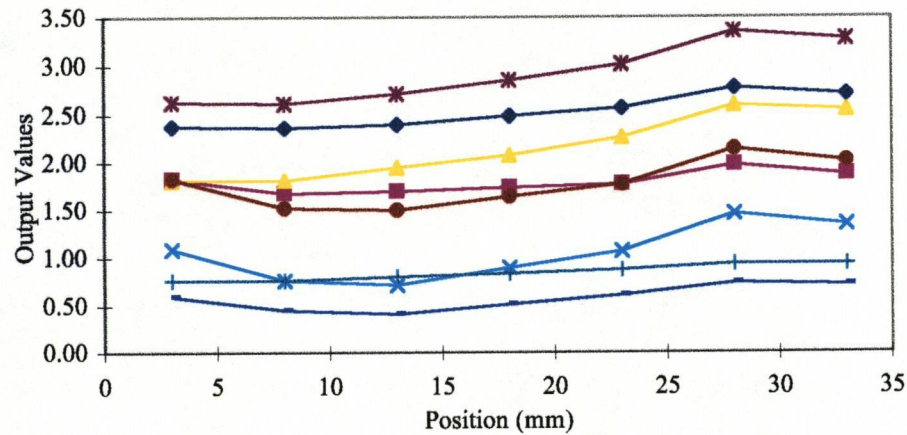


Influence of WS on Bead Characteristics for Both Orifice Diameters Utilised (HI₁: 11A, PGFR: 0.6l/min, ESB: 1.7mm, HIS: 20sec*A)

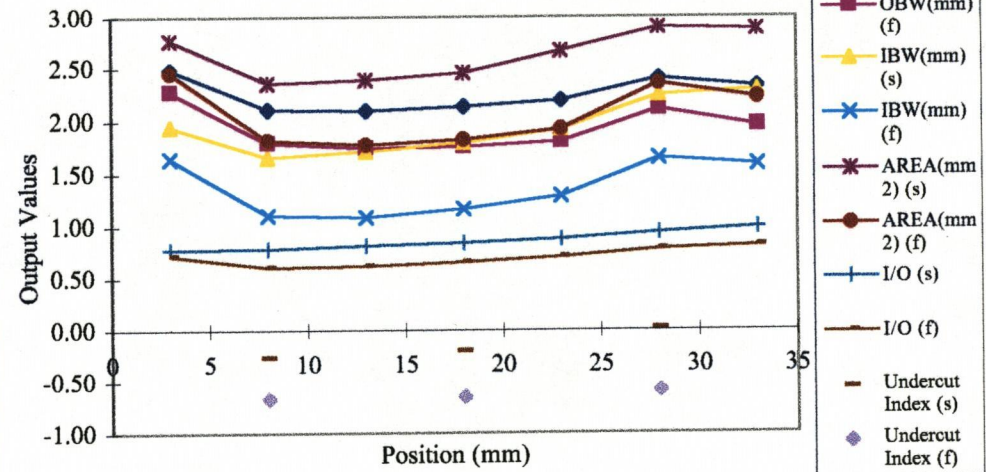
	ORIFICE DIAMETER: 0.79mm						ORIFICE DIAMETER: 0.56mm					
Position	3	8	13	18	23	28	3	8	13	18	23	28
OBW(mm)-2mm/sec	2.46	2.49	2.58	2.93	3.13	3.21	2.42	2.55	2.63	2.77	3.00	3.05
OBW(mm)-3mm/sec	2.19	2.06	2.01	2.14	2.33	2.42	2.18	2.04	2.09	2.14	2.37	2.42
Variation	-0.27	-0.43	-0.57	-0.79	-0.80	-0.79	-0.24	-0.51	-0.54	-0.63	-0.63	-0.63
% Variation	-10.98	-17.27	-22.09	-26.96	-25.56	-24.61	-9.92	-20.00	-20.53	-22.74	-21.00	-20.66
IBW(mm)-2mm/sec	1.84	1.85	2.09	2.47	2.75	2.85	1.77	1.89	2.00	2.33	2.62	2.69
IBW(mm)-3mm/sec	1.39	1.12	1.12	1.33	1.75	1.81	1.46	1.23	1.20	1.42	1.73	1.81
Variation	-0.45	-0.73	-0.97	-1.14	-1.00	-1.04	-0.31	-0.66	-0.80	-0.91	-0.89	-0.88
% Variation	-24.46	-39.46	-46.41	-46.15	-36.36	-36.49	-17.51	-34.92	-40.00	-39.06	-33.97	-32.71
AREA(mm ²)-2mm/sec	1.29	1.30	1.40	1.62	1.76	1.82	1.26	1.33	1.39	1.53	1.69	1.72
AREA(mm ²)-3mm/sec	1.08	0.95	0.94	1.04	1.22	1.27	1.09	0.98	0.99	1.07	1.23	1.27
Variation	-0.21	-0.35	-0.46	-0.58	-0.54	-0.55	-0.17	-0.35	-0.40	-0.46	-0.46	-0.45
% Variation	-16.28	-26.92	-32.86	-35.80	-30.68	-30.22	-13.49	-26.32	-28.78	-30.07	-27.22	-26.16
I/O-2mm/sec	0.75	0.74	0.81	0.84	0.88	0.89	0.73	0.74	0.76	0.84	0.87	0.88
I/O-3mm/sec	0.64	0.55	0.56	0.62	0.75	0.75	0.67	0.60	0.57	0.66	0.73	0.75
Variation	-0.11	-0.19	-0.25	-0.22	-0.13	-0.14	-0.06	-0.14	-0.19	-0.18	-0.14	-0.13

Figure 109a: Investigation of the Influence of Welding Speed (WS) on Weld Bead Characteristics for Both Orifice Diameters Utilised, Based on a Typical Input Parameter Combination and Two Different Welding Speeds (2.0mm/sec and 3.0mm/sec).

Melt-in Mode Welding of 316L Tubes



Keyhole Welding of 316L Tubes



Influence of WS on Bead Characteristics in Plasma Welding of 316L Tubes

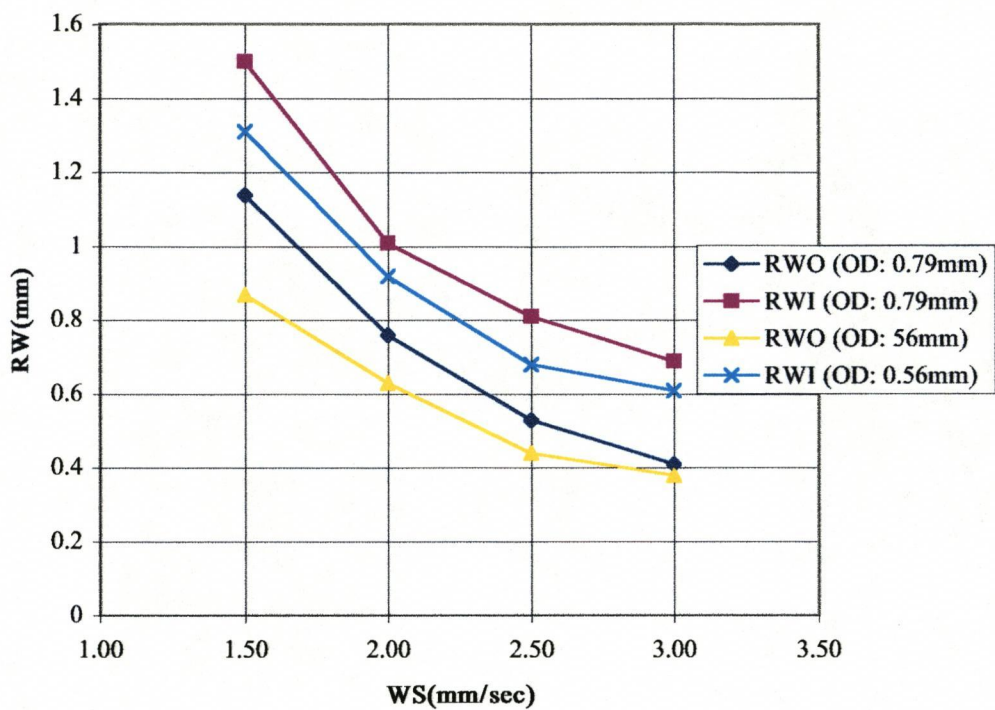
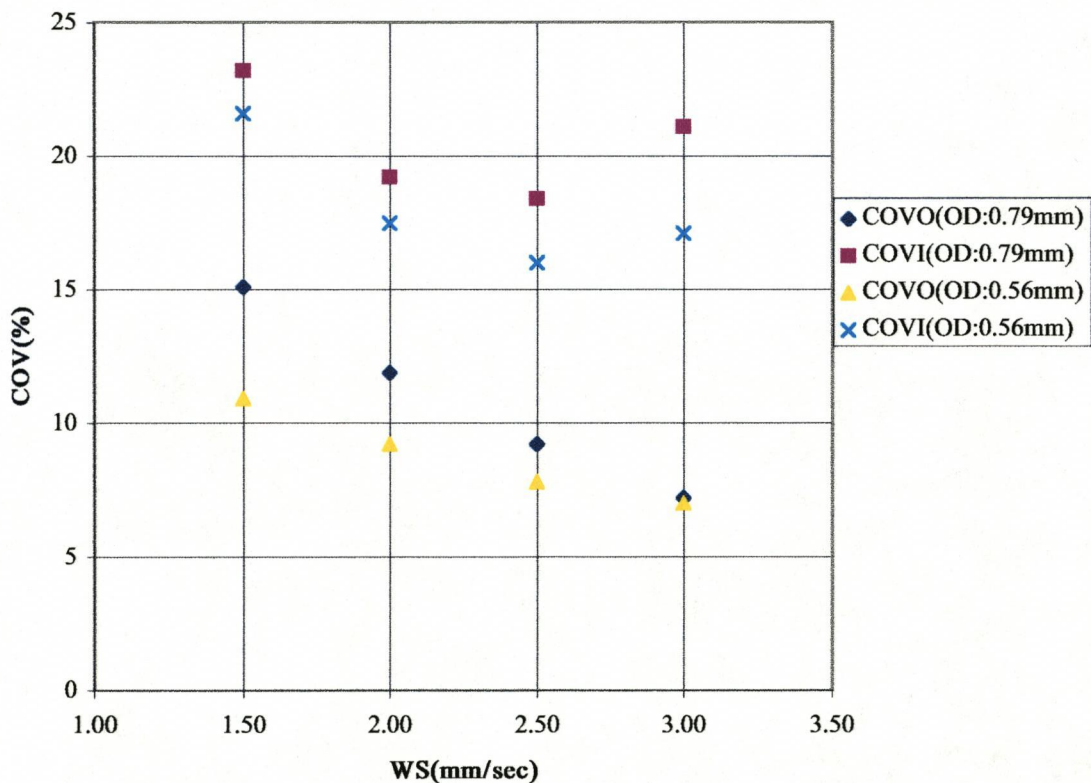
	Melt-in Mode Welding of 316L Tubes							Keyhole Welding of 316L Tubes						
Position	3	8	13	18	23	28	33	3	8	13	18	23	28	33
OBW(mm) (s)	2.38	2.37	2.40	2.49	2.57	2.78	2.71	2.49	2.11	2.10	2.14	2.19	2.40	2.32
OBW(mm) (f)	1.83	1.68	1.70	1.74	1.78	1.98	1.88	2.28	1.80	1.75	1.76	1.81	2.11	1.96
Variation	-0.55	-0.69	-0.70	-0.75	-0.79	-0.80	-0.83	-0.21	-0.31	-0.35	-0.38	-0.38	-0.29	-0.36
% Variation	-23.11	-29.11	-29.17	-30.12	-30.74	-28.78	-30.63	-8.43	-14.69	-16.67	-17.76	-17.35	-12.08	-15.52
IBW(mm) (s)	1.82	1.82	1.95	2.08	2.27	2.60	2.55	1.95	1.66	1.72	1.80	1.93	2.24	2.29
IBW(mm) (f)	1.10	0.77	0.72	0.90	1.08	1.47	1.35	1.65	1.11	1.09	1.17	1.29	1.65	1.59
Variation	-0.72	-1.05	-1.23	-1.18	-1.19	-1.13	-1.20	-0.30	-0.55	-0.63	-0.63	-0.64	-0.59	-0.70
% Variation	-39.56	-57.69	-63.08	-56.73	-52.42	-43.46	-47.06	-15.38	-33.13	-36.63	-35.00	-33.16	-26.34	-30.57
AREA(mm²) (s)	2.63	2.62	2.72	2.86	3.02	3.36	3.28	2.77	2.36	2.39	2.46	2.67	2.90	2.88
AREA(mm²) (f)	1.83	1.53	1.51	1.65	1.78	2.15	2.02	2.46	1.82	1.78	1.83	1.93	2.35	2.22
Variation	-0.80	-1.09	-1.21	-1.21	-1.24	-1.21	-1.26	-0.31	-0.54	-0.61	-0.63	-0.74	-0.55	-0.66
% Variation	-30.42	-41.60	-44.49	-42.31	-41.06	-36.01	-38.41	-11.19	-22.88	-25.52	-25.61	-27.72	-18.97	-22.92
I/O (s)	0.77	0.77	0.81	0.84	0.88	0.94	0.94	0.78	0.79	0.82	0.84	0.88	0.94	0.99
I/O (f)	0.60	0.46	0.42	0.52	0.61	0.74	0.72	0.72	0.61	0.62	0.66	0.71	0.78	0.81
Variation	-0.17	-0.31	-0.39	-0.32	-0.27	-0.20	-0.22	-0.06	-0.18	-0.20	-0.18	-0.17	-0.16	-0.18
Undercut Index (s)									-0.26		-0.20		0.02	
Undercut Index (f)									-0.66		-0.64		-0.58	
Variation									-0.40		-0.44		-0.60	

Figure 109b: Influence of Welding Speed (WS) on Weld Bead Characteristics for:

a) Melt-in Mode Welding of 316L Tubes (12.7mm X 0.7mm)-(HI₁: 11A, PGFR: 0.4l/min, ESB: 1.7mm, WS(s): 2.0mm/sec, WS(f): 3mm/sec)

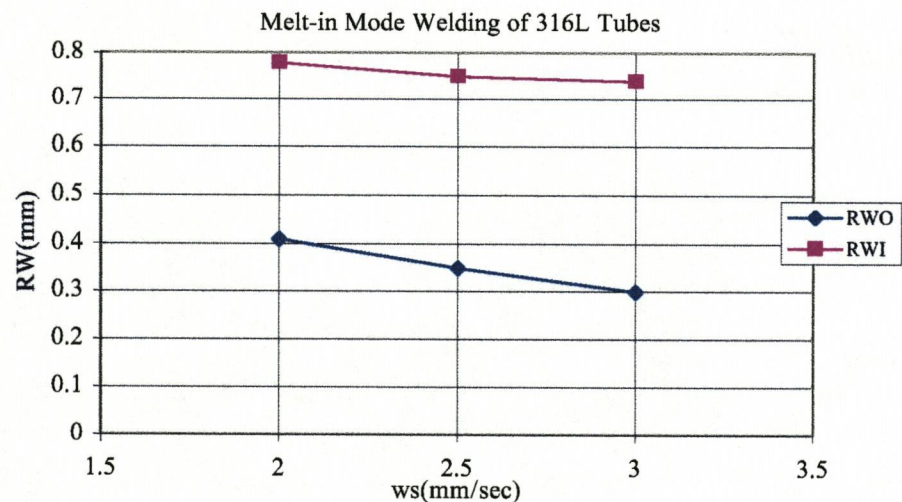
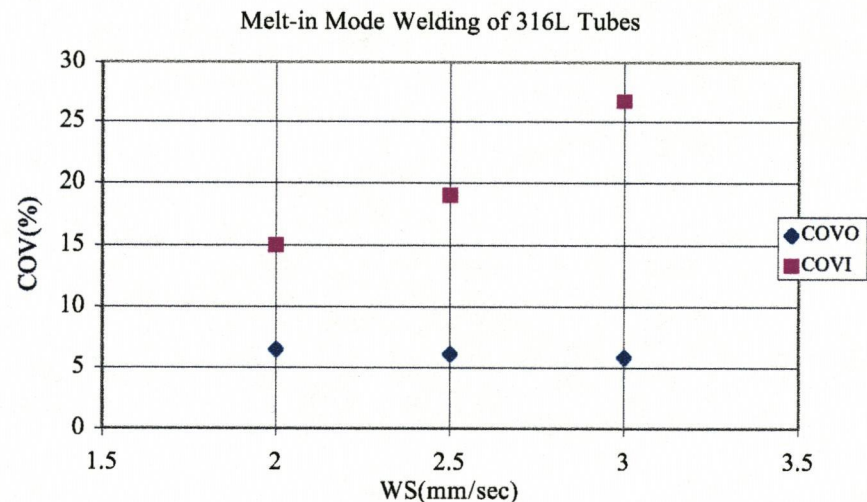
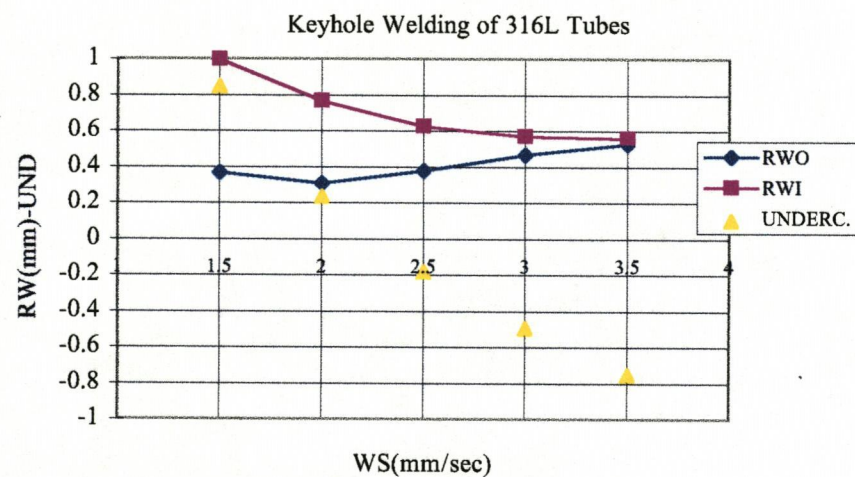
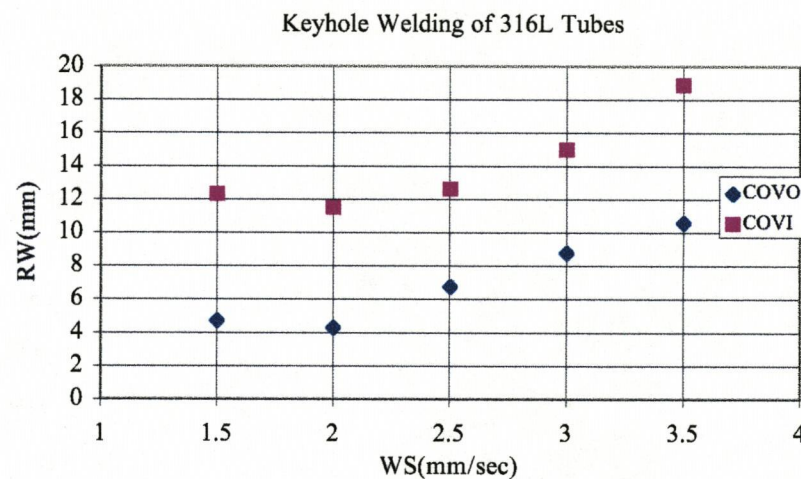
b) Keyhole Welding of 316L Tubes (12.7mm X 1.25mm)-(HI₁: 18A, PGFR: 2.1l/min, ESB: 1.7mm, WS(s): 2.5mm/sec, WS(f): 3.5mm/sec)

s: Initial Welding Speed, f: Final Welding Speed



RW: Width Range Between Maximum and Minimum Outer(RWO) or Inner (RWI) Bead Widths
COV: Coefficient of Variation for the Outer (COVO) or Inner (COVI) Bead Widths

Figure 109c: Influence of Welding Speed(WS) on Weld Bead Uniformity for Both Orifice Diameters(0.79mm and 0.56mm) Utilised, Based on a Typical Input Parameter Combination (HI₁:11A, PGFR: 0.6l/min, ESB: 1.7mm, HIS: 20sec*A)

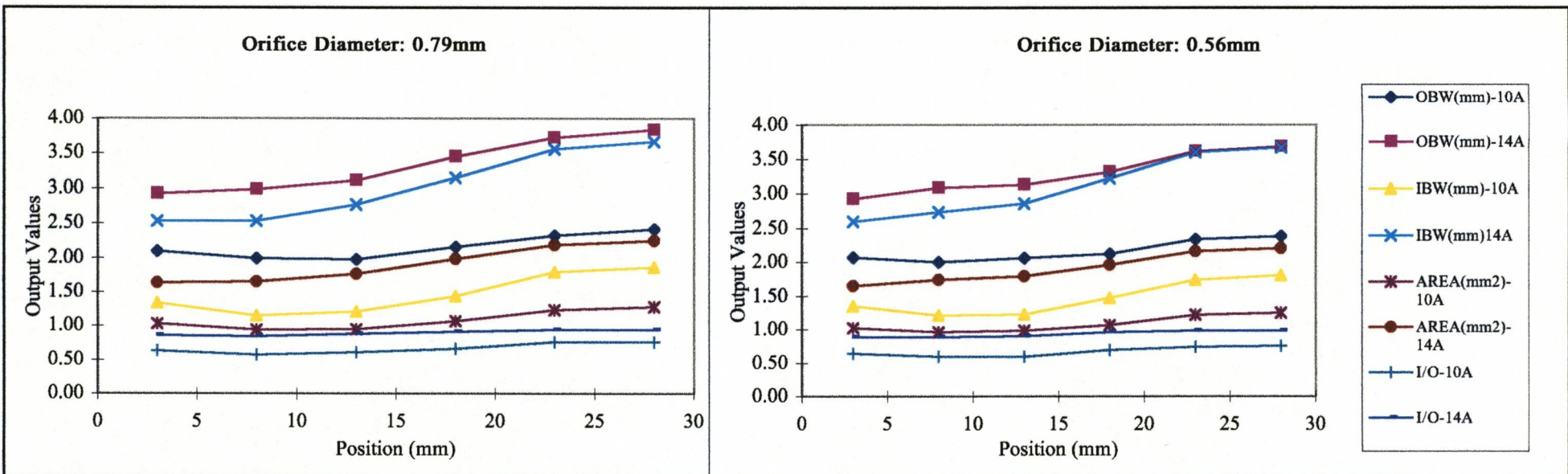


RW: Range Between Maximum and Minimum Outer (RWO) or Inner (RWI) Bead Widths
 COV: Coefficient of Variation for the Outer(COVO) or Inner(COVI) Bead Widths
 UNDERC: Average Undercut Indication Index

Figure 109d: Influence of Welding Speed on Weld Bead Uniformity and Undercut (for Keyhole Welding) for:

a: Keyhole Welding of 316L Tubes (HI₁: 18A, PGFR: 2.1l/min, ESB: 1.7mm)

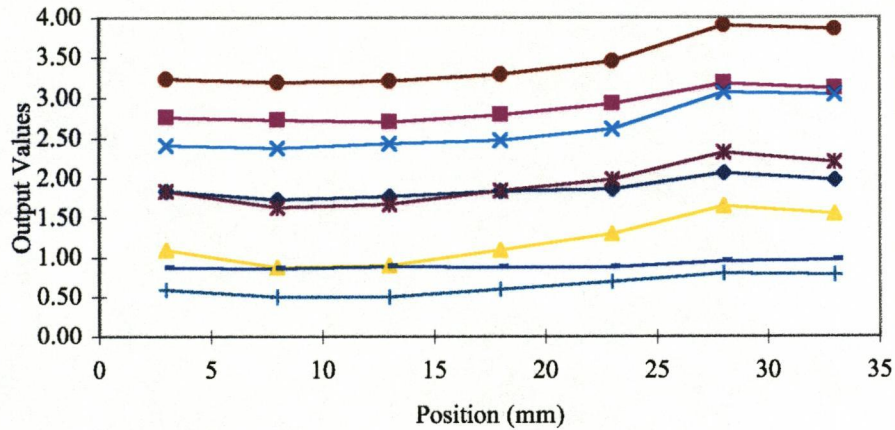
b: Melt-in Mode Welding of 316L Tubes (HI₁: 10A, PGFR: 0.4l/min, ESB: 1.7mm)



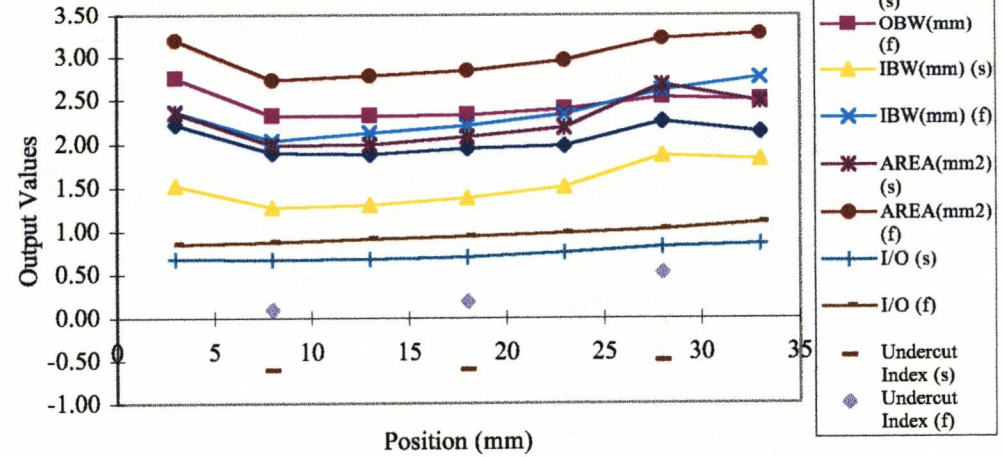
Influence of HI_1 on Bead Characteristics for Both Orifice Diameters Utilised (WS: 2.5mm/sec, PGFR: 0.6l/min, ESB: 1.7mm, HIS: 20sec*A)												
	ORIFICE DIAMETER: 0.79mm						ORIFICE DIAMETER: 0.56mm					
Position	3	8	13	18	23	28	3	8	13	18	23	28
OBW(mm)-10A	2.10	2.00	1.98	2.16	2.33	2.42	2.08	2.01	2.07	2.13	2.34	2.39
OBW(mm)-14A	2.93	2.99	3.12	3.46	3.73	3.84	2.93	3.09	3.14	3.32	3.62	3.69
Variation	0.83	0.99	1.14	1.30	1.40	1.42	0.85	1.08	1.07	1.19	1.28	1.30
% Variation	39.52	49.50	57.58	60.19	60.09	58.68	40.87	53.73	51.69	55.87	54.70	54.39
IBW(mm)-10A	1.35	1.16	1.22	1.45	1.80	1.87	1.36	1.22	1.24	1.48	1.75	1.82
IBW(mm)-14A	2.54	2.54	2.77	3.16	3.56	3.67	2.60	2.74	2.86	3.23	3.60	3.67
Variation	1.19	1.38	1.55	1.71	1.76	1.80	1.24	1.52	1.62	1.75	1.85	1.85
% Variation	88.15	118.97	127.05	117.93	97.78	96.26	91.18	124.59	130.65	118.24	105.71	101.65
AREA(mm ²)-10A	1.04	0.95	0.96	1.08	1.24	1.29	1.03	0.97	0.99	1.08	1.23	1.26
AREA(mm ²)-14A	1.64	1.66	1.77	1.99	2.19	2.25	1.66	1.75	1.80	1.97	2.17	2.21
Variation	0.60	0.71	0.81	0.91	0.95	0.96	0.63	0.78	0.81	0.89	0.94	0.95
% Variation	57.69	74.74	84.38	84.26	76.61	74.42	61.17	80.41	81.82	82.41	76.42	75.40
I/O-10A	0.64	0.58	0.62	0.67	0.77	0.77	0.65	0.60	0.60	0.70	0.75	0.76
I/O-14A	0.87	0.85	0.89	0.92	0.95	0.95	0.89	0.89	0.91	0.97	0.99	0.99
Variation	0.23	0.27	0.27	0.25	0.18	0.18	0.24	0.29	0.31	0.27	0.24	0.23

Figure 110a: Investigation of the Influence of Welding Current (HI_1) on Weld Bead Characteristics for Both Orifice Diameters Utilised, Based on a Typical Input Parameter Combination and Two Different Welding Currents (10A and 14A).

Melt-in Mode Welding of 316L Tubes



Keyhole Welding of 316L Tube Welding



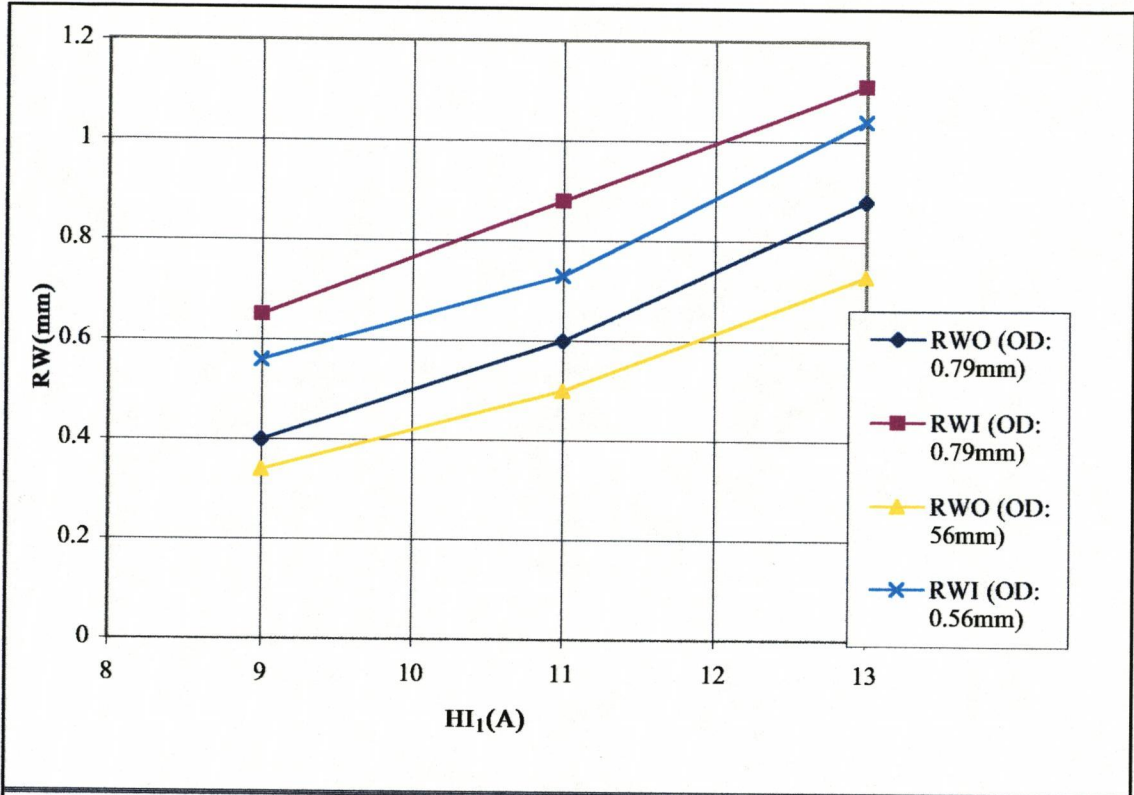
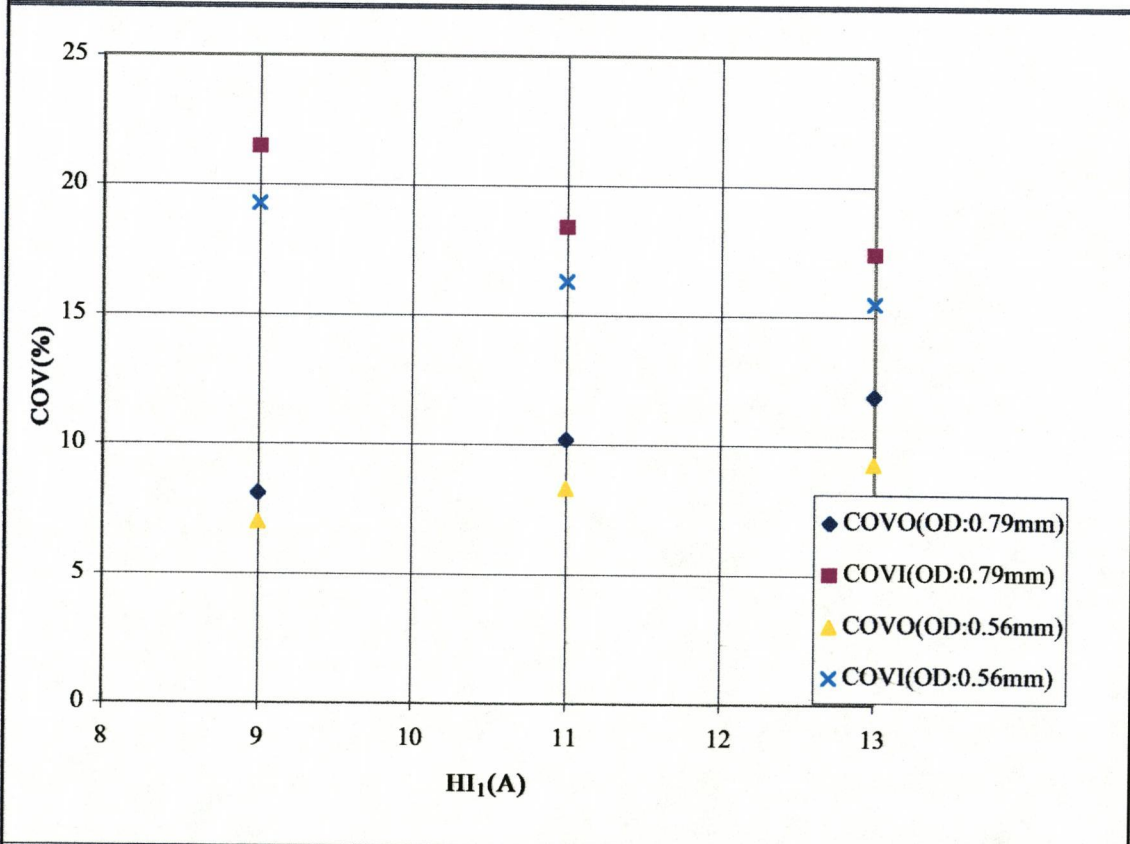
Influence of HI_1 on Bead Characteristics in Plasma Welding of 316L Tubes

	Melt-in Mode Welding of 316L Tubes							Keyhole Welding of 316L Tubes						
Position	3	8	13	18	23	28	33	3	8	13	18	23	28	33
OBW(mm) (s)	1.84	1.74	1.78	1.84	1.87	2.07	1.98	2.23	1.90	1.89	1.95	1.98	2.26	2.14
OBW(mm) (f)	2.76	2.73	2.71	2.80	2.93	3.18	3.12	2.75	2.32	2.32	2.33	2.40	2.53	2.50
Variation	0.92	0.99	0.93	0.96	1.06	1.11	1.14	0.52	0.42	0.43	0.38	0.42	0.27	0.36
% Variation	50.00	56.90	52.25	52.17	56.68	53.62	57.58	23.32	22.11	22.75	19.49	21.21	11.95	16.82
IBW(mm) (s)	1.11	0.89	0.91	1.11	1.31	1.66	1.56	1.53	1.28	1.31	1.39	1.52	1.87	1.83
IBW(mm) (f)	2.42	2.38	2.44	2.48	2.62	3.07	3.05	2.37	2.04	2.13	2.21	2.34	2.61	2.76
Variation	1.31	1.49	1.53	1.37	1.31	1.41	1.49	0.84	0.76	0.82	0.82	0.82	0.74	0.93
% Variation	118.02	167.42	168.13	123.42	100.00	84.94	95.51	54.90	59.38	62.60	58.99	53.95	39.57	50.82
AREA(mm ²) (s)	1.84	1.64	1.68	1.85	1.99	2.33	2.21	2.36	1.99	2.00	2.09	2.19	2.68	2.48
AREA(mm ²) (f)	3.24	3.20	3.22	3.30	3.46	3.91	3.86	3.20	2.73	2.78	2.84	2.96	3.22	3.28
Variation	1.40	1.56	1.54	1.45	1.47	1.58	1.65	0.84	0.74	0.78	0.75	0.77	0.54	0.80
% Variation	76.09	95.12	91.67	78.38	73.87	67.81	74.66	35.59	37.19	39.00	35.89	35.16	20.15	32.26
I/O (s)	0.60	0.51	0.51	0.61	0.70	0.81	0.79	0.69	0.68	0.69	0.71	0.76	0.83	0.86
I/O (f)	0.88	0.87	0.90	0.89	0.89	0.96	0.98	0.86	0.88	0.92	0.95	0.98	1.03	1.10
Variation	0.28	0.36	0.39	0.28	0.19	0.15	0.19	0.17	0.20	0.23	0.24	0.22	0.20	0.24
Undercut Index (s)									-0.61		-0.60		-0.50	
Undercut Index (f)									0.10		0.20		0.53	
Variation									0.71		0.80		1.03	

Figure 110b: Influence of Welding Current (HI_1) on Weld Bead Characteristics for:

a) Melt-in Mode Welding of 316L Tubes (12.7mm X 0.7mm)-(WS: 2.50mm/sec, PGFR: 0.4l/min, ESB: 1.7mm, HI_1 (s): 10A, HI_1 (f): 14A)

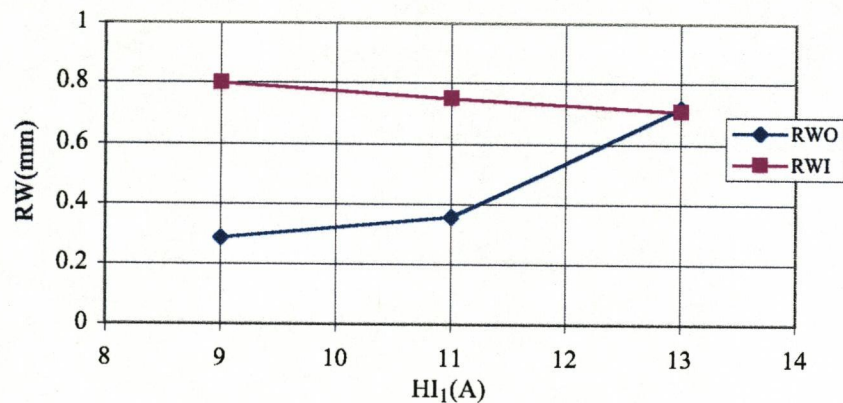
b) Keyhole Welding of 316L Tubes (12.7mm X 1.25mm)-(WS: 2.50mm/sec, PGFR: 2.1l/min, ESB: 1.7mm, HI_1 (s): 16A, HI_1 (f): 20A)



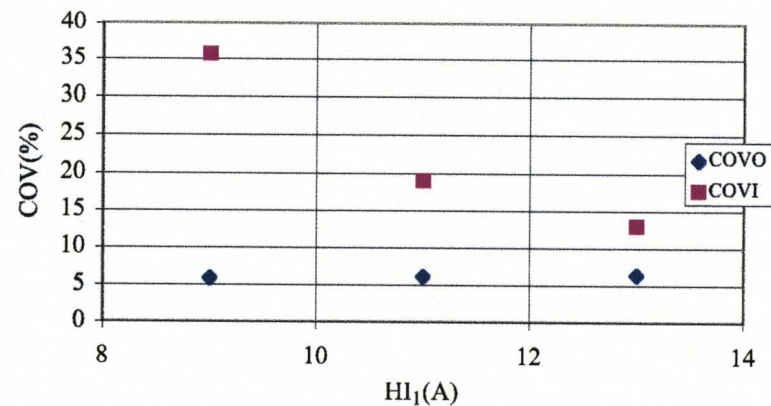
RW: Width Range Between Maximum and Minimum Outer (RWO) or Inner (RWI) Bead Widths
 COV: Coefficient of Variation for the Outer (COVO) or Inner (COVI) Bead Widths

Figure 110c: Influence of Welding Current (HI_1) on Weld Bead Uniformity for Both Orifice Diameters (0.79mm and 0.56mm) Utilised, Based on a Typical Input Parameter Combination (WS:2.3mm/sec, PGFR: 0.6l/min, ESB: 1.7mm, HIS: 20sec*A).

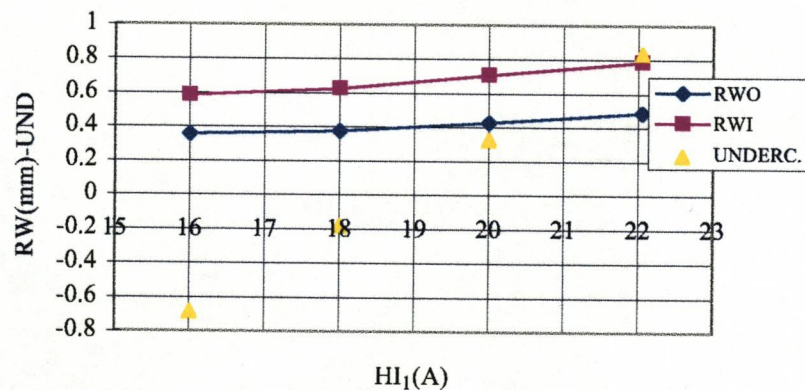
Melt-in Mode Welding of 316L Tubes



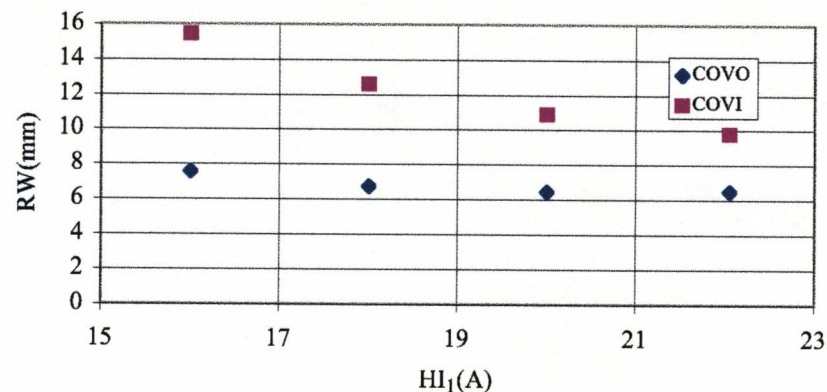
Melt-in Mode Welding of 316L Tubes



Keyhole Welding of 316L Tubes



Keyhole Welding of 316L Tubes



RW: Width Range Between Maximum and Minimum Outer (RWO) or Inner (RWI) Bead Widths

COV: Coefficient of Variation for the Outer (COVO) or Inner (COVI) Bead Widths

UNDERC: Average Undercut Indication Index

Figure 110d: Influence of Welding Current on Weld Bead Uniformity and Undercut (for Keyhole Welding) for:

a: Keyhole Welding of 316L Tubes (WS: 2.5mm/sec, PGFR: 2.1l/min, ESB: 1.7mm)

b: Melt-in Mode Welding of 316L Tubes (WS: 2.5mm/sec, PGFR: 0.4l/min, ESB: 1.7mm)

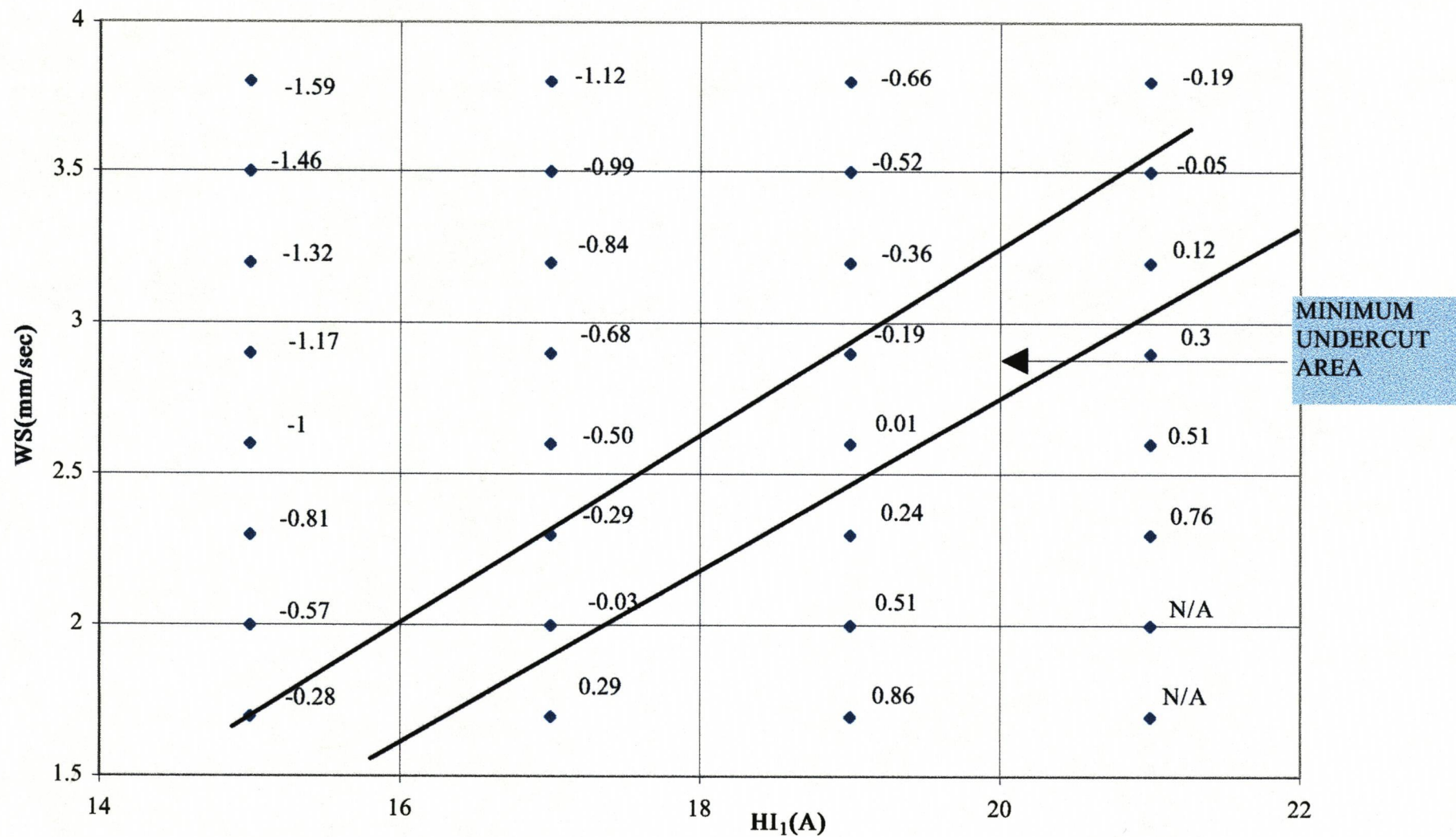


Figure 110e: Minimum Undercut Area for a Number of Welding Current-Welding Speed Combinations (Based on the "Average Undercut Indication" Index - PGFR:2.11/min, ESB: 1.7mm).

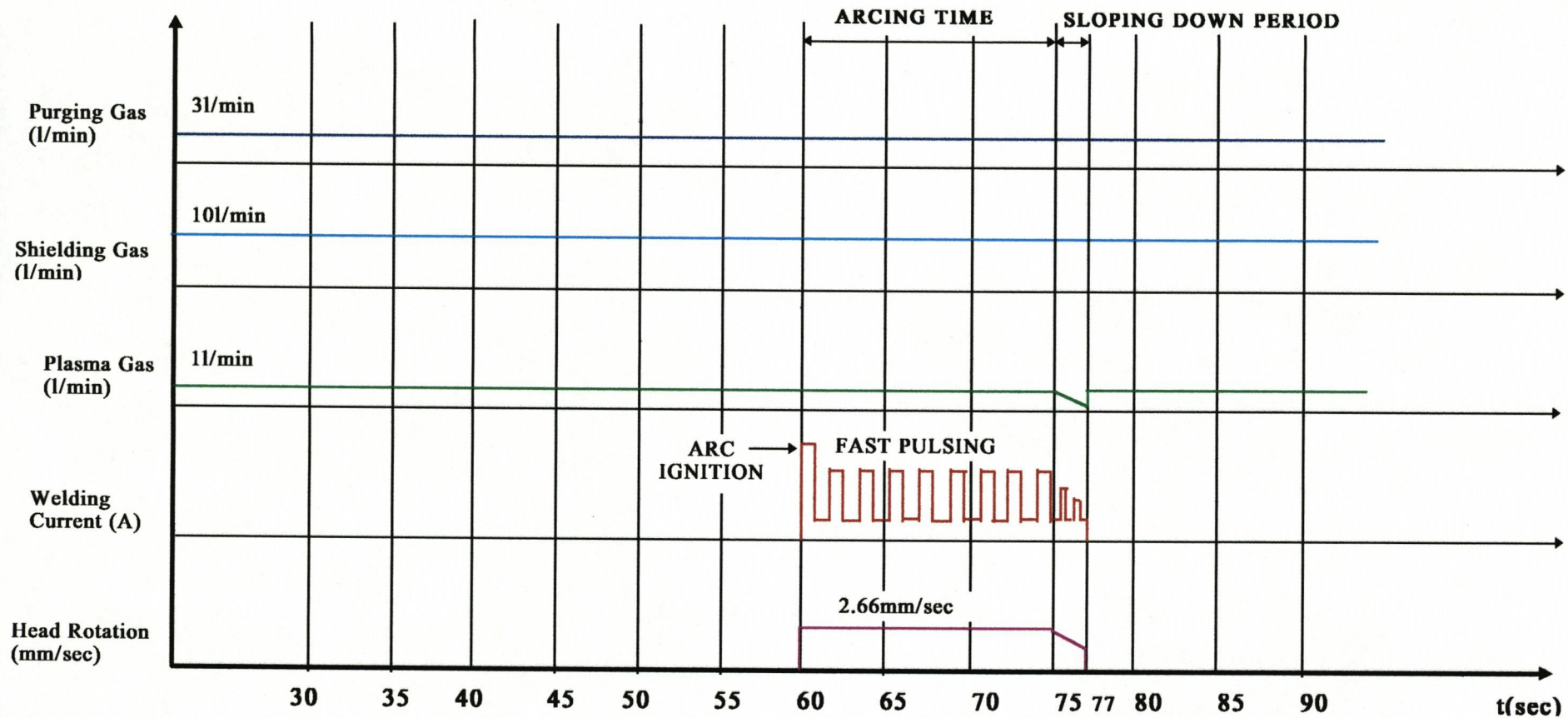


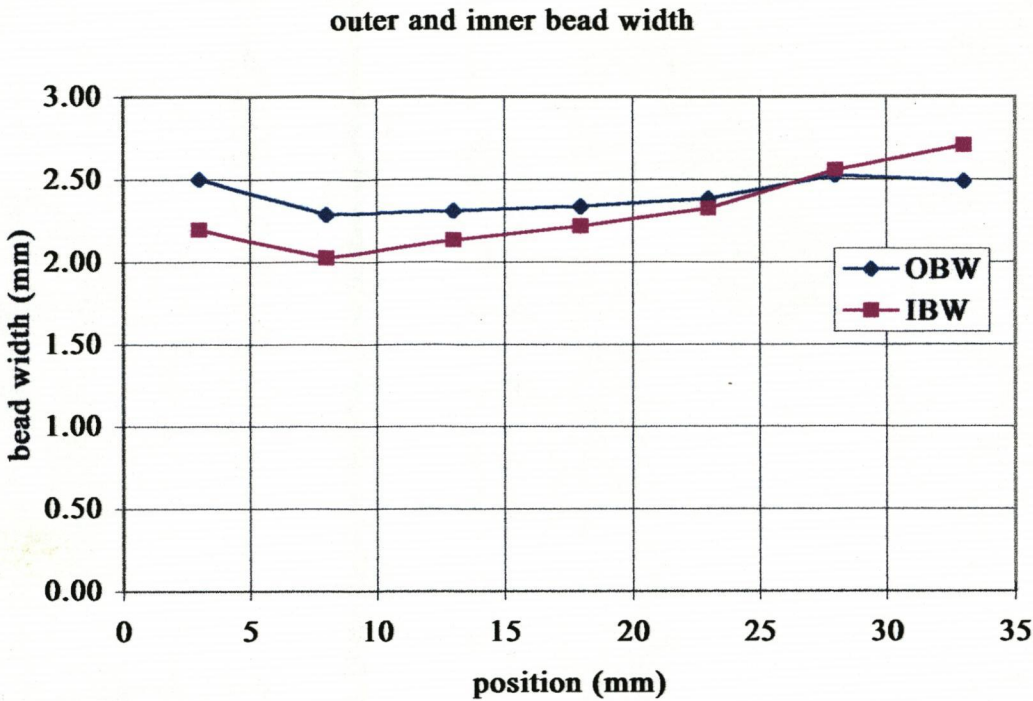
Figure 111: Typical Structure of the Welding Cycle Utilised During this Investigation for Orbital Plasma Welding of Small Bore Tubes.

ORBITAL KEYHOLE PLASMA WELDING OF 316L SEAMLESS STAINLESS STEEL TUBE (12.7mm X 1.25mm)

VALUES WITHIN THE OPERATIONAL ENVELOPE

Input variables			
←		→	WI 19.0
←		→	WS 2.32
←		→	PGFR 2.0
←		→	ESB 1.3

WELD BEAD DIMENSIONS AND INDICES				POSSIBILITY FOR UNDERCUT FORMATION		
OBW3	2.50	IBW3	2.19	ABS. VAL.		
OBW8	2.28	IBW8	2.02	UND8	0.04	0.04
OBW13	2.31	IBW13	2.13	UND18	0.12	0.12
OBW18	2.34	IBW18	2.22	UND28	0.41	0.41
OBW23	2.38	IBW23	2.32	MAX ABS 0.41		
OBW28	2.52	IBW28	2.55	ABS UND 0.23		
OBW33	2.49	IBW33	2.70			
minOBW(3-33)	2.28	minIBW(3-33)	2.02	G(UND)	0.23	0.23
maxOBW(3-33)	2.52	maxIBW(3-33)	2.70	NO	TYPE 1-2	
minOBW(8-23)	2.28	minIBW(8-23)	2.02	NO	TYPE 2	
maxOBW(8-23)	2.38	maxIBW(8-23)	2.32	NO	TYPE 2-3	
SDEV(3-33)	0.10	SDEV(3-33)	0.24	NO	TYPE 3	
COV(3-33)	4.12	COV(3-33)	10.5	NO	TYPE 1	
SDEV(8-23)	0.04	SDEV(8-23)	0.13	NO	TYPE 1-4	
COV(8-23)	1.82	COV(8-23)	5.95	YES	TYPE 4	
RW(3-33)	0.24	RW(3-33)	0.68	NO	TYPE 4-5	
RW(8-23)	0.10	RW(8-23)	0.30	NO	TYPE 5	



OBJECTIVE FUNCTIONS

G1	G6
G2	G7
G3	G8
G4	G9
G5	G10

CUTTING SUSCEPTIBILITY BASED ON THE I/O RATIO

LOW CUTTING RISK FOR POS.23
 LOW CUTTING RISK FOR POS.28
 LOW CUTTING RISK FOR POS.33

LIST OF CONSTRAINTS

min OBW	1.2 mm
max OBW	4.8 mm
min IBW	1.2 mm
max IBW	4.8 mm
max I/O	1.2
MAXABSU	0.5
RWI(3-33)	0.7

LIST OF PARAMETER CONSTRAINTS

WI	min	15	max	22
WS	min	1.66	max	3.99
PGFR	min	1.9	max	2.5
ESB	min	1.3	max	2

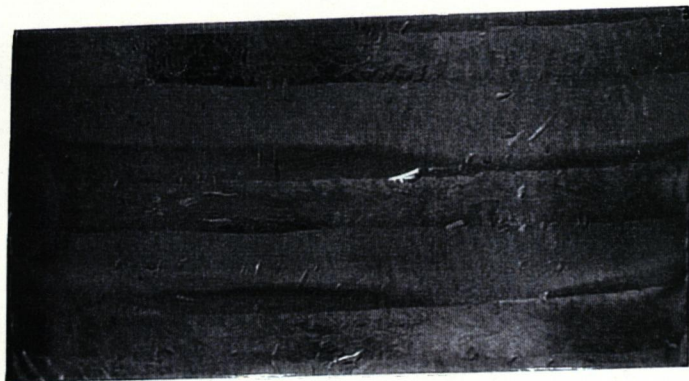
Position	IBW/OBW FUSION AREA (mm ²)	
3	0.88	2.93
8	0.88	2.69
13	0.92	2.77
18	0.95	2.85
23	0.98	2.94
28	1.01	3.17
33	1.09	3.25
SDEV(8-23)	0.04	0.11
COV(8-23)	4.16	3.81

Figure 112: Illustration of a Typical Procedure Optimisation Spreadsheet.

HIS: 20sec*A

HIS: 30sec*A

HIS: 40sec*A

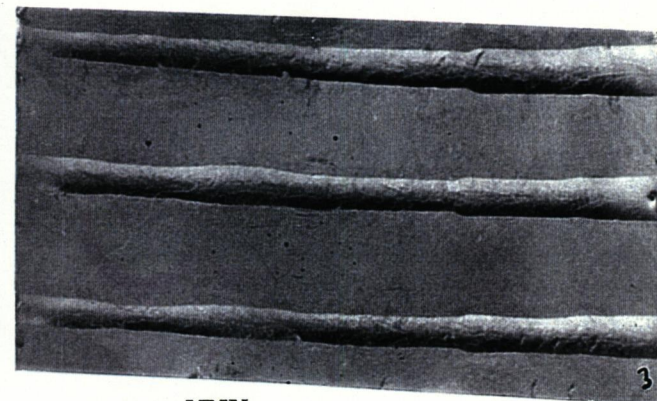


OBW

HIS: 40sec*A

HIS: 30sec*A

HIS: 20sec*A



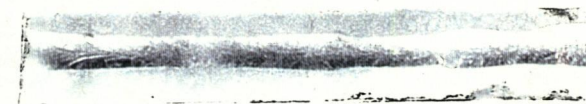
IBW

Influence of HIS on Weld Bead Characteristics in Ti-3Al-2.5V Tube Welding (OD: 0.79mm, WI: 12A, I_p : 19A, t_p : 50msec, I_b : 5A, t_b : 50msec, Frequency: 10Hz, WS: 3.14mm/sec, PGFR: 0.3l/min, ESB: 1.95mm).



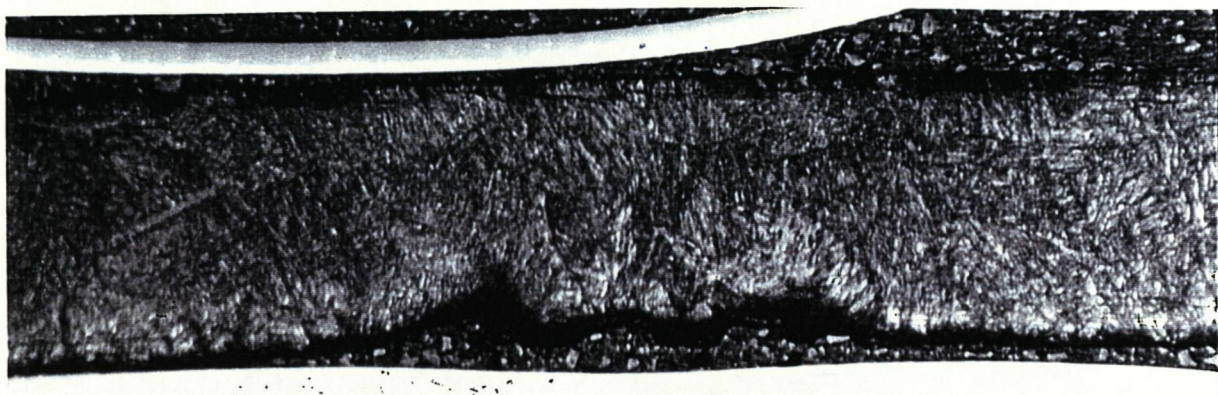
OBW

Enhanced Weld Bead Uniformity Obtained With the Use of Two Segments During the Torch Rotation in Ti-3Al-2.5V Tube Welding (OD: 0.79mm, WS: 2.5mm/sec, PGFR: 0.3l/min, ESB: 2.0mm, HIS: 24sec*A, Frequency: 10Hz, t_p : 50msec, t_b : 50msec).
1st Segment: WI: 10.5A, I_p : 16A, I_b : 5A.
2nd Segment: WI: 9A, I_p : 13A, I_b : 5A.

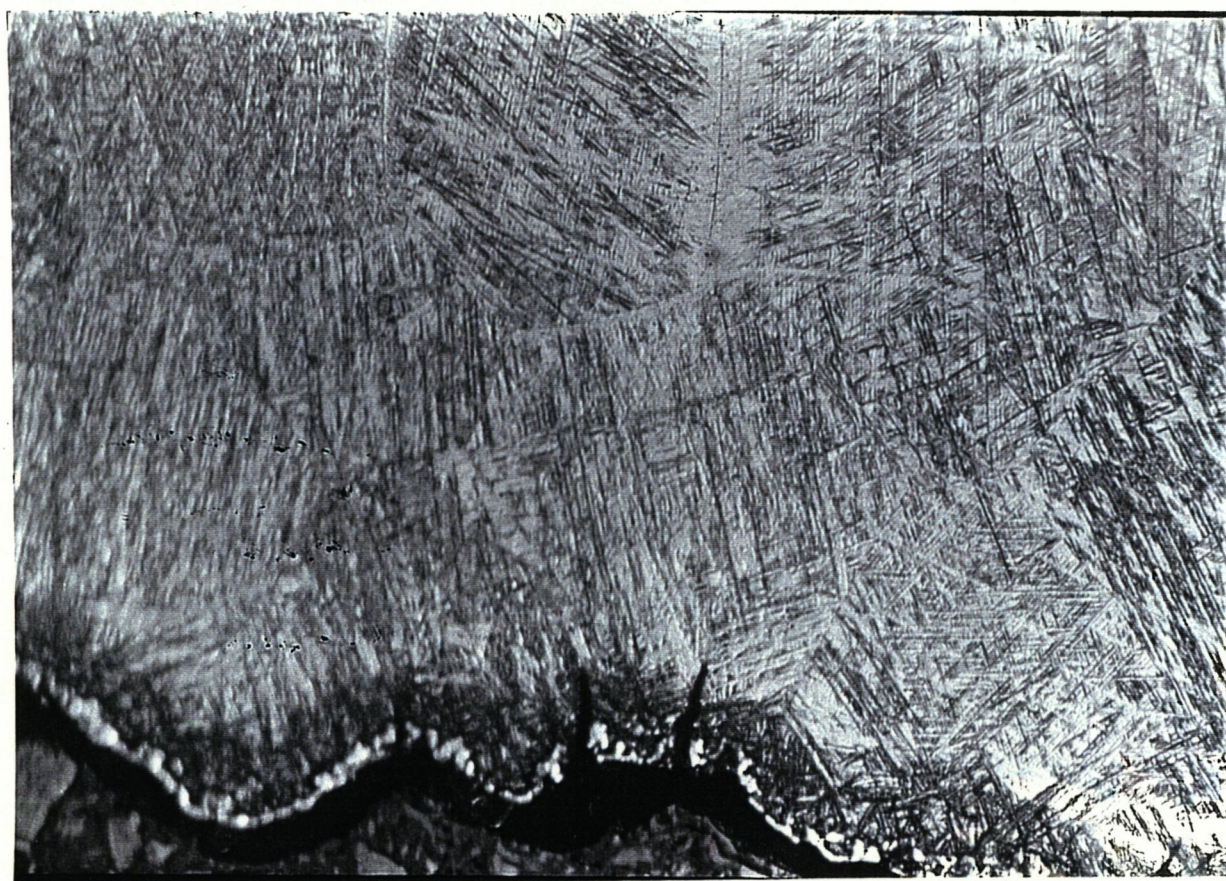


IBW

Figure 113: Outer and Inner Beads Obtained in Ti-3Al-2.5V Orbital Plasma Tube Welding.

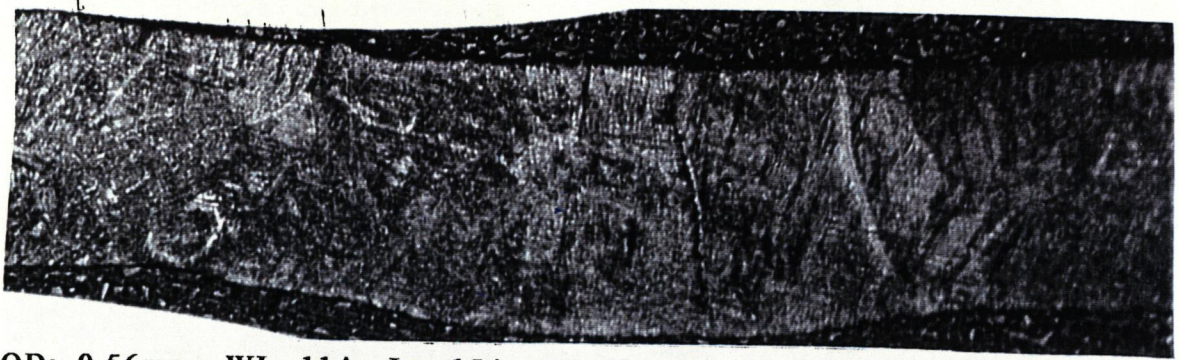


Weld and Heat Affected Zones (X60)

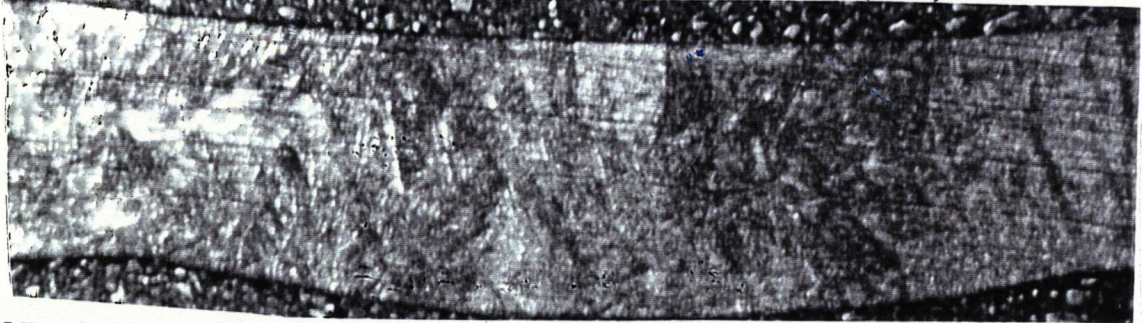


Weld Zone Microstructure - Inner Weld Bead (X240)

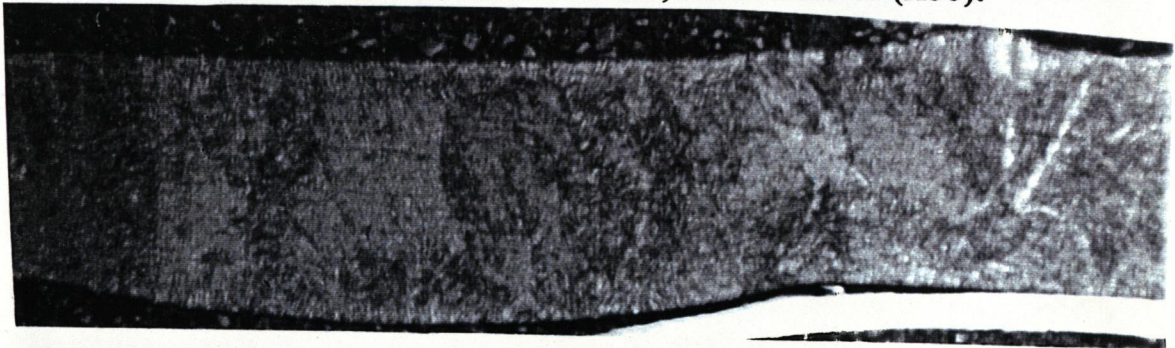
Figure 114: Weld Shape and Microstructure of an Oxidised Ti-3Al-2.5V Inner Bead (OD: 0.79mm, WI: 12A, I_p : 19A, t_p : 50msec, I_b : 5A, t_b : 50msec, WS: 2.62mm/sec, PGFR: 0.3l/min, ESB: 1.95mm).



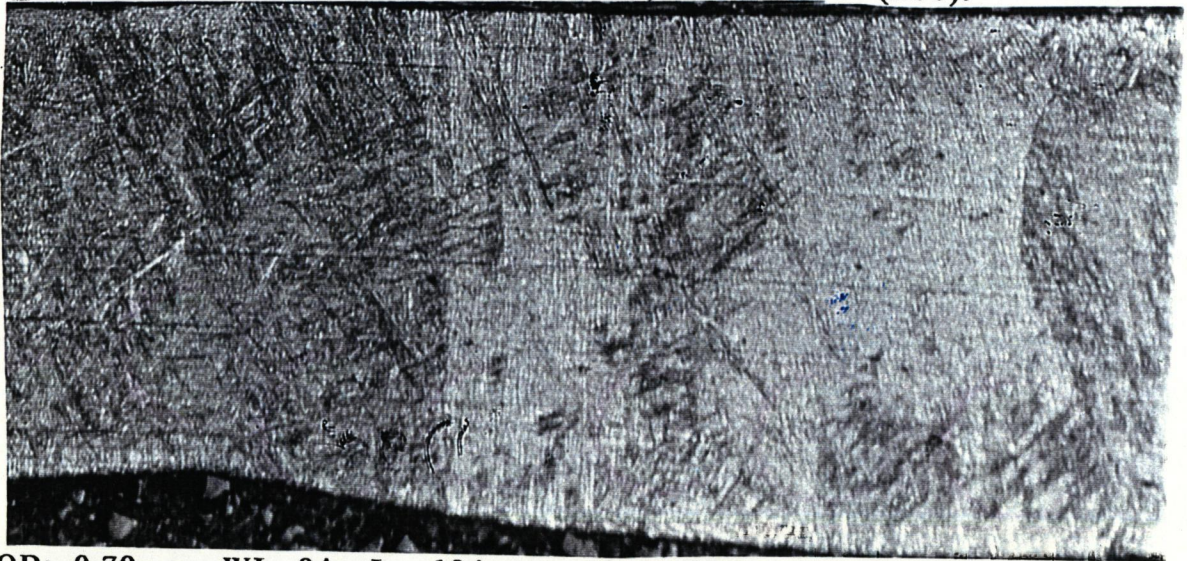
OD: 0.56mm, WI: 11A, Ip: 15A, tp: 50msec, Ib: 7A, tb: 50msec, WS: 2.50mm/sec, PGFR: 0.4l/min, ESB: 2.0mm, HIS: 15sec*A (X50).



OD: 0.56mm, WI: 10A, Ip: 15A, tp: 50msec, Ib: 5A, tb: 50msec, WS: 1.57mm/sec, PGFR: 0.6l/min, ESB: 1.50mm, HIS: 20sec*A (X50).

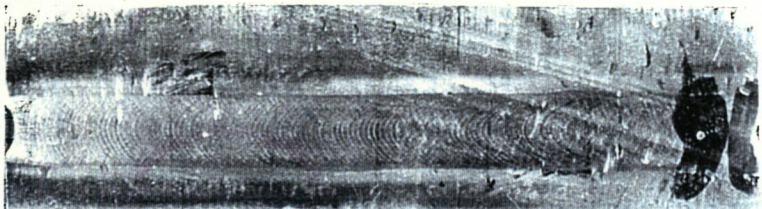
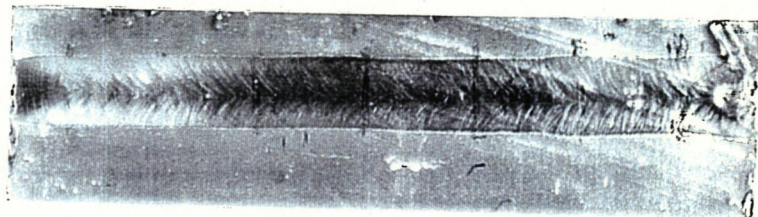


OD: 0.79mm, WI: 9A, Ip: 13A, tp: 50msec, Ib: 5A, tb: 50msec, WS: 1.57mm/sec, PGFR: 0.6l/min, ESB: 1.50mm, HIS: 20sec*A (X50).



OD: 0.79mm, WI: 9A, Ip: 13A, tp: 50msec, Ib: 5A, tb: 50msec, WS: 1.57mm/sec, PGFR: 0.6l/min, ESB: 1.50mm, HIS: 20sec*A (X120).

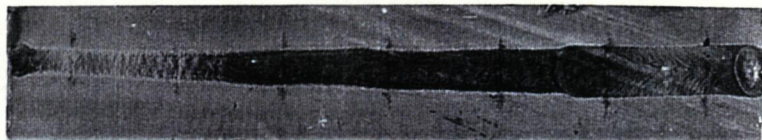
Figure 115: Typical Weld and Heat Affected Zone microstructures of Ti-3Al-2.5V tube welding.



OBW

WI: 14.2A, I_p : 28A, t_p : 20msec, I_b : 5A, t_b : 30msec, WS: 2.66mm/sec, PGFR: 0.6l/min, ESB: 1.95mm

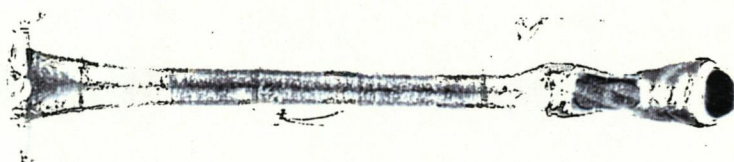
IBW



OBW

WI: 9A, I_p : 15A, t_p : 20msec, I_b : 5A, t_b : 30msec, WS: 1.99mm/sec, PGFR: 0.6l/min, ESB: 1.95mm

IBW

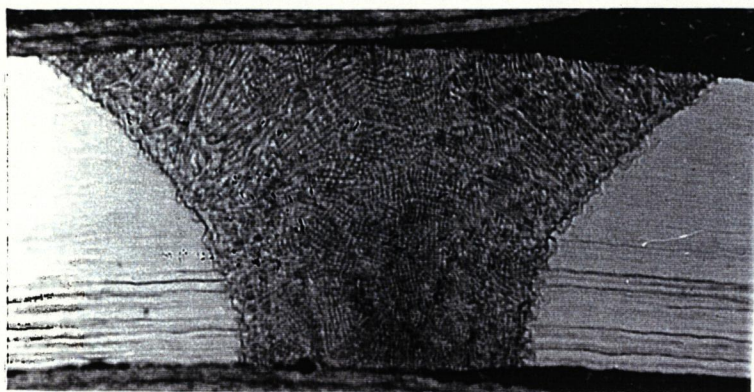


OBW

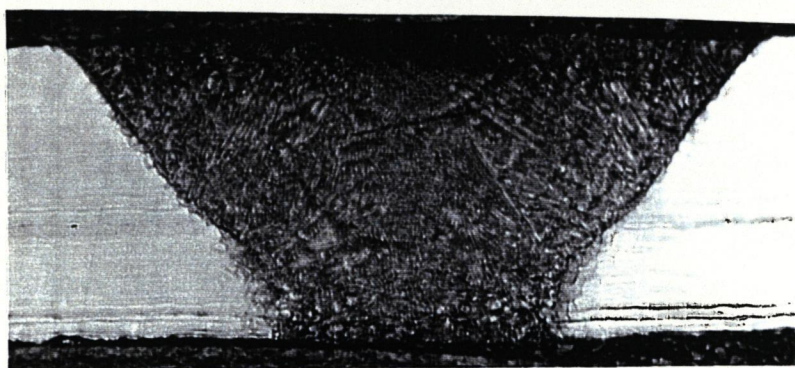
WI: 15A, I_p : 30A, t_p : 20msec, I_b : 5A, t_b : 30msec, WS: 3.99mm/sec, PGFR: 0.6l/min, ESB: 1.45mm

IBW

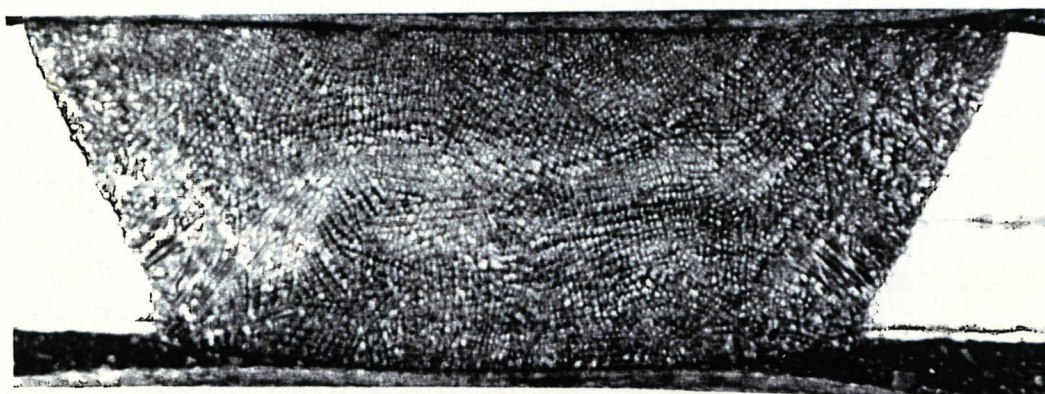
Figure 116: Typical Outer and Inner Beads from the Melt-In Mode Welding of 316L Tubes.



WI:10.2A (I_p : 18A, t_p : 20msec, I_b : 5A, t_b : 30msec), WS: 1.99mm/sec, PGFR: 0.6l/min, ESB: 1.95mm, (X60).

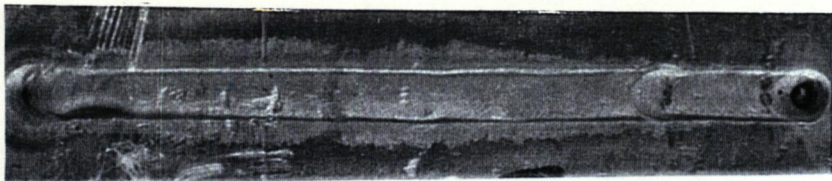


WI:12.2A (I_p : 23A, t_p : 20msec, I_b : 5A, t_b : 30msec), WS: 3.32mm/sec, PGFR: 0.6l/min, ESB: 1.45mm, (X60).

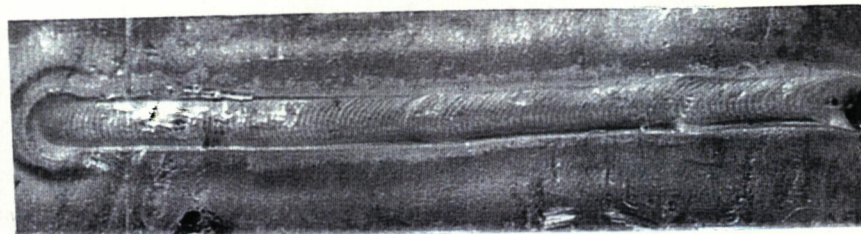


WI:12.2A (I_p : 23A, t_p : 20msec, I_b : 5A, t_b : 30msec), WS: 2.66mm/sec, PGFR: 0.4l/min, ESB: 1.45mm, (X60).

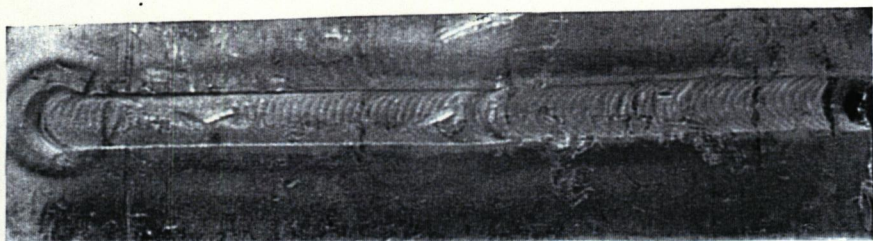
Figure 117: Weld Zone Shapes and Microstructures for Three Typical Parameter Combinations in Melt-In Mode Welding of 316L Tubes.



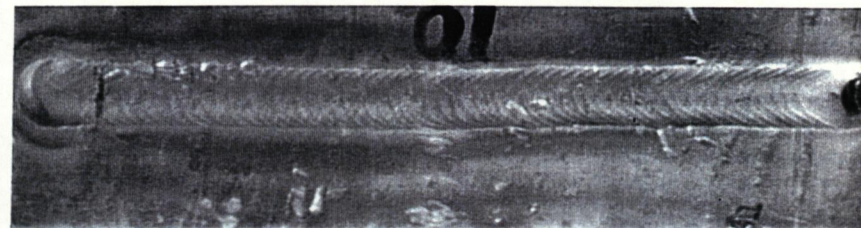
Frequency: 16.7Hz (OBW)



Frequency: 10Hz (OBW)

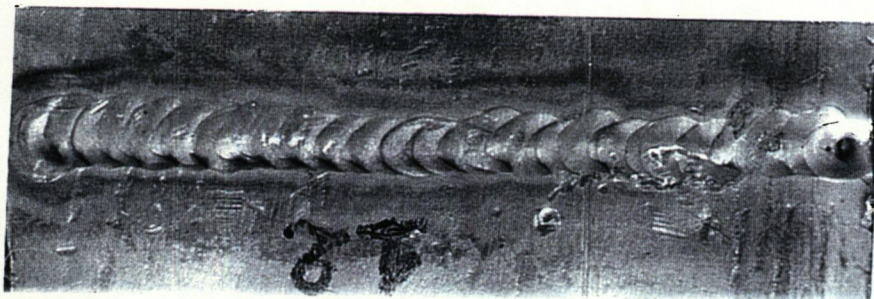


Frequency: 6.7 (OBW)

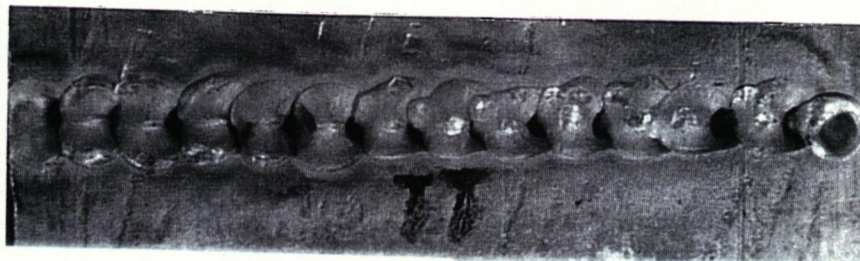


Frequency Current: 5.1Hz (Top: OBW, Bottom: IBW)

Figure 118: Influence of Frequency Pulsation on Weld Bead Characteristics (WI: 14A, I_p : 23A, I_b : 5A, WS: 2.66mm/sec, PGFR: 1.8l/min, SGC: Ar+5%H₂). The 5Hz Frequency Resulted in Undercut Elimination for the Specific Parameter Combination Utilised.



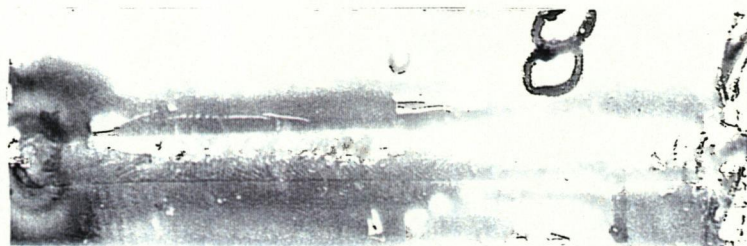
Frequency: 2Hz (OBW)



Frequency: 1Hz (OBW)

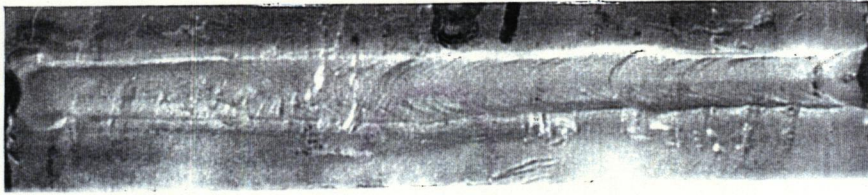


Frequency: Continuous Current (OBW)

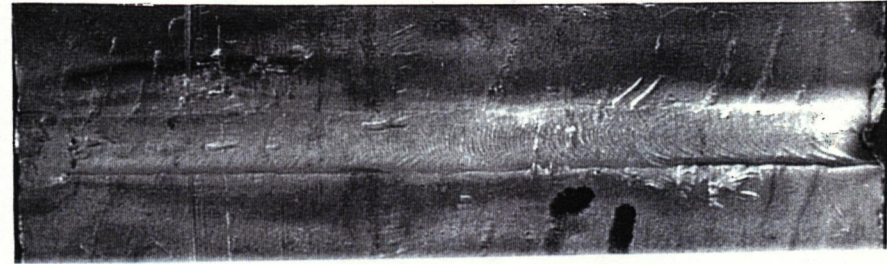


Frequency Current: Continuous Current (IBW)

Figure 119: Influence of Frequency Pulsation on Weld Bead Characteristics (WI: 14A, I_p : 23A, I_b : 5A, WS: 2.66mm/sec, PGFR: 1.8l/min, SGC: Ar+5% H_2). For the 2Hz and 1Hz Frequencies Intermittent Keyholing Gives Rise to a Series of Stitched Holes while Continuous Current Provides a Smooth Inner and Outer Bead Width.



Frequency: 16.7 Hz (OBW)



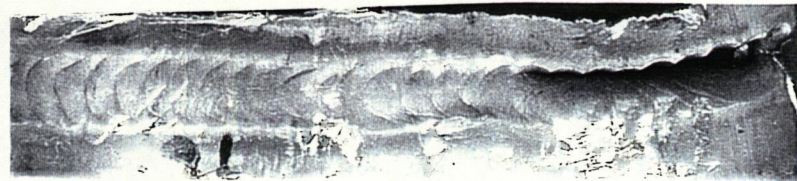
Frequency: 10Hz (OBW)



Frequency: 5.1 (OBW)

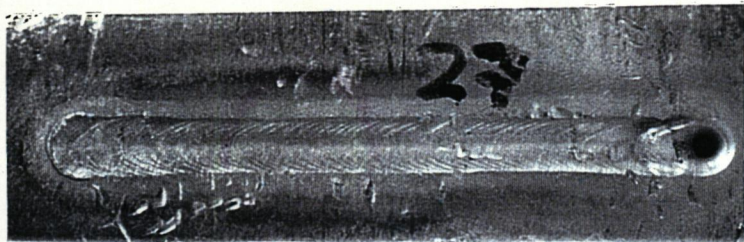
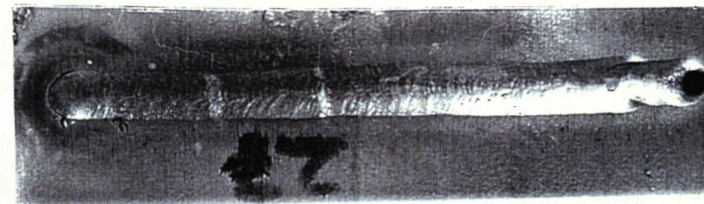


Frequency: 2.5Hz (OBW)



Frequency: 1.25Hz (OBW)

Figure 120: Influence of Frequency Pulsation on Weld Bead Characteristics (WI: 12.5A, I_p : 20A, I_b : 5A, WS: 1.7mm/sec, PGFR: 1.8l/min, SGC: Ar+5% H_2). Low Current Pulsation Can Lead to Weld Pool Collapse in the Last Section of the Weld. Undercut formation is Significantly Affected By the Frequency Utilised (10Hz and 5.1Hz Seem to Provide the Best Conditions for the First Half of the Weld).



OBW

IBW

Undercut Elimination: WI: 18.5A, I_p : 28A, I_b : 9A, Frequency: 25Hz, PGFR: 1.9l/min, WS: 2.33mm/sec, SGC: Pure Argon



OBW

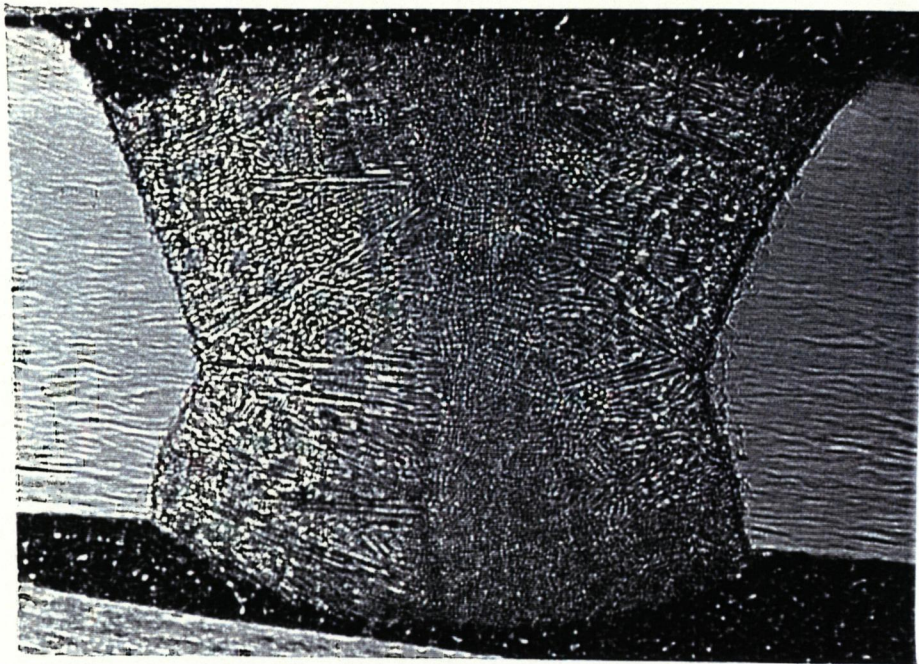
Slight Undercut: WI: 20A, I_p : 28A, I_b : 12A, Frequency: 25Hz, PGFR: 2.1l/min, WS: 2.66mm/sec, SGC: Pure Argon



OBW

Significant Undercut (Tramline Effect): WI: 16A, I_p : 27A, I_b : 5A, Freq.: 25Hz, PGFR: 2.5l/min, WS: 3.66mm/sec, SGC: Pure Argon

Figure 121: Various Undercut Types Observed for a Number of Parameter Combinations (Shielding Gas: Pure Argon).

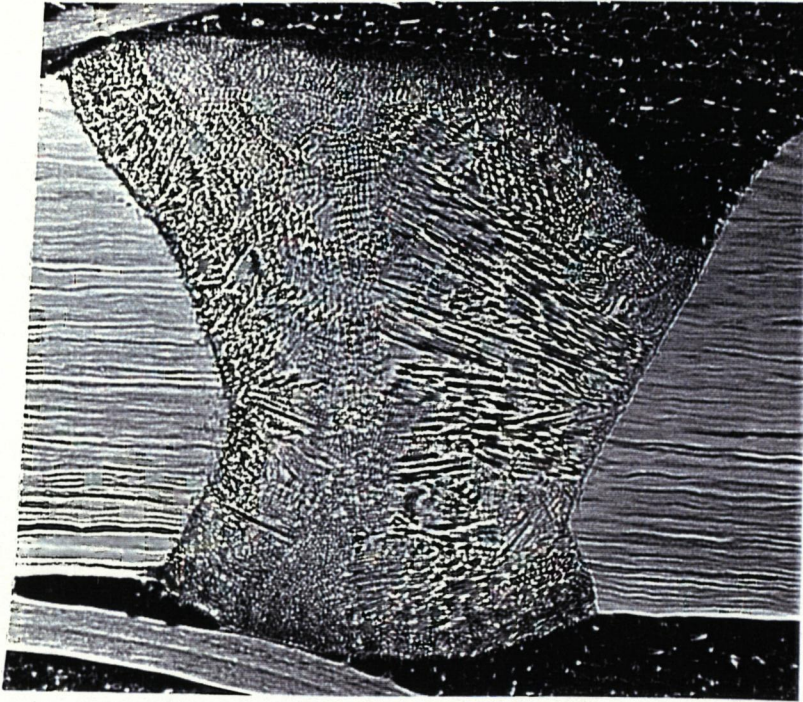


WI:18.5A (I_p : 28A, t_p : 20msec, I_b : 9A, t_b : 20msec), WS: 3.66mm/sec, PGFR: 2.1l/min, ESB: 1.3mm, Average Undercut Indication Index: -0.71 (X50).

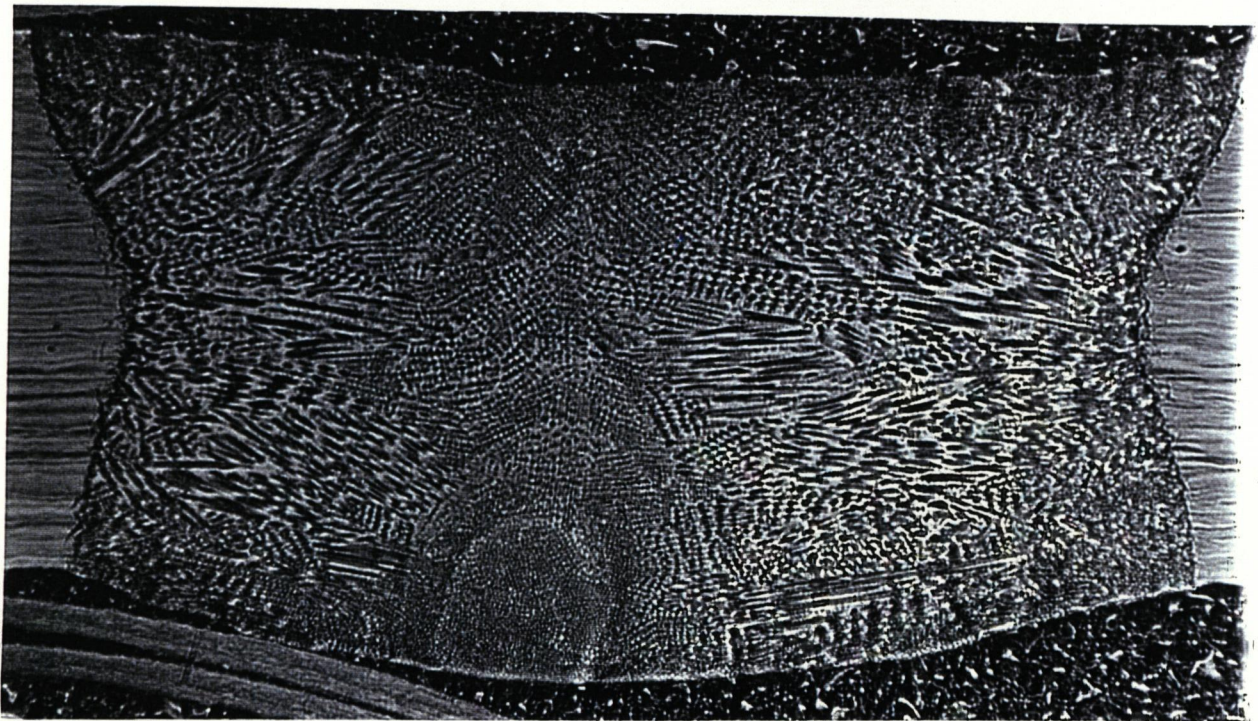


WI:22A (I_p : 28A, t_p : 20msec, I_b : 16A, t_b : 20msec), WS: 3.99mm/sec, PGFR: 2.1l/min, ESB: 2.0mm, Average Undercut Indication Index:-0.07 (X60).

Figure 122: Weld Zone Shapes and Microstructures for Two Typical Parameter Combinations in Keyhole Welding of 316L Tubes (Shielding Gas: Pure Argon).

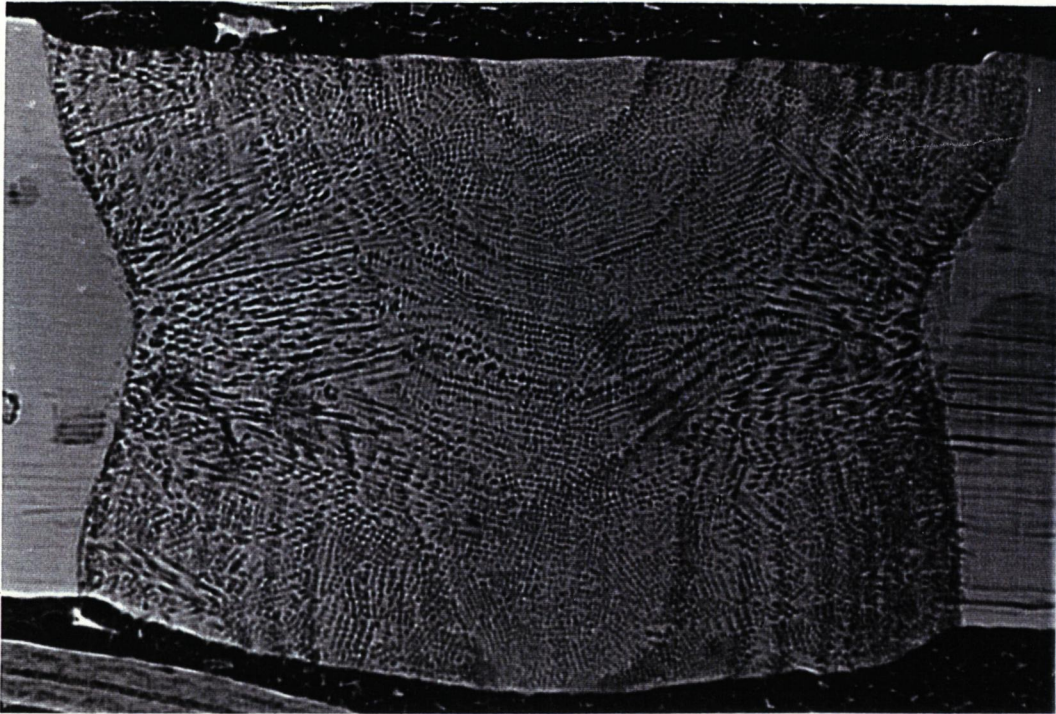


WI:17A (I_p : 28A, t_p : 20msec, I_b : 6A, t_b : 20msec), WS: 3.66mm/sec, PGFR: 1.7l/min, ESB: 1.3mm, Average Undercut Indication Index: -1.07 (X50).

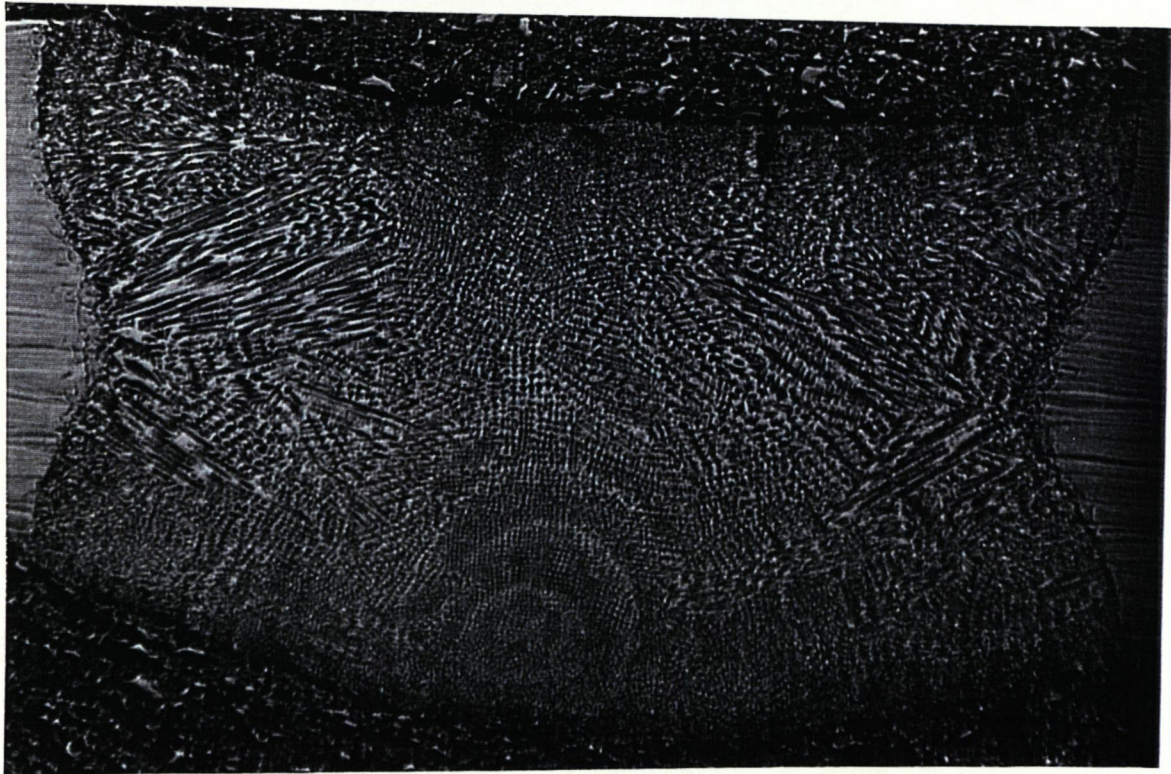


WI:18.5A (I_p : 28A, t_p : 20msec, I_b : 9A, t_b : 20msec), WS: 2.0mm/sec, PGFR: 2.1l/min, ESB: 2.0mm, Average Undercut Indication Index: +0.37 (X60).

Figure 123: Weld Zone Shapes and Microstructures for Two Typical Parameter Combinations in Keyhole Welding of 316L Tubes (Shielding Gas: Pure Argon).



WI:11.5A (I_p : 18A, t_p : 20msec, I_b : 5A, t_b : 20msec), WS: 2.66mm/sec,
PGFR: 1.9l/min, ESB: 1.0mm, SGC: Ar+10%H₂ (X60).



WI: 12.5A (I_p : 20A, t_p : 20msec, I_b : 5A, t_b : 20msec), WS: 3.66mm/sec,
PGFR: 1.6l/min, ESB: 1.0mm, SGC: Ar+5%H₂ (X60).

Figure 124: Weld Zone Shapes and Microstructures for Two Typical Parameter Combinations in Keyhole Welding of 316L Tubes (with hydrogen addition in the shielding gas):