

CRANFIELD INSTITUTE OF TECHNOLOGY

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Statistical Modelling of the Narrow Gap
Gas Metal Arc Welding Process

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Statistical Modelling of the Narrow Gap
Gas Metal Arc Welding Process

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ABSTRACT

The J-laying technique for the construction of offshore pipelines requires a fast welding process that can produce sound welds in the horizontal-vertical position. The suitability of narrow gap gas metal arc welding (NG-GMAW) process for this application was previously demonstrated.

The present programme studied the influence of process parameters on the fusion characteristics of NG-GMA welding in a range of different shielding gas compositions and welding positions. Statistical techniques were employed for both designing the experimental programme and to process the data generated. A partial factorial design scheme was used to investigate the influence of input variables and their interaction in determining weld bead shape. Modelling equations were developed by multiple linear regression to represent different characteristics of the weld bead. Transformation of the response variable based on the Cox-Box method was commonly used to simplify the model format. Modelling results were analysed by graphical techniques including surface plots and a multiplot approach was developed in order to graphically assess the influence of up to four input variables on the bead shape.

Conditions for acceptable bead formation were determined and the process sensitivity to minor changes in input parameters assessed. Asymmetrical base metal fusion in horizontal-vertical welding is discussed and techniques to improve fusion presented.

At the same time, the interaction between the power supply output characteristic and the bead geometry was studied for narrow gap joints and the effect of shielding gas composition on both process stability and fusion of the base metal was assessed. An arc instability mode that is strongly influenced by arc length, power supply characteristic and shielding gas composition was demonstrated and its properties investigated. An optimized shielding gas composition for narrow gap process was suggested.

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NOTATION

A_a	Axial penetration area
A_{al}	Lower axial penetration area
A_{au}	Upper axial penetration area
A_d	Deposited area
A_p	Lateral penetration area
A_{pl}	Lower side lateral penetration area
A_{pu}	Upper side lateral penetration area
A_t	Bead area
A_{und}	Undercutting area
A_w	Wire cross section.
AC	Alternating current
Ar-20	Argoshield 20
Ar-5	Argoshield 5
b	Vector of regression estimates.
B	Magnetic flux density.
c	Specific heat, composition.
CC	Constant current
CV	Constant voltage
DC	Direct current
DC+	Reverse polarity (positive electrode polarity)
DC-	Straight polarity (negative electrode polarity)
e	Electronic charge (1.602×10^{-19} C), residual.

E	Electric field strength in the arc column.
E(x)	Espected value of x.
f	Wire feed speed, gas flow rate.
f_p	Penetration factor.
f_u	Undercutting factor
f_v	Fraction of material vaporized.
F	Frequency
FCAW	Flux cored arc welding
g	Gravity acceleration (9.8 m/s^2).
GMAW	Gas metal arc welding
H,h	Thickness.
h	Standoff distance
h_{mean}	Mean height
H_m	Energy necessary for heating and fusion.
H_v	Latent heat of vaporization.
He-1	Helishield 1
He-101	Helishield 101
I	Current.
I_b	Background current.
I_{eff}	Effective current.
I_{mean}	Mean current.
I_p	Peak current.
I_{st}	Current level at stable operation mode
I_{us}	Current level at unstable operation mode

J	Current density.
k	Thermal conductivity, Boltzmann's constant (1.38×10^{-23} J/K).
l_a	Arc length.
l_f	lack of fusion length
MIG	Metal inert gas
MSx	Mean square sum of x.
NGW	Narrow gap welding
p	Pressure.
p_a	Maximum axial penetration
q	Arc heat.
Q	Heat.
R,r	Radius.
R	Height/width factor, Electric resistance.
R_{alu}	A_{al}/A_{au} ratio.
R_{plu}	A_{pl}/A_{pu} ratio.
s	Electrode stickout.
s_p	Standard deviation of I_p .
SAW	Submerged arc welding.
SMAW	Shielded metal arc welding.
SSe	Residual sum of squares.
SSx	Sum of squares of x
t	Time, power transformation coefficient.
t_b	Background time.

t_p	Peak time.	
t_{prod}	Production time	
t_{us}	Time of unstable arc operation.	
T	Temperature.	
T_d	Droplet temperature just before detachment from the	wire tip.
T_m	Melting point.	
TIG	Tungsten inert gas	
v	welding speed, velocity.	
V	Voltage.	
$V(y)$	Variance of y .	
V_a	Anodic drop voltage.	
V_{arc}	Arc voltage.	
V_c	Cathodic drop voltage.	
V_s	Voltage drop along the electrode stickout.	
V_{st}	Intermediate arc voltage level	
V_{uns}	High arc voltage level	
V_0	Short circuit voltage	
w	Wire melting speed.	
$\mathbf{X}$	Matrix of input variables.	
x_i	Input variable.	
y	Response.	
y_{f_i}	Filtered data point.	
y_{gm}	Geometric mean of y .	
y_{mean}	Mean of y .	

—	Arc burnoff coefficient, thermal diffusibility.
β	Resistance burnoff coefficient, parameters vector.
—	Experimental error.
—	Density, standard deviation of a population.
n	Arc efficiency, Dynamic viscosity coefficient.
—	Work function.
—	Surface tension, Electric resistivity.

CHAPTER 1

1. INTRODUCTION

The J-laying technique for the construction of offshore pipelines requires a fast welding process that can produce sound welds in the horizontal-vertical position. The suitability of narrow gap gas metal arc welding (NG-GMAW) process for this application was previously demonstrated (Fennel 1986). NGW-II technique (i. e., narrow gap welding where the control of sidewall penetration is performed through manipulation of welding parameters and not by arc oscillation) was adopted together with a reduced gap width (under 9 mm) in order to minimize the welding time and to prevent the weld pool from sagging when working in the horizontal-vertical position. This study indicated that a multihead NG-GMAW system could perform pipe welding in a time similar to that obtained with sophisticated and expensive processes such as electron beam and laser welding. However, an extensive study which could provide a better understanding of the relationship between process variables and the physical processes involved in the formation of the weld bead in NG-GMA welding had not been carried out.

Traditionally an "one-variable-at-a-time" strategy has been used to study the influence of welding parameters on bead shape. Although this strategy has been useful in many situations, it can fail to detect important inter-relationships amongst the predictors and, when the number of possible predictor variables is high, it can require a very high number of experimental trials. Pure theoretical modelling of the weld bead shape has greatly advanced in the last few years but it is still limited to very simple situations. An alternative approach based on statistical experimental modelling, mainly factorial design, has already been used in the study of welding problems (see §2.4.2.2). Particularly, factorial experimental design has been recently used to model a NGW-II SAW process (Alfaro 1989).

The present work makes considerable use of techniques based on statistical experimental modelling. A step-by-step approach was used throughout the experimental programme to determine the large number of variables that could affect the process. Each step consisted of one or more blocks of welding trials based on the results of previous tests. The blocks were initially designed as 2^k factorial experiments with central points. However, the strong inter-relationship amongst variables observed in the GMA process forced the introduction of a certain degree of collinearity into the experiment in order to generate stable welding conditions for all experimental points. The results of the first experimental blocks suggested that shielding gas composition played a major factor in controlling weld bead shape. Consequently, an extensive study was performed to optimize the gas mixture composition in terms of process stability and weld bead characteristics in narrow gap welding.

CHAPTER 2

2. LITERATURE SURVEY

2.1. CONSTRUCTION OF SUBMARINE PIPELINES

The girth welding of pipelines in the field has been performed since the 1920's and is one of the longest established applications of fusion welding (Salter et al. 1981). Submarine pipelines have been laid for almost the same period of time. However, up to mid 1960's, they were restricted to shallow waters near the coast line. From this time on, the trend of new oil field discoveries has been that they are located in more environmentally hostile and deeper water areas. To face the new requirements, successive generations of specially designed pipelaying barges of increasing capacity have been built (Brown 1977a). It is foreseen that, by the 1990's, around 40% of the world's oil and gas production will come from offshore fields, most of which will be in very deep waters located off the continental shelf. Therefore, pipelines will have to be built for 1000-2000 meters water depth rather than depths of 200m met in the continental shelf (Palla et al. 1985).

To date, the most common method used for submarine pipeline installation is based on a lay barge from which the pipe is lowered to the sea bottom in the shape of an S curve (figure 2.1). The pipe is constructed in a production line arranged along the deck of the barge and composed of work areas designed for special purposes. Most lay barges have six to eight production work stations (Culbertson and Gumm 1979). The pipe segments are aligned, and welding is performed in a number of work stations (3-5) simultaneously. The welding can be manual, generally with basic or cellulosic electrodes, semi-automatic, or automatic. Non-destructive testing and the application of a protective coating are carried out in the succeeding stations. Each time the pipeline moves along the production line, the laybarge moves ahead and the completed pipeline moves down one joint length.

To limit its curvature and to prevent buckling, the pipe is supported by a stinger in the upper part of the S curve while the curvature in the lower part of the curve is controlled by applying tension to the pipe on the deck of the laybarge. The curvature near the sea bottom tends to increase as the water depth increases. To counteract this, the pipe tension must be raised and/or the length of the stinger increased (Timmermans 1979). There are, however, limits for both tension level and stinger size. Too high tension can damage the pipe surface or coating and create practical problems for positioning the laybarge, specially under severe weather conditions. On the other hand, the size of the stinger is limited by the likelihood of it being damaged by waves and marine currents. So the S-curve pipelaying method is not very suitable for deep-water operation and its practical limit of application seems to be around 1000m depth (Langer and Ayers 1985).

Another method, the reel method, uses a continuous pipe coiled onto a reel at a shore station. The pipe is transported on a laybarge to the location where it is connected to the end of the previously laid pipeline and uncoiled while the barge moves forward. Its main advantage is its high speed of laying the pipeline. Disadvantages include the limitations on pipe diameter

and wall thickness, and limitations in the use of protective coating (Lochridge 1979, Brown 1979). An offshore pipeline can also be built by towing a length of pipe from the shore on either the surface or the bottom of the sea. Both towing methods present some limitations when considered for very deep-water operation. The surface towing method is very sensitive to environmental and traffic conditions on the surface while pipeline positioning and connection can become very expensive for the bottom towing method (Brown 1977b).

The J-curve pipelaying technique has been proposed as an alternative method to the conventional S-curve method. The laying takes place from a laybarge equipped with a vertical or inclined ramp where the pipeline is welded. After welding, the barge moves forward and the pipe is submerged in a J-curve configuration (figure 2.2). The technique greatly reduces horizontal tension by eliminating the pipe overbending. As a result, the requirements for positioning the laybarge in ultra-deep water operation are greatly reduced and the stinger can be eliminated (Timmermans 1979). The process is considered to be feasible for water depths from 300 to 3000m and pipe diameters up to 910mm (Fennel 1986). However, the production space available in the vertical ramp is rather short, restricting the area for welding to a single station. As a result, the low pipe-laying speeds when using conventional welding techniques have been a major factor in holding back the practical application of the J-curve method. Different feasibility studies have suggested that some joining methods can be fast enough to be used in J-pipelaying and result in laying speeds similar to the ones obtained in the S-curve method:

- . Electron beam welding (Levert and Hamon 1986, Cottrill 1982, Sayegh and Cazes 1979, Sivry and Bonnet 1979).
- . Laser welding.
- . Cold forging (Dopyera 1979).
- . Flash butt welding (Turner 1985, Koenig and Muesch 1980, Off-shore Engineer 1983).
- . Radial friction welding (Johansen 1984).
- . Magnetically impelled arc butt welding (Edson 1983).
- . Multihead orbital gas tungsten arc welding (Palla et al. 1985).
- . Multihead orbital narrow gap gas metal arc welding (Fennel 1986).

The time for a complete production cycle, comprising the joining and necessary auxiliary operations, ranges from 15 to 45 minutes for the different processes. The gas metal arc welding study (Fennel 1986) indicated that, by using multihead equipment and narrow gap joints, the pipe joining operation could be performed in a time similar to that obtained with

sophisticated and expensive processes such as electron beam and laser welding. Gas metal arc welding is already commonly used in the pipeline industry and procedures for its control and inspection are also well established. One clear economic advantage of this process over more sophisticated ones is the equipment cost. Fennel (1986) indicates a 10:1 relationship between the costs of a laser and a GMAW machine.

2.2. GAS METAL ARC WELDING

2.2.1. Introduction

Gas-shielded arc welding techniques comprise a group of welding processes where the arc, the molten metal and the surrounding area are protected from atmospheric contamination by a stream of gas or a mixture of gases that is fed through the welding torch. The first of these processes was developed in the United States, in the 1940's, for the welding of aluminum. It utilizes a non-consumable electrode of tungsten and is known as gas tungsten arc welding (GTAW or TIG). A few years later, the gas metal arc welding process (GMAW or MIG, metal inert gas) was introduced in an attempt to overcome limitations in the GTAW process for welding of thicker pieces of aluminum. In the GMAW process, the electrode is a continuous wire that also provides filler metal. Only pure helium or argon were used for shielding at that time.

Initially, the high cost of both equipment and shielding gases together with a poor arc stability and the difficulty in guaranteeing an adequate fusion level for the weld, deterred the use of the GMAW process for steels. Since then, many factors have contributed to an increasing use and acceptance of GMA welding for steel and non-ferrous alloys:

- Carbon dioxide was introduced as a much cheaper shielding medium for steel welding in the 1950's. Due to the active nature of CO₂, the process is termed MAG (metal active gas). The use of short circuit arc (or dip transfer) techniques allowed reasonably good control in GMAW welding (Smith 1962).
- The increasing demand for inert shielding gases was met by a reduction in their prices. At the same time, gas mixtures containing oxygen or CO₂ additions to argon were used in welding of steel providing good weld quality and process stability (Green and Krieger 1952).
- The pulsed GMAW process emerged in the 1960's, enabling a spray-like transfer over a range of welding current below the transition current (Boughton and Luncey 1965, Needhan 1962).
- Developments in power supply design, together with the application of new control ideas, particularly the so-called synergic or "one-knob" control, made it

easier to reliably set suitable welding conditions (Amin and Naseer-Ahmed 1986a).

Currently the GMAW process is widely used for both ferrous and non-ferrous alloys. Variations of the process have been developed, and one, flux cored arc welding (FCAW), has been applied widely in fabrication. Some typical applications are the CO₂ welding of thin steel plates in the automotive industry, pipe welding, ship building, nuclear and aerospace welding, etc. Several basic reviews of the GMAW process can be located in the literature (for instance, Weld. Des. & Fab. 1988, Sekiguchi 1984).

A schematic diagram of the GMAW process is shown in figure 2.2. Filler wire is continuously fed through a contact tip, where an electrical connection is made to the power supply. An electric arc is sustained between the wire and the workpiece and melts both. In order to have the process operating stably, at least two basic requirements are to be satisfied: (i) The mean wire melting speed (w) has to be equal to the speed at which the wire is being fed (f), i. e.:

$$f = w \quad [2.1]$$

(ii) The molten metal from the wire has to be transferred to the weld pool causing minimal process disturbances. Some of the main factors that can affect these basic requirements will be discussed in the sections below.

2.2.2.The Welding Arc

The arc is an electrical discharge sustained by a relatively high current (typically from 1 to 2000 A, for welding applications) flowing between two electrodes. To be useful for welding, the arc should operate under stable and controllable conditions and provide enough energy to melt the workpiece and, in consumable electrode welding, the electrode itself.

There are many technical applications that involve arcs (e.g., welding, switchgear, arc furnaces, arc heaters, fusion reactors, etc) but, in spite of the large volume of experimental and theoretical study connected to arc phenomena, many of its processes are still rather unclear. As far as the use of the arc in welding is concerned, one of the first reviews of the subject was presented by Spraragen and Lengyel (1943). Jackson (1960) extended the material which was revised to include new welding processes, i.e., gas shielded arc and submerged arc welding. Papers by Gillette and Breymeier (1951) and Quigley (1977) discussed experimental techniques for studying the welding arc. Recent reviews of welding physics that include extensive discussions of arc processes have been published by Lancaster (1986, 1987a, 1987b). Not directly related to welding but of interest are the reviews by Guile (1971, 1984) on electrode processes and engineering applications, and by Jones and Fang (1980) on the arc column.

The voltage distribution in the arc is well established (Spraragen and Lengyel 1943) and is schematically shown in figure 2.3. There is a sharp drop of voltage close to the surface of each electrode (cathode and anode drops) and a gradual and ideally linear fall along the arc column.

The cathode drop is a very thin region (approx. 10^{-8} m) characterized by a positive space charge which causes a steep voltage difference (V_C) of around 5 V for thermionic cathodes or 10-20 V for non-thermionic cathodes (Lancaster 1986), and, consequently, very strong electric fields. The stability of the arc depends to a large extent on the cathode drop region behaviour because it is the primary source of electrons to the arc. The mechanisms of electron emission by the cathode can be separated in two basic groups: thermionic and non-thermionic emission. Thermionic emission requires a very high temperature in order to generate a current density high enough to be used in welding, and is commonly the operative process in GTAW welding.

In the GMA welding of steel, aluminium and other refractory metals, the cathode temperature is not enough to sustain the process by thermionic emission of electrons. Other mechanisms that are generically grouped under the designation of non-thermionic or cold emission have to operate. Experimental study, mainly by high speed cinematography and observation of the arc marks on the cathode surface by electron scanning microscopy (Guile and Jüttner 1980, Jüttner 1987), indicates that non-thermionic cathodes are characterized by the formation and very rapid decay (lifetimes from 4.5 to 200 ns) of numerous small emitting sites. Current density in the sites is estimated to range from 2×10^{11} A/m² to 10^{14} A/m², much higher than the values associated with thermionic emission (10^6 to 10^8 A/m²) (Lancaster 1986). The emitting sites tend to group together in mobile bright spots at the surface of the cathode. Oxide layers are removed from the surface by the action of the cathode spots as is well known in the gas-shielded welding of aluminum. There is strong evidence that, in electrodes covered by oxide layers, non-thermionic emission is provoked by oxides being turned conductive by very strong electric fields (Lancaster 1986). Different mechanisms, not completely understood yet, should operate on the arc in vacuum with a clean cathode (Rakhovsky 1987). When the cathode surface of an arc in the vacuum is not very homogeneous, the arc will tend to deflect in order to reach cathode regions covered by oxide (Guile 1971). If the arc cannot root in an oxidized region, its voltage may change abruptly reflecting changes in cathode emission mechanism (Fu 1989).

In electrode positive GMA welding, the cathode spots are often not immediately below the wire tip, but are situated on the solid workpiece at the edge of the weld pool (Essers and van Gorpel 1984). When welding steel with a completely inert gas, the cathode spots consume the oxide layer and move outwards away from arc axis in a continuous search for fresh surface oxide. If no oxide can be reached, a single vapour cathode is formed on the weld pool surface (Boughton and Amin Mian 1972). Vapour dominated cathodes are generally related to vacuum arcs (Guile 1982). When the electrode is negative, the cathode spots move erratically on the drop and wire surface, vapour reaction can develop and deflect the metal

drop from the workpiece. Arc root wander can be inhibited by emissive material coating the electrode or by high pressure (Lancaster 1986).

The anode region, although essential for preserving the arc continuity, is not as important as the cathode for the maintenance of the arc and, consequently, it has been far less studied. Measured values of the anode voltage drop (V_a) range from 1 to 10 V (Guiles 1971) and, for welding conditions, values from 1 to 4 V have been reported.

The arc column is formed by a mixture of neutral particles, ions and free electrons, and is characterized by high temperatures and intensive mass flow. The temperature distribution and values are determined by the balance between joule heating and losses due to thermal conduction, convection and radiation. Measurements for both GTAW and GMAW arcs performed by different investigators indicate temperatures around 10^4 K in the arc core with the higher values close to the electrode. The presence of iron and other metal ions, however, can reduce the joule heating in the arc and cause a drop in temperature to around 6000 K (Lancaster 1987a). Key (1983) found that the peak temperatures were about the same in the GTAW arc for different Ar/He and Ar/H₂ mixtures, although the radial temperature distribution was flatter when either He or H₂ was present. This result agrees with the expected increase in radial heat loss by the arc column due to the presence of higher thermal conductivity gases such as He, H₂ and CO₂.

The gas flow in the column is generally directed from the electrode to the workpiece. Its main driving force has been established as the pressure gradient magnetically induced by the smaller arc diameter close to the electrode. This gas flow results in the plasma exerting a pressure over the weld pool. When the arc is moving, this pressure distribution will blow the liquid from the front to the rear of the weld pool and can be one of the mechanisms responsible for penetration (Halmoy 1979b). Distortion in the expected flow pattern can be caused by vapour or gas jets or the formation of single spots at the workpiece. Under these circumstances, the welding operation is, generally, more difficult because the liquid droplets at the tip of the electrode tend to be repelled from the workpiece.

The electric field strength along the arc column is roughly constant and independent of the arc length (figure 2.4). So, the column voltage (V_{col}) can be approximately represented by ($E l_a$), where E is the column electric field strength and l_a is the arc length, and the total arc voltage by:

$$V = V_a + V_c + E l_a \quad [2.2]$$

This equation does not consider the effect of current on either V_a , V_c or E . It has been used by several authors (Lund 1979, Smati 1986, Wilgoss 1984) for modelling the GMAW process, on the assumption that the process is operating on the flatter part of the IV characteristic of the arc and, therefore, the arc voltage is not very influenced by current. Typical values of E for Ar and He shielding are 0.8 V/mm and 1.5 V/mm respectively

(Allum 1986). A different equation which considers the rising part of the arc characteristic was employed by Oshida et al.(1982):

$$V = \alpha l_a + \beta + (\gamma l_a + \delta) I \quad [2.3]$$

where α , β , γ and δ are constants characterizing the arc. Finally, Ayrton's equation developed in the beginning of the century for low current carbon arcs is still commonly used in representing the overall arc characteristic curve:

$$V = a + b l_a + (c + d l_a) / I \quad [2.4]$$

2.2.3.Metal Transfer

The way in which the molten metal is transferred from the electrode tip to the weld pool affects spatter and fume levels, positional capabilities, bead characteristics, and process stability and performance. The study of metal transfer has been of interest since consumable arc welding was introduced. The work in this area, done up to the early forties and related mainly to manual metal arc welding, was reviewed by Spraragen and Lengyel (1943). After the development of the GMAW process, most of the investigations shifted to the new process partially because of its ideal characteristics for studying metal transfer. During the late fifties and early sixties, the phenomena of metal transfer and its governing mechanism received considerable attention (see, for instance, Cooksey and Milner 1962, Amson and Salter 1962, and Smith 1962). In the seventies and eighties, the area of study has changed to include the effect of arc current pulsing on metal transfer, flux cored wires, plasma-MIG welding and the development of theoretical models. A practical review on the subject has been recently presented by Norrish and Richardson (1988) and more fundamental ones by Lancaster (1986, 1987b).

There have been several attempts to classify, on a phenomenological basis, the numerous transfer modes observed in welding. Unfortunately, the many facets of metal transfer together with the overlapping and, sometimes, confusing terminology, make it difficult to present a standard classification for metal transfer modes (Killing 1984). The classification system developed by the International Institute of Welding is reproduced in table 2.1. Some of the transfer modes more relevant to GMAW are briefly described in table 2.2 and illustrated in figure 2.5.

The transfer mode is determined by several factors, such as, welding current and voltage, polarity, wire diameter and material, shielding gas composition, arc length and electrode stickout.

A simplified representation of the relationship between welding current and voltage, and metal transfer mode is shown in figure 2.6. In the welding of some metals (including aluminum and steel) with electrode positive and argon based shielding, a well defined current

level above which the transfer mode changes from globular to spray (transition current, line A-A' in figure 2.5) is observed. Lesnewich (1958b) performed an extensive study of the effect of several factors on the transition current. Chilung et al. (1982) associated the transition current with alterations in the arc root in the electrode and showed that oxygen additions to argon first decrease and, when more than 5% O₂ is present in the shielding mixture, increase the transition current. CO₂ additions to argon based shielding always increase the transition current.

Odd arc instabilities and disordered metal transfer have been observed under spray-transfer conditions, and ascribed to variations in material composition (Hutt and Lucas 1982). Strong gas or vapour evolution and droplet explosions were observed with the aid of high speed cinematography for both aluminum alloys (Woods 1980) and steel (Lucas and Amin 1975). Rodwell (1985) observed arc instabilities and changes in metal transfer, weld bead profile and wire melting rate when welding with mild and stainless steel wires. These conditions were attributed to the composition or surface condition of the wire, rather than to any feature of the welding technique.

Spray transfer is not commonly observed in negative electrode GMAW because reaction forces created by the cathode spots on the wire surface prevent the metal drops from detaching. However, spray transfer can be induced by wire activation (Lesnewich 1958a), by higher ambient pressure (Nishiguchi and Matsunawa 1976), or by running the arc inside a narrow gap or groove (Ono et al. 1981).

Several models have been proposed for the qualitative and quantitative interpretation of metal transfer. Most of these models are based on the supposition that several different forces act in the molten metal at the wire tip, and that the transfer process is governed by the static balance of these forces. Some of the forces that can participate in metal transfer are (Norrish and Richardson 1988):

- Gravitational force.
- Gas flow induced force.
- Electric magnetic forces.
- Vapour/gas jet forces.
- Surface tension.

General expressions for these forces were reviewed by Jilong Ma (1982) and Norrish and Richardson (1988). Jilong Ma (1982) also reviewed the models for metal transfer based on the balance of forces assumption. A different modelling approach for metal transfer, based on the instability of a current-carrying cylinder, has been adopted by Lancaster (1979) and extended by Allum (1985a). These models are far more complicated than static models and have had a limited use so far.

Pulsed GMA welding was introduced to extend spray-type transfer to current ranges below the spray transition current where metal transfer is generally less controllable. It is based on the use of a low background current to pre-melt the wire tip in combination with a peak

current above the transition current level to detach the molten material as a small droplet (Needham and Carter 1965). If the peak duration is too long or its intensity is too high, a number of drops transfer, generally by stream spray transfer, during one peak period. Low peak current or short peak duration results in one drop transferring over several peaks. A condition of one pulse-one drop transfer can be achieved by a proper selection of peak intensity and duration, and better transfer characteristics are obtained under this condition (Jilong Ma 1982, Maruo and Hirata 1982).

Several authors have determined conditions for one pulse-one drop transfer for different wire compositions and diameters, and different shielding gases (Matsuda et al. 1983, Ueguri et al. 1984, 1985, Amin 1983, Trindade and Allum 1984, Smati 1986, Foote 1986 and Oliveira Santos 1986). In most of these studies the conditions for one pulse-one drop transfer could be related to peak current and duration by a simple empirical relationship:

$$I_p^n t_p^n = D \quad [2.5]$$

where D is the detachment parameter and n has a value close to 2. Using the instability theory and a simplified pulse structure, Allum (1985a) found $n = 1.556$. The conditions for one pulse-one drop transfer found by different authors for 1.2 mild steel wire are shown together in figure 2.7. The results generally agree rather well considering the different experimental conditions that were used.

2.2.4. Wire Melting Rate

It is generally accepted that the wire melting rate in GMA welding can be calculated from the energy balance at the wire tip (Lancaster 1986):

$$Q_{out} = Q_{in} \quad [2.6]$$

Q_{out} is the power necessary to heat a wire being fed at a speed w , up to its melting point, fuse it, overheat the molten metal up to its temperature just before detachment, and, finally, vaporize a fraction of the molten metal. This can be summarized by the equation below:

$$Q_{out} = \sigma w A_w [H_m + (T_d - T_m) c_p + f_v H_v] \quad [2.7]$$

where σ is the wire density,

w is its melting rate,

A_w is the wire cross section,

H_m is the energy for wire heating and fusion,

T_m is the material's melting point,

c_p is the material's thermal capacity,

T_d is the molten metal temperature just before its detachment from the wire tip,

f_v is the fraction of material vaporized, and

H_V is the material's latent heat of vaporization.

Assigning a value to Q_{out} can be difficult because of the uncertainties related with experimental measurement of T_d and f_v and the effect of welding parameters on them. According to Lancaster (1987b), results from different authors suggest, for steel wires, temperatures well above 2000°C. However Halmoy (1979) has found evidences of temperatures close to the melting point.

Several factors, such as joule heating of the wire, heating generated at the anode (electrode positive) or the cathode (electrode negative), radiation and convection from the arc column, radiation from the weld pool, heat generated by chemical reactions at the drop, etc, can be candidates to contribute to the formation of Q_{in} . However, it is well established in the literature that most of Q_{in} is made up of the two first factors (Lesnewich 1958a, Lancaster 1986):

$$Q_{in} = Q_{joule} + Q_a \quad (\text{for DC+}) \quad [2.8]$$

The anode heating (Q_a) is generated by electrons entering the anode from the arc. It is formed by the thermal energy of the electrons ($(3/2)kT/e$), the kinetic energy they receive crossing the anodic fall ($V_a I$) and the energy they release being absorbed by the metal structure (ϕI):

$$Q_a = [(3/2)kT/e + \phi + V_a] . I \quad [2.9a]$$

If the terms inside the brackets are considered constant, the anode heating will be proportional to the welding current:

$$Q_a = k_1 . I \quad [2.9b]$$

When welding with electrode negative, Q_a should be replaced by the cathode heating (Q_c) (Lancaster 1986):

$$Q_c = [V_c - (\phi + (3/2)kT/e)] . I \quad [2.9c]$$

Where V_c is the cathode fall voltage.

The importance of joule heating for wire melting was recognized by Wilson et al. (1956). This heating term cannot be calculated directly because the temperature of the wire in the stickout changes from room temperature, close to the contact tip, up to the material's melting or boiling point in the arc root, and, consequently, electrical resistivity is not constant along the stickout. The temperature distribution and voltage drop in the electrode stickout have been theoretically calculated by Villeminot (1967), Amson (1972), Waszink and Heuvel (1979), Halmoy (1979) and Wilgoss (1984). Waszink and Heuvel (1979) also measured the voltage drop along the stickout using a tungsten probe. Villeminot (1967), Lund (1979),

Waszink and Heuvel (1979) and Halmoy (1979) concluded that the electrical resistivity of the wire stickout can be considered approximately independent of welding current and, therefore, the joule heating term can be represented as:

$$Q_{joule} = k_2 \cdot s \cdot I^2 / A_w \quad [2.10]$$

where k_2 is a constant, and s is the stickout. Using equations [2.6] to [2.10] it can be shown that, for electrode positive:

$$w = (k_1 I + k_2 s I^2 / A_w) / \{ \sigma A_w [H_m + (T_d - T_m) c_p + f_v H_v] \} \quad [2.11a]$$

or

$$w = \alpha \cdot I + \beta \cdot s \cdot I^2 \quad [2.11b]$$

and

$$\alpha = k_1 / \{ \sigma A_w [H_m + (T_d - T_m) c_p + f_v H_v] \} \quad [2.12a]$$

$$\beta = k_2 / \{ \sigma A_w^2 [H_m + (T_d - T_m) c_p + f_v H_v] \} \quad [2.12b]$$

Similar equations can be developed for electrode negative.

Quintino (1986) and Oliveira Santos (1986), working with mild and stainless steels, suggested that the α and β coefficients are roughly proportional to the inverse of A_w and of A_w squared, respectively, as expected from equations [2.12a] and [2.12b]. Lesnewich (1958a) obtained similar empirical relationships but with a different power of A_w .

Equation [2.11b] was first proposed by Lesnewich (1958a) and, later, by Halmoy (1979). This expression is the most accepted in the literature and has been extensively used in modelling the GMAW process (Lund 1979, Smati 1986), process control (Fujimura et al. 1988), and extended to pulsed welding (Quintino and Allum 1984, Smati 1986, Foote 1986). Different equations based on regression analysis of experimental data have been proposed by Thorn et al. (1982) and Chandel (1988). Chandel's equations included a VI and a constant term in addition to the terms of equation [2.11b]. However, he used in his model the standoff distance instead of the electrode stickout. Therefore, his s term included also the arc length and was sensitive to changes in voltage. Thorn obtained, for experiments with constant stickout, a simple linear relationship between current and melting rate and argued that the inclusion of a I^2 term did not contribute significantly to the model. However, his results can also be described well by equation [2.11b], even when coefficients from other authors are used.

The β coefficient represents the mean resistivity of the electrode stickout and depends on the electrode composition. It is negligible for high conductivity metals such as aluminum but can

have considerable importance for steel wires and its value depends on steel composition (Foote 1986). The joule heating of the electrode tends to be higher in pulsed GMAW than in non-pulsed welding. This can be shown by integrating equation [2.11b] over a pulse period (Quintino and Allum 1984, Smati 1986):

$$w = \alpha I_{mean} + \beta I_{eff}^2 \quad [2.13a]$$

or (Richardson and Nixon 1985), assuming a square shaped pulse current:

$$w = w_{np} + \beta (I_p - I_b)^2 t_p t_b / (t_p + t_b)^2 \quad [2.13b]$$

Where I_{mean} is mean welding current, I_{eff} is effective current, w_{np} is the melting rate for non-pulsed welding with $I = I_{mean}$, t is time and the subscripts p and b refer respectively to peak and base levels. As effective current increases, for the same mean current, when peak current is increased, the wire melting rate should also increase as confirmed by different authors (see, for instance, Takeuchi 1984, Allum 1983).

The anodic heating coefficient (positive electrode welding) depends mainly on the electrode composition (Lancaster 1986). Several studies have shown it to be roughly independent of the welding current, shielding gas composition (Lesnewich 1958a, Quintino and Allum 1984, Ono et al. 1981), arc length and voltage (Lesnewich 1958a, Nunes 1982), electrode surface condition, joint gap width (Matumoto et al. 1980) and pressure.

Kyohara et al. (1977 and 1979) observed an increase in the melting rate of aluminum alloys when the arc length was less than 8mm and explained such behaviour by changes in anodic heating and droplet temperature due to alterations in arc shape. Similar results were found by Trindade (1984). Kinks or "discontinuities" in the melting rate when plotted against current were found by Nunes (1982) and Jilong Ma and Apps (1982). These irregularities were close to the spray transition and were also associated with changes in anode heating and droplet temperature.

The cathodic melting coefficient is generally higher than the anodic coefficient in GMAW. The difference varies from around 75% in aluminum to 30% in copper (Lancaster 1986). The cathodic melting coefficient is significantly affected by current level, electrode surface condition (Lesnewich 1958a), shielding gas composition (Yamauchi and Jackson 1976, Ono 1981), joint gap width (Matumoto 1980), arc length and pressure. The cathode burnoff can become lower than the anodic burnoff under the influence of electrode surface treatments or high pressure (Lancaster 1987).

2.2.5. Shielding Gases

The primary reason for using any sort of shielding medium in welding is to protect the arc, wire tip, molten pool and surrounding base material from atmospheric contamination.

Furthermore, many other factors, such as metal transfer mode, spatter and fume generation, weld bead geometry and composition, etc are affected by shielding gas composition.

Some of the first attempts to weld with consumable electrodes under both inert and active gas protection were performed by Doan and co-workers (1938, 1940) who already recognized, at that time, the greater difficulty in welding mild steel with pure inert gas. When the process was commercially introduced in the forties for welding aluminium alloys, only pure argon and helium were used for shielding. Eventually, mixtures containing oxygen were developed for stainless and mild steel. In the mid fifties, carbon dioxide was introduced as a cheaper alternative for mild steel welding. Since then, different Ar-O₂-CO₂ mixtures have been developed commercially for the welding of steel in an effort to obtain the best balance amongst the many conflicting factors that are influenced by gas shielding. The same basic mixtures have been used for pulsed GMAW. Quintino and Allum (1984), and Cuny (1988) recommend mixtures containing >90% Ar, plus oxygen and carbon dioxide, for pulsed GMAW of mild and low alloy steels. The selection and basic characteristics of shielding gases and mixtures have been revised many times since the introduction of gas shielded processes: Helmbrecht and Oyler (1957), Salter and Dye (1971), Cresswell (1972), Brosilow (1978), Weld. Design & Fab. (1988), Hilton and Norrish (1988), for instance. Table 2.3 summarises the gas mixtures available and their applications. This section will be concluded by a discussion about the influence of additions of He on the argon shielded welding arc.

In GTAW, the argon arc is bell-shaped and whitish-grey (Hiraoka et al. 1986) and has an electric field strength of approximately 0.7-0.9 V/mm. When helium is gradually added to the shielding, the arc is altered by a progressive change to a spherical light-green form. At the same time, arc voltage increases (Helmbrecht and Oyler 1957, Hiraoka et al. 1986) while arc pressure and radial temperature gradient decrease. Its electric field strength, however, remains approximately constant up to 75% He and then increases sharply to around 1.3-2.0 V/mm (Ludwig 1959, Hiraoka et al. 1986). When welding aluminum with alternating current, the use of helium results in poor arc stability and poor cleaning action (Helmbrecht and Oyler 1957). Such changes in arc behaviour have been ascribed to the difference in physical properties of the two gases, namely, their ionization potential and thermal conductivity (table 2.4). However, a clear mechanism for such differences is not yet available.

Trends similar to those described above are present in GMAW. Moreover, helium additions tend to make it more difficult to obtain spray transfer and, above 80% He, only globular transfer and a consequent loss in arc stability are obtained (Kennedy 1970). When studying the arc shape and metal transfer for different shielding gases, Hazlett and Gordon (1957) observed that, in helium shielded welding, the arc was mainly confined to the region between the bottom of the drop and the workpiece. Periodically the arc seemed to extend up the wire. When argon was used for shielding, the metal transferred mainly by spray but some disturbances in metal transfer were also observed. In pulsed welding, Hilton and Norrish (1988) suggested a limit of 85% He above which the process stability deteriorates.

Studies of the effectiveness of shielding gas cover using Schlieren techniques (Cunningham and Cook, 1953) indicate that, due to its lower density (table 2.4), helium requires a flow two to three times that of argon for equivalent shielding. As a rule of thumb, Hilton and Norrish (1988) suggested that adequate shielding will be obtained with helium containing mixtures, by using an argon flowmeter and setting the flow reading to that of an argon/carbon dioxide mixture.

The total bead area is increased by additions of helium and other gases that increase the arc voltage (at a fixed current). The bead width and the secondary penetration tend to increase with the helium content while the finger penetration is less affected in aluminum GMA welding (Kennedy 1970).

2.2.6. Equipment and Process Control

The primary equipment for GMA welding comprises a power supply, a wire feeder, welding cables, a welding gun, flowmeter, regulator and hose for shielding gas supply, and, optionally, a water cooling system. Basic information concerning this equipment can be found elsewhere (Houldcroft and John 1988). Only a brief introduction on power supplies and control in conventional GMAW and a review of some recent advances will be presented here.

2.2.6.1. Power Supplies

With regard to the electrical design and operative principle, the most widely used power supplies for GMA welding can be broadly categorized into the following groups (Kolasa et al. 1985):

- (1) Conventional transformer-rectifiers with magnetic flux control,
- (2) Solid state AC phase controlled rectifiers (thyristor control),
- (3) DC controlled power transistors (transistor series regulator and secondary chopper power supplies), and
- (4) Primary inverters.

Conventional transformer-rectifiers rely mainly on mechanical or electrical systems for output adjustment and have changed little since the introduction of GMAW. The operational principles and construction of conventional power supplies have been thoroughly discussed by Manz (1973).

The common feature of the latter three groups is the use of semiconductor devices for direct control of output current and/or voltage. When compared with conventional power supplies, the electronic based ones are characterized by (Yamamoto 1984, IIW Commission XII 1982):

- Higher performance: Dynamic response and reproducibility far superior to conventional power supplies.
- Multiple functions: The possibility of controlling the output by a small current and the use of feedback control allowed the development of power supplies with multiple VI characteristics.
- Easier connection with peripheral equipment and programmability: The use of electronic circuitry allows the power supply to receive input signals from sensors, internal microprocessors, external computers, etc. Pre-programmed "optimal" welding conditions or a set of pre-established rules (logic) for parameter selection can be stored in electronic memory and used to define the power supply operation. Such capability permitted the development of power supplies that can be prepared for operation through a single switch, the so-called "one-knob" machines.
- Reduction of weight and cost: The introduction in the 1980's of inverter type power supplies have resulted in massive reduction in transformer size due to its use of high frequency alternating current. Consequently, the weight, size and cost of electronic power supplies has decreased appreciably.

In spite of their increasing popularity and decreasing price, electronic power supplies are still much more expensive than conventional ones. Their more complicated design is another limitation. Basic constitutive aspects and characteristics of the different power supply types have been revised by the IIW Commission XII (1982), Kolasa et al. (1985), Norrish (1985) and Bréat (1987).

2.2.6.2. Control aspects in GMAW

Conventional GMAW operates with a power supply with a constant voltage (CV) characteristic and a constant wire feed speed which is generally set at the wire feeder. Under these conditions, voltage (and consequently arc length) and wire speed remain approximately unchanged during welding while current and electrode stickout values result from those and the standoff distance. Any perturbations in welding conditions (for instance, variations in standoff distance by the welder) are mainly absorbed by changes in current and stickout. The capability of keeping the arc length relatively constant (self-adjusting arc) is one of the main reasons for the high popularity of constant-voltage equipment in GMAW until today (Weld. Metal & Fab. 1988). Another advantage of a CV system is ease of arc ignition due to the rapid increase in current in the instant the electrode touches the workpiece.

In dip transfer welding, too fast an increase in current during the short circuit can lead to an explosive rupture of the liquid bridge between the wire and the weld pool, which results in spatter. Conventionally the current rise rate has been controlled by either sloping the VI characteristic or regulating the dynamic response of the power supply.

One problem with CV operation is that the system achieves equilibrium through variations in current which is one of the most important variables affecting formation of the weld bead. In pulsed GMAW, metal transfer stability depends strongly on the pulse current and duration. The use of conventional CV power supplies with voltage pulses when pulsed GMAW was first introduced made it difficult to determine favourable conditions for stable metal transfer (Nixon and Norrish 1988). Pulsed GMAW welding is often performed under CC characteristics nowadays although some alternative systems do exist (see below).

The development of electronically controlled power supplies in recent years brought about a revolution in terms of control methods (Allum et al. 1985). It has been particularly important for pulsed transfer where the selection of welding parameters is complicated by the need for specifying the pulse structure for stable transfer. Some of the control techniques proposed for GMAW welding are described below:

- . Synergic MIG: This term embraces a group of control techniques in which the current structure is determined by the wire feed rate or vice-versa. Generally, a tachogenerator signal from the wire feed system provides a control signal for the power supply. The idea was originally developed in the Welding Institute for one-knob pulsed GMAW but the concept has also been applied to short-circuit transfer (Norrish 1988). The relationship between power supply output and wire speed is determined by a set of rules called synergic algorithms (Quintino 1986). Several algorithms have been presented in the literature for both pulsed (Amin 1981, Allum 1983) and short-circuit transfer (Amin 1986b). Synergic MIG control has been achieving an increasing acceptance over the last few years and it has been considered for use, together with real time seam tracking, in future adaptive control systems for production welding (NMAB 1987).
- . Voltage/arc length control: An alternative approach to synergic MIG has been suggested in which a control signal from the arc voltage is used to drive the power supply output (Ditschun et al. 1985, Essers and van Gompel 1984, Allum 1985b). This type of control system mimics, by different mechanisms, the self-adjusting arc of CV systems and, therefore, suffers from similar limitations.
- . CVCC operation: This technique has been implemented to improve arc self-adjustment in pulsed GMA welding without disturbing metal transfer (Nixon and Norrish 1988). It uses a constant voltage characteristic during the pulse phase and a constant current characteristic in the background period. By using high peak currents of short duration the system operates in a region in which the one pulse-one drop transfer is not sensitive to peak current (see figure 2.7).
- . Adaptive control: This technique involves feedback plus allowance for interaction between varying factors (i.e., arc length, travel speed, torch orientation, wire feed speed, track guidance, fusion control, joint fill, defect

formation, etc) measured, fed back, and compared with original set points and then perhaps modified by a complex interpretation of the process dynamics (Emerson 1988). A few systems have been suggested in which real time monitoring is used to control welding conditions and joint tracking, and perform any necessary correction. Different monitoring techniques have been proposed such as through-the-arc monitoring (Thompson 1986, Nomura et al. 1986), inductive sensing (Blume et al. 1988) and weld pool imaging (Oshima 1988).

The recent advances in welding power supplies and process control have revolutionized the application of the GMAW process. However, they have not been able to solve one of the major limitations of the process, namely the likelihood of fusion problems. A more profound understanding of the basic mechanisms in GMAW in conjunction with the tighter controllability available nowadays can be a possible approach to alleviate such problems.

2.3.NARROW GAP WELDING

2.3.1.Introduction

Although narrow gap welding (NGW) has generated great interest in the welding industry and has been the subject of much investigation in the last twenty years, there is still some controversy around a proper definition for the technique. Most authors agree that narrow gap welding is performed in thick joints using an essentially square butt joint preparation with small gaps (Henderson 1978, Baxter 1979, Nazarchuk and Sterenbogen 1984). Bicknell and Patchett (1985) suggested that a joint aspect ratio (plate thickness to gap width) of 5 or more defined a welding process as "narrow gap". Electro-slag welding and even electron beam welding have been included as narrow gap processes by some authors, whereas others have restricted the term to arc welding only. In an attempt to systematize the concept of narrow gap welding, Malin (1983, 1987) distinguished the following features of NGW:

- NGW is not a welding process, it is a special bead deposition technique,
- NGW is associated only with an arc welding process, for instance, gas metal arc welding (GMAW-NG) or submerged arc welding (SAW-NG),
- NGW features a fixed bead deposition layout that is characterized by a constant number of beads per layer (1-3) deposited one on top of the other,
- NGW requires a square groove only. When a groove angle is used, it is intended for distortion compensation rather than for better access to the joint. When used, the groove angle is generally around 2-3 degrees only.
- NGW requires low or medium heat input.

and, based on those features, defined narrow gap welding as:

"NGW is a property-oriented bead-deposition technique associated with an arc welding process characterized by a constant number of beads per layer that are deposited one on top of the other in a deep, narrow square groove."

A very similar definition is given by Manzoli and Caccia (1989).

The development of NGW was intended to reduce weld metal volume in thick plate welding and hence reducing welding cost, time and distortion level. The technique was first described in the USSR (Dudko et al. 1957) and in the United States (Meister and Martin 1966), and it was developed and used mainly in Japan, where several different approaches have been proposed in order to overcome its limitations. A classification of the NGW processes commonly used in Japan is shown in figure 2.8 (Nomura and Sugitani 1984). A more recent and comprehensive classification is given by Malin (1987), figure 2.9. This classification is based on the criteria below:

- Welding processes associated with NGW.
- NGW technique, including electrode feeding technique, bead deposition layout and number of electrodes used simultaneously.

The main welding processes associated with NGW are gas metal arc welding, submerged arc welding (SAW), gas tungsten arc welding (GTAW) and flux cored arc welding (FCAW). According to Lucas (1984), NGW is basically applied to GMAW (78%), SAW (18%) and GTAW (4%) in Japan. In the western countries, NGW is much less common and more used with SAW (Malin 1987, Lucas 1984, Bicknell and Patchett 1985). Recent developments in filler metal and flux formulation, and the greater tolerance of SAW-NG to welding parameter variation (when compared with GMAW-NG) have increased the interest in narrow gap techniques based on SAW (Malin 1989). However such applications are basically confined to the flat position.

NGW processes can be separated into two groups based on the electrode feeding technique used to ensure adequate sidewall penetration. The first group (NGW-I) achieves sidewall penetration through electrode/arc manipulation, including directing fixed electrodes towards the sidewall (NGW-Ia), oscillating (NGW-Ib) or rotating (NGW-Ic) the arc. The second group (NGW-II) attempts to control sidewall penetration through manipulation of welding parameters (Malin 1987).

NGW is more frequently performed with one or two passes per layer (monopass or bi-pass deposition layouts). A tri-pass layout is less common. Finally, according to the electrode arrangement, NGW torches can be single or double-electrode.

Some of the advantages attributed to NGW processes, when compared with other welding processes for thick joints, are listed below:

- reduction in welding time,

- lower consumable costs,
- reduction in slag removal time,
- reduction in preparation cost,
- reduction in post-weld heat treatment,
- improved toughness, and
- reduction in angular distortion.

These advantages, which are directly related to the lower weld metal volume and heat input of NGW, are expected to result in lower costs for welding thick material when compared with conventional processes such as SAW and ESW (figure 2.10).

The main problems with narrow gap techniques are associated with the high sensitivity of NGW to the formation of defects such as lack of fusion, undercutting and centre line cracking as a result of minor variations in welding conditions. Pore formation due to improper gas shielding and magnetic arc blow are also frequent problems associated with GMAW-NG, whereas entrapped slag can occur in SAW-NG. These problems, together with the difficulty in repairing welding defects in thick joints, have led to the development of complicated and expensive welding equipment for NGW (Malin 1987) that requires a very experienced and well trained operator in order to achieve reliable operation (Hunt 1985). Results obtained with the industrial implementation of both GMAW-NG and SAW-NG suggested that the likelihood of defect formation in the former was higher than in the latter (Hunt 1985).

Several reviews of narrow gap welding have been published since its introduction in the sixties, for instance, Henderson (1978), Baxter (1979), Malin (1983 and 1987) and Ellis (1988).

2.3.2. Narrow gap GMAW

Gas metal arc welding was the first process to be used in NGW and it is still the one most commonly associated with the technique. This preference is related to the easily observable arc, relatively narrow groove, high welding quality, productivity and cost effectiveness (Malin 1987). However, GMAW-NG is rather prone to defect formation in the sidewalls, spattering and shielding gas deficiencies. These problems, which are associated with the difficulty in feeding the electrode and supplying a proper shielding gas coverage into a very narrow and deep groove, and in obtaining well balanced arc heating between the side walls and the bottom of the joint, have been the major obstacles to a greater acceptance of GMAW-NG. In order to overcome these limitations, several wire deposition strategies and torch designs have been proposed, developed and some of them used in industrial applications since the introduction of narrow gap welding.

NGW-I techniques for GMAW have been developed mainly in Japan and comprise several process variations including:

- Pre-casting the wire and depositing alternating stringer beads (Meister and Martin 1966), NGW-Ia.
- Oscillating the wire inside the groove using a straight long contact tube that is swung across or along the groove (Nakayama et al. 1976, Futamura et al. 1978), NGW-Ib.
- Rotating alternately a bent contact tip about its axis inside the groove (Innyi et al. 1975), NGW-Ib.
- Plastically deforming the wire into some wavy shape before its entrance in the contact tube in order to oscillate the arc across the groove (Sawada et al. 1979, Probst and Hartung 1988), NGW-Ib.
- Rotating the arc by feeding the wire through an eccentric contact tube that rotates (Nomura and Sugitani 1984), NGW-Ic.
- Rotating the arc by using a special "twist" electrode wire (Kimura et al. 1979), NGW-Ic.

Thin wires (less than 2.0mm) are typically employed with NGW-I techniques. This is explained by the necessity of bending or plastically deforming the wire in almost all the processes. One exception is the twist wire technique that employs two 2.0mm intertwined wires with an equivalent diameter of 2.8mm. The heat input in some of the processes is low enough to allow their use in positional welding. Gap width depends on the specific technique employed and wire diameter, and values between 6mm and 20mm have been reported in the literature. Mechanical wear of contact tube and other parts, fluctuations in the current pick-up point and inconsistencies in wire feeding are potential problems associated with most of NGW-I processes (Render 1984, Allum and Foote 1984). Making the arc oscillate across the joint, however, has the positive effect of increasing the process tolerance to groove width variations, reducing side wall defects and, consequently, enlarging the process operational envelope when compared with NGW-II techniques.

The main general characteristics of NGW-II techniques are the following (Malin 1987): a relatively large electrode diameter is used, ranging from 1.6mm to 5mm, a long electrode stickout is maintained in the centre of the groove with the contact tip located out of the joint gap, the heat input and the deposition rate are higher, and the gap opening is generally wider (11-16mm) than those employed in NGW-I. The high heat input generally limits use to the flat position only. Overheating and softening of the electrode wire by joule effect heating limit the maximum thickness (around 150mm) that can be welded to a much lower value than that achieved by NGW-I techniques. The equipment for NGW-II is basically the same as that used in conventional GMAW apart from slight modifications. Sidewall penetration is controlled by careful selection of welding parameters, including electrode polarity and

shielding gas composition (Kurokawa et al. 1966, Jackson and Sargent 1967, Lebedev 1977). A different approach for NGW-II has been recently considered by Fennel (1986) who, based on an earlier analysis of Allum and Foote (1984), used relatively thinner wires (1.2mm), narrower gaps (around 7mm) and pulsed current for high speed horizontal welding of pipelines in the horizontal-vertical position.

A comprehensive review of most of the GMAW-NG processes was presented by Malin (1987) and a summary of Japanese NGW techniques can be found in a paper by Jones (1984).

Argon plus 10-25% CO₂ is the most commonly used shielding gas mixture for welding mild and low alloy steel with NGW. Mixtures containing higher levels of CO₂ (Belchuk and Titov 1970, Kurokawa et al. 1966, Jackson and Sargent 1967), Ar-5%CO₂ (Matsunawa and Nishiguchi 1979), Ar-5%CO₂-2%O₂ (Fennel 1986) and ternary mixtures containing Ar, He and CO₂ (Jackson and Sargent 1967, Lebedev 1977, Fennel 1986) have also been considered. Carbon dioxide additions to argon affect both arc stability and bead shape. Ar-10%CO₂ is considered the most acceptable mixture in terms of arc stability in NGW (Malin 1987). Working with the "twist" wire process, Kimura et al. (1979b) found a maximum of penetration depth at the bottom of the joint for around 10%CO₂, and a steady growth in sidewall penetration with the CO₂ content (up to 40%) in the mixture. A similar improvement on sidewall penetration is associated with the helium content in the mixture, specially when it is more than 50%. However, helium additions also impair the process stability, particularly when helium content is over 75% (Lebedev 1977). Working with NGW-II, thin wires and pulsed current, Fennel (1986) also observed an improved lateral fusion when a helium based commercial mixture (Helishield 1, Ar-85%He-1.5%CO₂-250Vmp O₂) was compared with an argon based mixture (Argoshield 5, Ar-5%CO₂-up to 2%O₂).

A major difficulty in GMAW-NG is to ensure an effective shielding gas coverage for the arc and weld pool inside the gap. The geometric configuration of the joint can promote air being entrained by the shielding gas column inside the groove while the relatively long distance that sometimes separates the gas nozzles from the arc, renders the process very sensitive to draughts (Kender 1984). As a result, porosity can be formed. A number of techniques have been proposed to improve the shielding conditions in GMAW-NG. The most commonly used practice is to increase simply the gas flow rate proportionally to the thickness of the joint (Probst and Hartung 1988). Using a NGW-II process, Kurokawa (1966) observed that, above 100mm of joint thickness, the gas flow rate required to produce porosity free weld increases sharply from its initial value of 25 l/min (figure 2.11). Gas boxes seating directly over the joint and fitted with protective shrouds to prevent air from being entrained, and flat nozzles inserted into the joint to shield the arc area are generally used together for welding thick plates with the NGW-I technique.

Voltage, or perhaps arc length, is a key factor in providing adequate lateral penetration (Belchuk and Titov 1970, Kurosawa et al. 1966, Baxter 1979, Malin 1987) and process

stability (Lebedev 1977, Matsunawa and Nishiguchi 1979). When the arc voltage is too low, the side walls receive insufficient heat and lack of fusion is likely to develop. At the same time, short circuiting conditions, spattering and an unstable arc can be observed. Increasing arc voltage improves lateral fusion but, if the arc length becomes too long relative to the gap width, the arc tends to jump to the side walls. Undercutting, slag entrapment and lack of fusion at the bottom of the joint are then likely to develop. Under high voltage conditions and in a very narrow I groove, the arc can climb up rapidly along the side walls and render the process inoperative. Matsunawa and Nishiguchi (1979) associated such behaviour with the distribution of cathode spots on the joint and reduced the problem by increasing the CO₂ content in the shielding gas. The effect of voltage on bead formation and process stability is summarised in figure 2.12.

Current affects deposition rates, arc stability and bead geometry. Penetration at the bottom of the joint and deposition rate increase when the current rises whereas lateral penetration is less affected in both NGW-I (Kurokawa 1966, Belchuk and Titov 1970) and NGW-II (Kimura et al. 1979). Therefore, height/width ratio and sensitivity to centre line cracking also tend to increase. Current is generally kept above the spray transition level and pulsed current can be used to further stabilize the arc.

Unlike conventional GMA welding, which is performed almost exclusively with electrode positive, most of the work related to NGW-II indicates a preference for electrode negative (Jackson and Sargent 1967, Kurokawa et al. 1966, Belchuk and Titov 1970, Lebedev 1977). The following beneficial aspects have been associated with welding with electrode negative inside a narrow gap: higher productivity, greater sidewall penetration, lower height/width ratio and, therefore, lower sensitivity to centre line cracking. In electrode negative GMAW-NG, the confining walls of the groove affect the arc shape, resulting in an increase in arc stability, a change in metal transfer mode from repulsive globular to spray and a reduction in melting rate, whereas in reverse polarity no significant alteration was observed (Matumoto et al. 1980). However, electrode negative GMAW-NG still presents arc stability problems during the final passes when the groove influence over the arc becomes unimportant.

Welding speed influences the tendency of the weld pool to flow under the arc, the lateral penetration and the heat input. At low speed, the weld pool is likely to flow under the arc, preventing it reaching the lower corners of the groove and causing incomplete fusion (Kurokawa et al. 1966, Belchuk and Titov 1970). Increasing speed lowers the heat input in the weld. However, excessive speeds can cause incomplete fusion into the sidewall, due to insufficient heating of the wall (Malin 1987).

GMAW-NG is still the most used of the narrow gap processes. However, many problems, such as the tendency to lack of fusion, porosity and spatter generation, still remain basically unsolved. As a result, SAW has been increasingly used in narrow gap applications in the downhand position. There are, however, positional welding situations, such as the J-laying welding of pipelines, where neither SAW nor GMAW-NG with arc oscillation can be applied.

2.4. MODELLING OF THE WELD BEAD SHAPE

2.4.1. Introduction

Modelling is an activity constantly performed by man in both scientific and non-scientific situations. It involves creating an idealized representation of a real-world situation or system to promote a better understanding of its behaviour, i. e., a model (Cross and Moscardini 1985). A model, far from being an exact replica of the system, is a simplification of it and contains only those elements or features that the modeller considered important and was able to implement. At the same time, different approaches can be used for developing a model. Therefore, there is not a unique model for a system. Several different models can be developed for a given system by considering different features of the system, by using different interpretations for the same features, or by considering different approaches for model-building. Modelling is a fundamental tool for knowledge formation. However, a model must never be confused with reality. Failure to distinguish model from reality has frequently happened and generally resulted in retarding the development of new ideas.

One the first steps in model-building is to clearly state the reason or objectives of the model. The objectives and the resources available (both material and intellectual) will greatly influence the developing strategy, final form and applicability of the model. Cross and Moscardini (1985) suggested five main categories for models based on their objectives:

- . system understanding,
- . design,
- . optimization with respect to prescribed constraints,
- . control, and
- . training.

Models can be classified in many ways. A classification system presented by Gordon (1978) first separated them into physical and mathematical models (figure 2.13).

Physical models are based on some analogy between such systems as mechanical and electrical or electrical and hydraulic, or between the behaviour of different materials in similar situations (for instance, plasticine has been used for studying the forming of metals, Awano and Danno 1972).

Mathematical models use symbolic notation and mathematical equations to represent the system. Both mathematical and physical models can be either static or dynamic according to the influence of time on the model. Finally, Gordon classified mathematical models as analytical or numerical based on the technique used to solve them. Mathematical models can be further separated into theoretical or empirical, mechanistic or stochastic (statistical), and

discrete or continuous. Many other classifications for models are possible. It must be emphasized, however, that any classification system is rather artificial and should be used only as a reference. Models often present characteristics that do not allow them to be placed into only one class.

2.4.2. Mathematical modelling

There is a strong motivation for modelling the formation of a weld bead. A welding procedure is specified by parameters such as welding current, voltage, speed, gas composition, etc, but, as far as the weld applicability is concerned, the really important factors are the output variables (welding geometry, fusion characteristics, mechanical properties, etc). The inter-relationship between input and output variables in arc welding processes is rather complex and is traditionally obtained by a trial-and-error approach, based on previous experience and subjective judgement. This approach has, however, some drawbacks. It is subject to human error; it is not of universal application; it contributes little to the understanding of the problem and yields a solution which, while being acceptable, is not necessarily optimum in terms of cost or quality (Galopin and Boridy 1986).

A considerable amount of work has been undertaken to model the relationship between weld bead shape and welding parameters. However, the large number of complex and interacting variables and, until recently, the relatively poor precision and controllability of welding equipment, particularly power supplies, have created some scepticism regarding the use of mathematical models in procedure specification and process control. This trend seems to be reversing in the last 10 years. Several factors have contributed to this change, for instance:

- . Computers have become cheaper and more powerful.
- . The use of electronic power supplies and other modern welding equipment have increased the reproducibility and precision of welding, and made it possible to directly inter-connect welding equipment, computer and sensing devices.
- . There has been a trend to switch from manual and semi-automatic welding, where the welder subjectively adjusts welding parameters in order to control bead formation, to automatic welding, where the scope for such intervention is much reduced and may never be considered.

The work related to mathematical modelling of weld bead geometry has been reviewed by Shinoda and Doherty (1978), and McGlone (1982). In both papers the different models are divided into two main categories: theoretical and empirical approaches. Although this criterion is rather artificial, it is as good as any other criterion used to organise the different trends for modelling the weld bead shape and will also be used in the present work.

2.4.2.1. Theoretical approach

Theoretical studies of the weld bead formation have been mainly based on the work by Rosenthal (1946) who solved analytically the heat flow equation:

$$\rho \frac{\partial}{\partial t}(cT) + \rho \vec{v} \cdot \nabla(cT) = \nabla \cdot (k \nabla T) + s \quad [2.14]$$

where v is the welding velocity,

k is the thermal conductivity of the workpiece,

ρ is the density,

c is the specific heat, and

s is the heat created or absorbed,

for welding conditions using the following assumptions:

- . the physical characteristics of the metal are independent of the temperature and physical state of the metal,
- . quasi-equilibrium of thermal conditions,
- . the heat source is reduced to either a point, a line or a plane,
- . the workpiece has a very simple geometric shape in which one, two or all three dimensions are infinite.

For the case where a point heat source is moving on the surface of a very thick plate, Rosenthal's solution is:

$$T = T_0 + \frac{q}{2\pi k R} \exp\left[-\frac{v}{2\alpha}(x + R)\right] \quad [2.15a]$$

for a linear heat source moving in a plate of thickness h the solution is:

$$T = T_0 + \frac{q}{2\pi k} \exp\left(-\frac{vx}{2\alpha}\right) K_0\left(\frac{vr}{2\alpha}\right) \quad [2.15b]$$

where T is the temperature at point (x, y, z) ,

T_0 is the plate initial temperature,

$\alpha = k/\sigma c$ is the thermal diffusivity,

$q = nVI$ is the arc effective heat input,

$R = (x^2 + y^2 + z^2)^{1/2}$,

$r = (x^2 + y^2)^{1/2}$, and

K_0 is the modified Bessel function of zero order.

Rosenthal's model has been modified and extended by several workers. For instance, Wells (1952) simplified equation [2.15b] in order to obtain the bead width, Adams (1958)

calculated the peak temperature distribution in the workpiece, Cline and Anthony (1977) considered the effect of a gaussian heat source, and Nunes (1983) introduced the concept of thermal dipoles to account for the heat liberated by phase transformations. The validity of Rosenthal's model was investigated by Christensen et al (1965) by transforming [2.15a] and [2.15b] into dimensionless equations and comparing the theoretical bead area, width and penetration with a large number of experimental results. Moore et al. (1985) compared the cooling times from Rosenthal's model against the results of a finite elements model. It has been shown that the model predicts adequately well temperatures and cooling rates at some distance from the weld pool, and the cross-sectional areas of the fusion zone (autogenous welding) and the heat affected zone, provided the welding speed is sufficiently slow (Kovitya et al 1986). Equation [2.14] has also been solved numerically by different authors in an attempt to reduce the simplifications necessary for an analytical solution, for instance, Ushio et al (1977), Kou and Lee (1983), Kovitya et al (1986), and Tekrival and Mazumder (1986).

Rosenthal's model and the work following his approach have ignored fluid flow in the weld pool completely. This flow can be an important factor in the formation of the weld bead, determining, for instance, the occurrence of finger type penetration in spray-GMA welding (Halmoy 1979b). It is also associated with cast-to-cast variations of penetration in GTA welding (Heiper and Roper 1982). Convective motion is caused by electromagnetic, buoyancy and surface tension forces. In order to obtain the convective profile in the weld pool, the equation of continuity:

$$\nabla \cdot \mathbf{v} = 0 \quad [2.16]$$

the momentum equation:

$$\sigma \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla p - \nabla n \nabla v + \sigma \mathbf{g} + \mathbf{J} \times \mathbf{B} \quad [2.17]$$

and thermal balance equation [2.14] have to be solved. Different boundary conditions may be considered (Szekely 1986):

- . heat and current flux distribution in the free surface,
- . latent heat to be supplied or released at the solid-liquid interface,
- . surface tension value and gradient at the free surface,
- . free surface profile,

Several solutions for this problem have recently been presented in the literature. Atthey (1980) studied convection due to electromagnetic forces in a hemispherical weld pool. Oreper and Szekely (1984) and Craine (1987) analyzed the formation of the weld pool in stationary GTAW considering the effect of surface tension gradients on weld pool convection and bead shape. Kou and Wang (1986) modelled continuous operation GTA welding. Finally, Zacharia et al. (1988 a,b) studied bead formation in both non-autogenous and autogenous GTA welding considering the influence of a non-planar free surface, and Tsao

and Wu (1988) modelled stationary GMA weld pool. Similar models were also proposed for electron beam (Wei and Giedt 1985) and laser welding (Davis et al. 1986).

The static pressure balance of surface tension and gravity forces was used by Nishiguchi et al. (1975, 1977) to model the weld reinforcement profile in overlay and horizontal fillet welding. To simplify the model solution, the theoretical analysis is made under the following assumptions:

- . The weld pool is considered infinitely long in the direction of welding (two dimensional model),
- . The digging action by the arc is negligibly small, and
- . The surface tension is constant all over the pool surface.

For bead-on-plate welding, and taking the origin at the vertex of the bead (figure 2.14), the pressure balance is given by:

$$\tau/R = \tau/R_0 - \sigma g y, 1/R = y''/(1 + y'^2)^{3/2} \quad [2.18]$$

Where τ is the surface tension,

$1/R_0$ is the curvature at origin, and

$1/R$ is the curvature at point (x,y).

From equation [2.18] the weld surface profile can be derived as function of elliptic integrals.

A similar approach has been used by Andrews et al. (1980) to model both face and root profiles for the horizontal welding of thin plates, by Berezovskii et al. (1983) to study the face profile in horizontal welding, and by Richardson (1986) to analyze weld pool sagging in narrow-gap horizontal welding.

2.4.2.2. Empirical approach

Empirical modelling, often used together with simple theoretical ideas based on Rosenthal's model and applied to a specific situation, has been the most commonly adopted modelling technique employed to study the relationship between process variables and weld bead shape. Submerged arc welding has been the process most frequently associated with these studies. This preference can be explained by the relative facility with which the levels of the welding parameters in this process can be made sufficiently distinct from one another to permit a general understanding of the relationship between input and output variables (McGlone 1982). The majority of the analysis has been carried out on downhand, bead-on-plate welding. Shinoda and Doherty reviewed the empirical modelling work performed up to 1978.

Thorn et al. (1982) obtained simple regression models for the dimensions of GMA welds. These results were compared with values predicted by theoretical models obtained by Wells

(1952), and Christensen et al. (1965). The empirical model by Jackson and Shrubbsall (1953) for penetration in SAW was also compared:

$$p = k.[I^4/(v.V^2)] \quad [2.19]$$

where k is a constant that depends on the welding process.

As expected, the regression models were considered the most appropriate to describe the experimental data from which they were created.

Quintino (1986) studied the fusion characteristics of pulsed GMAW in mild steel plates and, based on Wells' model, related dilution to the factor $I_{mean}v$. The semi-empirical relationship obtained was:

$$1/\delta = 1/\delta_{max} + k/(I_{mean}v) \quad [2.20]$$

where k is a constant,

δ is dilution, and

δ_{max} is the maximum dilution.

and a chart for the generalised representation of fusion characteristics was prepared (figure 2.15). A very similar approach was followed by Allum and Oliveira Santos (1986) in studying pulsed GMAW of stainless steel.

Chandel et al. (1987) extended Jackson's model for penetration (equation 2.19) in order to include the influence of electrode polarity and groove angle.

In the seventies, many investigations (Jones et al. 1977, McGlone 1980) were conducted at the Welding Institute to collect and present data in a suitable format for SAW procedure optimisation. This led to the so-called "tolerance box" procedure. This approach (figure 2.16) starts with a widely spaced factorial experiment and, based on some weld bead acceptance criteria, delineates the area of acceptable welding by further trials. The tolerance box technique is basically a graphical one. Its main limitations are the difficulty of representing the results when more than two input variables are used, and the lack of any quantitative information regarding the accuracy of the model. It is also an expensive and time consuming technique (Harris and Smith 1983). To overcome these limitations, an alternative approach was developed (McGlone 1980, Salter and Doherty 1981) based on factorial experimentation and multiple regression analysis. The predictive equations for the output variables, in the form:

$$\ln(\text{output variable}) = a_0 + a_1 \ln I + a_2 \ln V + \dots \quad [2.21]$$

where $a_0, a_1, a_2, \dots$ are the regression coefficients,

were used to create tolerance boxes and procedure optimisation computer programmes.

The application of statistics is not something new in welding research. However, its application has been limited mainly to the final analysis of the experimental results. Regression analysis is probably the most common technique used, and sometimes misused, for data analysis. The use of statistics for planning and designing welding experiments has been much less frequent. Response surface techniques were employed in ultrasonic welding in the early sixties (Ross 1961). As already mentioned, SAW procedure techniques based on factorial experiment were developed at the Welding Institute in the seventies. A similar technique was used by Chandel and Bala (1986) to study centerline cracking in SAW. Factorial experimental design has been used more frequently in the eighties, for instance, to study plasma cladding (Harris and Smith 1983), submerged arc welding (Brunmstrom and Harris 1985, and Chandel and Bala 1986), pulsed GMAW (Kumar and Parmar 1986), and flux cored arc welding (Raveendra and Parmar 1987).

2.4.3. Statistical design of experiments

2.4.3.1. Introduction

There are two aspects of an experimental programme that can be tackled by statistics: the design of the experimental procedure and the analysis of data obtained. Of these two aspects design is the most important. If the experimental design is poorly chosen, so that the resultant data do not contain much information, any data analysis technique, no matter how thorough and sophisticated it is, will not be able to extract much from the data (Box et al. 1978).

Figure 2.17 shows a schematic representation of an experiment. It consists of n experimental trials in which k input variables or factors ($X_1, X_2, X_3, \dots, X_k$) are set to specific values and a response Y (or responses) is obtained, i. e.:

$$X = \begin{matrix} & x_{11} & x_{12} & \dots & x_{1k} \\ \begin{matrix} X = \\ \\ \\ \end{matrix} & \begin{matrix} x_{21} \\ x_{22} \\ \vdots \end{matrix} & \begin{matrix} x_{22} \\ x_{22} \\ \vdots \end{matrix} & \begin{matrix} \dots \\ \dots \\ \dots \end{matrix} & \begin{matrix} x_{2k} \\ x_{2k} \\ \vdots \end{matrix} \\ & x_{n1} & x_{n2} & \dots & x_{nk} \end{matrix}, Y = \begin{matrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{matrix} \quad [2.22]$$

where the different values of the factors and response are given by the columns of $\mathbf{X}$ and $\mathbf{Y}$ respectively, and a specific trial is made up by a row of $\mathbf{X}$ and $\mathbf{Y}$.

Unknown or not completely controlled factors, and fluctuations either inherent to the system or occurring during measurement introduce a certain variability in the response that can mask partially or completely the influence of some of the input variables. At the same time, if two or more input variables (i. e., two or more columns of $\mathbf{X}$) are closely related, it will be almost impossible to draw any conclusion about the individual effects of these variables. Such

considerations become more important, as the complexity of the experiment increases, the control that the researcher has over the system decreases or the effects of interest become relatively smaller. Statistical design of experiments consists of planning, based on some statistical criteria, not only the matrix $\mathbf{X}$ but also a strategy to perform the experiment and collect data, in order to maximize the amount of useful information that can be obtained with a fixed resource. A model of the form below is usually assumed for data analysis:

$$\text{response} = \text{model} + \text{error} \quad [2.23]$$

where model states the effect of the input variables on the response and error describes the general form of departures from the model.

From a historical point of view, most of the developments in statistical experimental design have been in biological disciplines, in particular, agriculture, medicine and psychology. In engineering it has been mostly applied to chemical engineering problems. Most of the important principles of experimental design were developed in the twenties and thirties by Sir R. A. Fisher. His work and that of other researchers in the following years were greatly influenced by the calculating capacity available at that time. In the last three decades, however, the development of computer hardware and software has allowed major innovations in both experimental design and data analysis (Mead 1988, and Steinberg and Hunter 1984).

The three basic principles for the statistical design of experiments are replication, randomization and blocking. Replication (i. e., the repetition of trials) allows an estimate of the experimental error to be obtained. It can also increase the precision of the estimates of effects. Randomization implies that the allocation of resources and the sequence in which the experiment is performed are randomly determined. Randomization is essential because it usually validates the assumptions made by the statistical methods. A block is a portion of the experimental material (eg., a plate of steel) that is expected to be more homogeneous than a set of the material (eg., several plates of similar steel grade). By keeping the comparisons among different factors inside a block (blocking), the precision of the experiment can be increased. The application of these basic principles to practical situations has led to the development a large number of different experimental designs. There are several books discussing experimental design (for instance, Cochran and Cox 1957, Box et al. 1978, Montgomery 1984, and Mead 1988).

The simple application of a "statistical design" is not a guarantee that an experiment will be successfully performed. Each new problem should be treated carefully, and the initial steps of any experimental work (i. e., recognition of the problem, definition of objectives, analysis of possible factors, etc) must never be underestimated. Montgomery (1984) presents the following procedure to tackle an experiment:

- Recognition and statement of the problem.
- Choice of factors and level.

- Selection of response variable.
- Choice of experimental design.
- Data analysis.
- Conclusions and recommendations.

Finally, an interesting presentation of real-world difficulties that can be found in experimental design is given by Hahn 1984.

In the present review, only one experimental design technique (2^k factorial experiment) and one data analysis technique (linear regression analysis) will be considered.

2.4.3.2. Factorial design

Only a summary of the main points in 2^k factorial design will be covered by this review. The subject is a standard part of any textbook on experimental design (see, for instance, Daniel 1976, and Box et al. 1978) and was reviewed by Steinberg and Hunter (1984). A brief introduction to factorial design and its application to welding problems is presented by Brunnstrom and Harris (1985).

Factorial design is commonly used in experiments involving several factors where the cumulative effect of these factors on the response is to be studied. The simplest of the factorial designs is that in which each of the k factors is used at only two levels, i. e., a "high" and a "low" level. A complete experiment of this kind requires 2^k trials and is called 2^k factorial design.

The 2^k design is particularly useful in the early stages of an experimental program when the number of factors being investigated is likely to be large. This design, particularly in a fractional form, provides a way to investigate a large number of factors with a relatively small number of trials. It is also useful to investigate the behaviour of a response in a small region of the factor space, where a linear relationship among the factors can describe the response reasonably well. A factorial design can also be augmented to form composite designs (Box et al., 1978) or be used as building blocks to create more sophisticated models. Some desirable properties of factorial designs are (Box and Draper 1987, and Chatfield 1983):

- They allow multitudes of comparisons to be made and so facilitate model creation and criticism.
- They provide highly efficient estimates of the effects of the factors.
- They give rise to simple calculations.
- They provide a very good visualisation of the response behaviour.

Once the low (-) and high (+) levels of the k factors have been decided, the factors are transformed into a normalised form in which each factor has -1 and +1 values. The

experiment consists then of 2^k trials (points) whose levels are determined by every possible combination of the k +/- signs. Geometrically, the design obtained is formed by the vertices of a hypercube in k dimensions (figure 2.18). Table 2.5 shows designs for k up to 5. The trials should be performed in a sequence randomly determined and the measured responses can be used to calculate the main and interaction effects of the factors. The main effect of a factor is defined as the average difference between the responses at the points where that factor is high (+) and where it is low (-):

$$effect_i = (\Sigma y_{(+)} - \Sigma y_{(-)})/2^{k-1} \quad [2.24]$$

where $effect_i$ is the main effect of x_i . A similar definition applies to interaction effects. Now, $\Sigma y_{(+)}$ and $\Sigma y_{(-)}$ mean the sum of responses at the points where the product of the factors (in the normalised form) that are considered interacting is positive and negative respectively. Alternative and quicker methods to calculate main and interaction effects are the table of contrast coefficients and Yate's algorithm (Box et al. 1978).

For a complete 2^k factorial design, if $V(y) = \sigma^2$, then:

$$V(y_{mean}) = \sigma^2/2^k \quad [2.25]$$

$$V(effect) = \sigma^2/2^{k-2} \quad [2.26]$$

A linear model to estimate the responses that contains the main and interaction effects can be obtained. For instance, for $k=3$:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{23}x_2x_3 + a_{123}x_1x_2x_3 \quad [2.27]$$

where x_1 , x_2 , and x_3 are in the normalised form,

a_0 is the mean response (y_{mean}), and

the coefficients a_1 , a_2 , a_3 , a_{12} , etc are half the respective effect.

If there is an estimate s^2 of the experimental error, then the significance of each coefficient of equation [2.27] can be checked in an analysis of variance table. In single replicate designs, a direct estimate for experimental error is not usually available. In this situation, a common practice is to suppose that the high-order interactions are negligible and, therefore, their mean square sum:

$$MS_{high-order} = \Sigma (a_{high-order})^2/(N-1) \quad [2.28]$$

where N is the number of high-order interactions, can be used as an estimate of the experimental error. Generally this procedure is recommended for k more or equal to 4 (Montgomery 1984). An alternative method of analysis consists in plotting the effects on normal probability paper and consider significant those that do not lie along a straight line (Daniel 1976), figure 2.19.

There are many circumstances in which it is impossible to perform a complete 2^k factorial design in one block, where a block may be a plate of steel, a laboratory or welding machine, etc. If the effect of the blocks can be assumed to be additive, it can be confounded with high-order interactions without affecting low-order interactions and main effects by using a technique called confounding.

The same approach can be used to obtain fractional factorial designs. These designs allow the experimenter to study main effects and low-order interactions in fewer runs than required in a complete factorial design by sacrificing the high-order interactions. Fractional factorials are important when the number of factors is high and the high-order interactions are negligible because they can offer a great economy of time and resources. Confounding and fractionating of factorial experiments are thoroughly discussed in the literature (for instance, Box et al. 1978, Montgomery 1984, and Box and Draper 1987).

2.4.3.3. Regression analysis

Linear regression analysis is a statistical technique for investigating and modelling the relationship between variables. Gauss, in about 1809, is usually considered to have developed the method which changed very little until late 1950's, probably because of the lack of high-speed computing (Hocking 1983). Since then, the situation has dramatically changed and, nowadays, regression analysis is widely employed in almost every field and is one of the most commonly used statistical techniques. Regression models are used for several purposes, including (Montgomery and Peck 1982):

- . data description,
- . parameter estimation,
- . prediction and estimation, and
- . control.

The literature on regression analysis is enormous, including many textbooks (Draper and Smith 1981, Montgomery and Peck 1982, Weisberg 1985 and Rawlings 1988, for instance). The subject is also part of almost any textbook on applied statistics. The developments of regression analysis were recently discussed by Hocking (1983). The present review will only introduce the basic concepts and techniques associated with the method.

Regression analysis starts by postulating that a certain response y is adequately described by the linear model with k input variables or predictors (x_i):

$$y = \sum_{i=1}^k \beta_i x_i + \varepsilon \quad [2.29]$$

where β_i are unknown parameters and ε is the experimental error. For simplicity, the present discussion considers that the response and predictors are centred, i. e., they were transformed by subtracting the mean from each variable. Consequently, y and x_i ($i= 1..k$) have means

equal to zero and a b_0 term (a constant) is not included in [2.29]. In order to examine this model a random sample of size n of predictors and response has to be obtained. The data and the model are summarized in matrix notation as:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon} \quad [2.30]$$

where $\mathbf{y}$ is a $(n \times 1)$ vector of responses (see [2.22]),
 $\mathbf{X}$ is a $(n \times k)$ matrix of predictors (see [2.22]),
 $\boldsymbol{\beta}$ is a $(k \times 1)$ vector of unknown parameters, and
 $\boldsymbol{\varepsilon}$ is a $(n \times 1)$ vector of errors.

It is assumed that the experimental error is independent and has constant variance, i. e.:

$$E(\boldsymbol{\varepsilon}) = \mathbf{0} \text{ and } V(\boldsymbol{\varepsilon}) = \mathbf{I}\sigma^2 \quad [2.31a]$$

so:

$$E(\mathbf{y}) = \mathbf{X}\boldsymbol{\beta} \quad [2.31b]$$

Accepting that the model adequately represents the data, estimates for the parameters in $\boldsymbol{\beta}$ have to be obtained. In linear regression, the criterion used for parameter estimation is that the sum of the squared differences between the observed responses and the model predictions should be minimized. It can be shown that, if $\mathbf{X}'\mathbf{X}$ is not singular, the linear regression estimates are given by:

$$\mathbf{b} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y} \quad [2.32]$$

and the fitted model and the residuals are respectively:

$$\hat{\mathbf{y}} = \mathbf{X}\mathbf{b} \quad [2.33]$$

$$\mathbf{e} = \mathbf{y} - \hat{\mathbf{y}} \quad [2.34]$$

The linear regression vector of estimates ($\mathbf{b}$) has the following properties (Draper and Smith 1981):

- . it is an estimate of $\boldsymbol{\beta}$ that minimizes $\sum \varepsilon_i^2$ irrespective of any distribution properties of the errors,
- . the elements of $\mathbf{b}$ provide unbiased estimates of the elements of $\boldsymbol{\beta}$ which have minimum variances irrespective of distribution properties of the errors, and
- . if the errors follow a normal distribution, $\mathbf{b}$ is also the maximum likelihood estimate of $\boldsymbol{\beta}$.

If it can be further assumed that the errors follow a normal distribution, the regression model can be tested by an analysis of variance table to check if the coefficients $\mathbf{b}$ can be considered equal to a certain vector $\mathbf{b}_0$. If $\mathbf{b}_0$ is the null vector, the test is called a test for significance of regression. This test determines if it is reasonable to assume a linear relationship between the response and any regressor (table 2.6). If replicated runs are available, the model can also be tested for lack of fit (table 2.7).

The coefficient of multiple determination R^2 is frequently used as a measure of the fraction of variation of y that is explained by the regressor variables. However R^2 will always approach one when a predictor is added to the model. So, model with large number of predictors will tend to have high values of R^2 without any guarantee of performing well in prediction.

Analysis of the residuals plays an important role in judging model adequacy. It is basically a graphical method with several types of plot being used:

- . histogram of residuals,
- . normal probability plot,
- . time sequence plot,
- . residuals versus fitted values ($\hat{y}_i$),
- . residuals versus each regressor, and
- . residuals versus regressors not included in the model.

Plotting residuals can help to detect outliers and violations of the assumptions about the errors. Several numerical tests also exist for regression diagnostics (see, for instance, Weisberg 1985, chapter 5).

Transformations of the response or predictors can be used for reducing either nonconstant variance or nonlinearity (lack of fit). Also, errors in the transformed regression may be more normally distributed than the errors in the untransformed case. A transformation may also allow the use of a simpler model to describe the data. Transformations can be selected either empirically or theoretically (Box and Draper 1987). A power transformation is commonly used for the response:

$$y_{trans} = y^t \quad [2.35]$$

A best value for t can be interactively determined by maximizing the likelihood function (Box and Cox 1964):

$$L(t) = -(n/2)\ln(SSe_t) + n(t - 1)\ln(y_{gm}) \quad [2.36]$$

or minimizing the mean square error for regression models using the transformation below:

$$z_t = \begin{cases} (y^t - 1) / (t y_{gm}^{t-1}) & t \neq 0 \\ y_{gm} \ln(y) & t = 0 \end{cases} \quad [2.37]$$

where $L(t)$ is the log-likelihood function,
 n is the number of data points,
 SSe_t is the residual sum of squares, and
 y_{gm} is the geometric mean of the y 's.

The method discussed above should be used cautiously because it can be highly inefficient if the distribution of errors has heavier tails than the normal distribution and it is very sensitive to outliers (Carrol and Ruppert 1985).

An approximate $100(1 - \alpha)$ percent confidence interval on t can be calculated by (Montgomery and Peck 1982):

$$SS^* = SSe_t \cdot [1 + (t_{\alpha/2, v}^2)/v] \quad [2.38]$$

Where $v = n - k - 1$ is the number of residual degrees of freedom, and $t_{\alpha/2, v}$ is the upper $\alpha/2$ percentage point of the t distribution with v degrees of freedom. The confidence interval is then obtained by finding the points where the horizontal line SS^* intercepts the curve of SSe_t against t .

Predictor variables can be transformed to describe maxima and minima in the response (for instance, by including powers of predictors to model the response) or to accommodate nonlinearity.

In many applications, there are a number of candidate variables that may or may not be important for the model. The problem of finding an appropriate subset of regressors is called "variable selection" or "selection of the best regression equation". Two important aspects of variable selection are generating candidate models and selecting which candidate is better than others. Some possible criteria for model selection are:

- . Coefficient of multiple determination.
- . Adjusted R^2 .
- . Residual mean square (MSr).
- . Mallows' C_p statistic.
- . Partial F ratio

The main computational techniques for variable selection can be grouped as (Montgomery and Peck 1981, and Nie et al. 1975):

- . All possible regressions: All possible combinations containing the predictors are fitted and the best model is selected by some statistical criteria.
- . Forward inclusion: The procedure begins with the assumption that there are no predictors in the model. Variables are, then, entered in the model only if they

meet certain criteria. The order of inclusion is determined by the respective contribution of each variable to improve the model.

- . Backward elimination: The procedure starts with a model including all possible predictors. Those predictors that do not meet some criteria are eliminated one by one from the model.
- . Stepwise selection: This process is a modification of forward elimination in which at each step all predictors already in the model are checked by their partial F ratio. A regressor is dropped from the model if their partial F ratio is less than a critical value (F_{OUT}). The process finishes when no variable can be either added or dropped from the model.

The primary limitations of variable selection techniques are that (a) the procedure implies an order of importance to the variables, an order that may be misleading or confusing, (b) in case of early termination or the presence of collinearity, the procedure may fail to detect important variables, and (c) different selection techniques and criteria can result in different "best" models for the same set of data (Hocking 1983).

When all the predictors variables are orthogonal or independent, i. e., any two columns $\mathbf{X}_i$ and $\mathbf{X}_j$ ($i \neq j$) of the data matrix $\mathbf{X}$ has inner product nought ($\mathbf{X}_i \cdot \mathbf{X}_j = 0$), the use and interpretation of linear regression is relatively easy. In many cases the regressors are not orthogonal. When there is a nearly perfect linear relation among the predictor variables, the problem called "collinearity" exists. The consequences of collinearity are: (a) coefficient estimates tend to inflate and may have incorrect sign, (b) predicted values may be unreasonable, and (c) the stepwise, backward and forward variable selection methods can fail to detect important combinations of variables. Some techniques to deal with collinearity are (Montgomery and Peck 1984, Hocking 1983):

- . Collection of additional data,
- . model respecification,
- . elimination of some variables when the collinearity is inherent to the system, and
- . use some alternative estimation technique, such as Ridge regression, capable of provide some alternative estimator that is biased but could have a lower variance than the linear regression estimator.

TABLE 2.1 IIW classification for metal transfer modes (Lancaster 1987).

Designation of Transfer Type	Welding Processes (Examples)
1. Free flight transfer	
1.1 Globular	
1.1.1 Drop	Low-current GMA
1.1.2 Repelled	CO2 shielded GMA
1.2 Spray	
1.2.1 Projected	Intermediate-current GMA
1.2.2 Streaming	Medium-current GMA
1.2.3 Rotating	High-current GMA
1.3 Explosive	SMA (coated electrodes)
2. Bridging transfer	
2.1 Short-circuiting	Short-arc GMA
2.2 Without interruption	Filer wire addition
3. Slag protected transfer	
3.1 Flux-wall guided	SAW
3.2 Other modes	SMA, cored wire,electroslag

TABLE 2.2 Simplified description of the metal transfer modes most commonly found in GMAW.

TRANSFER MODES	CHARACTERISTICS
Free flight	A continuous arc is maintained and the metal is transferred across the arc in discrete droplets.
Globular (drop)	Metal drops substantially greater than the wire diameter are detached when their weight exceeds the restraining force of surface tension. This type of transfer cannot be used in out-of-position welding and is generally associated with high spatter levels. It occurs at low currents in Ar shielded welding and at all current levels in CO ₂ welding.
Globular (Repelled)	The large drops formed at the wire tip are deflected to the side or forced away from the workpiece. It has been observed in negative electrode GMA welding, flux cored welding and CO ₂ welding of steel.
Spray (Projected)	Metal droplets smaller than the wire diameter are formed and axially accelerated across the arc when the current density is sufficiently high. The process is dominated by electromagnetic forces. However, the high currents generally associated with spray transfer limit its use in positional welding of steel.
Spray (Streaming)	A long neck is formed at the electrode tip and fine droplets form at its end when the current is further increased.

TABLE 2.2(con)

Simplified description of the metal transfer modes most commonly found in GMAW.

TRANSFER MODES	CHARACTERISTICS
Spray (Rotating)	With very high current density and long stickout, the wire can lose mechanical resistance and start rotating under the influence of magnetic forces. The droplets are detached tangentially to the electrode end resulting in a high spatter level.
Explosive	Gas reactions cause the breaking of the liquid drops into small droplets that can be transferred into the weld pool or generate spatter.
Bridging	It is characterized by the filler wire or electrode contacting the weld pool.
Short-circuit	This is a bridging transfer mode in which a short circuit is established and the arc is extinguished when the electrode touches the workpiece. The liquid metal is then transferred by surface tension forces to the weld pool and the arc is re-ignited. The repeated short circuiting behaviour can cause process instability and the low heat input generally associated with the process is a liability in terms of lack of fusion formation. The process is mainly used in thin sheet steel and positional weldings.

TABLE 2.3 Gas mixtures available and their applications (Hilton and Norrish 1988).

Gas	Applications	Features
Argon	GTAW. All metals. GMAW Spray/Pulse aluminium, nickel, copper alloys	Stable arc performance. Poor wetting characteristics in GMAW. Efficient shielding. Low cost.
Helium	GTAW. All metals especially copper & aluminium. GMAW. High current spray aluminium	High heat input increased arc voltage
Argon+25 to 80%He	GTAW aluminium, copper, stainless steel. GMAW aluminium & copper	Compromise between pure Argon & pure He. Lower He contents normally used for GTAW
Argon+0.5 to 15% H_2	GTAW austenitic stainless steel, some copper nickel alloys	Improved heat input, edge wetting and weld bead profile
CO_2	GMAW plain carbon and low alloy steels	Low cost gas. Good fusion characteristics/shielding efficiency but stability and spatter levels poor. Normally used for dip transfer only.
Argon+1 to 7% CO_2 +up to 3% CO_2	GMAW plain carbon and low alloy steels. Spray transfer.	Low heat input, stable arc. Finger penetration. Spray transfer and dip on thin sections. Low CO_2 levels may be used on stainless steels but carbon pickup may be a problem.
Argon+8 to 15% CO_2 up to 3% O_2	GMAW Plain carbon and low alloy steels. General purpose.	Good arc stability for dip + spray pulse and FCAW. Satisfactory fusion & bead profile
Argon+16 to 25% CO_2	GMAW plain carbon and low alloy steels. Dip Transfer/FCAW.	Improved fusion characteristics for Dip.
Argon+1 to 8% O_2	GMAW. Dip and spray & pulse plain carbon and stainless steel.	Low O_2 mixtures suitable for spray and pulse but surface oxidation and poor weld profile often occur with stainless steel. No carbon pickup.
Helium+10 to 20% Argon+Oxygen+ CO_2	GMAW dip transfer stainless steel	Good fusion characteristics, high short circuit frequency not suitable for spray/pulse transfer
Argon+30 to 40%He + CO_2 + O_2	GMAW dip spray and pulse welding of stainless steels	Improved performance in spray and pulse transfer. Good bead profile. Restrict CO_2 level for minimum carbon pickup.
Argon +30 to 40%He +up to 1% O_2	GMAW dip, spray and pulse welding of stainless steels	General purpose mixture ⁷ with low surface oxidation and carbon pickup. (It has been reported ⁷ that these low oxygen mixtures may promote improved fusion and excellent weld integrity for thick aluminium alloys).

TABLE 2.4 Physical properties of gases used in shielding mixtures for welding.

Shielding Gas	First Ionisation Potential (eV)	Density (Kg/m ³)
Argon	15.75	1.784
Carbon dioxide	-	1.977
Helium	24.58	0.178
Hydrogen	13.59	0.083
Nitrogen	14.54	1.160
Oxygen	13.61	1.326

TABLE 2.5 Factorial combinations for up to 5 factors (Brunnstrom and Harris 1985).

[illegible]

TABLE 2.6 Analysis of variance for significance of regression.

Source of Variation	Sum of squares	Degrees of Freedom	Mean Square	F0
Regression	SSr	k	MSr	MSr/MSe
Residual	SSe	n-k-1	MSe	
Total	S _{yy}	n-1		

Obs: $.SSr = \mathbf{b}'\mathbf{X}'\mathbf{y} - n\bar{y}_{mean}^2$ (Sum of squares due to regression)

$$.MSr = SSr/k$$

$$.SSe = \sum (y - \hat{y})^2 \quad (\text{Sum of squares due to error})$$

$$.MSe = SSe/(n-k-1)$$

$$.S_{yy} = \sum (y - \bar{y}_{mean})^2 \quad (\text{Total corrected sum of squares})$$

TABLE 2.7 Analysis of variance for lack of fitting.

Source of Variation	Sum of squares	Degrees of Freedom	Mean Square	F0
Regression	SSr	k	MSr	MSr/MSe
Residual	SSe	n-k-1	MSe	
Lack of fit	SS _{LOF}	m-k-1	MS _{LOF}	MS _{LOF} /MS _{PE}
Pure error	SS _{PE}	n-m	MS _{PE}	
Total	S _{yy}	n-1		

Obs: m is the number of distinct experimental trials.

r_i is the number of replications at trial i .

$$.SS_{LOF} = \sum_{i=1}^m r_i (\bar{y}_i - \bar{y}_{mean})^2$$

$$.SS_{PE} = \sum_{i=1}^m \sum_{u=1}^{r_i} (y_{iu} - \bar{y}_{mean})^2$$

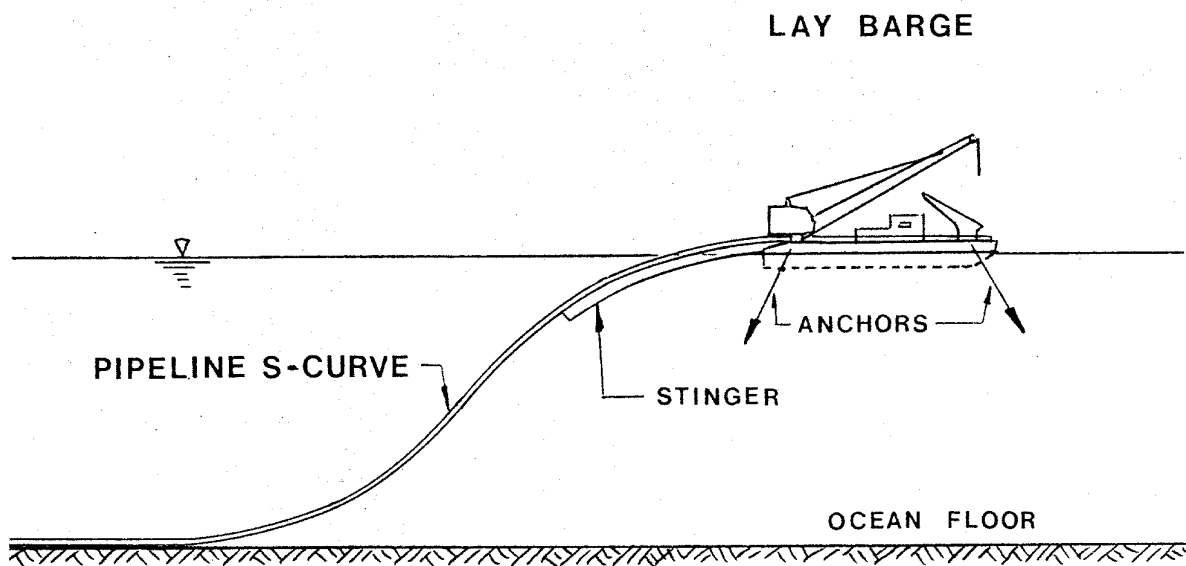


Figure 2.1 Illustration of the S curve pipelaying system (Fennel 1986).

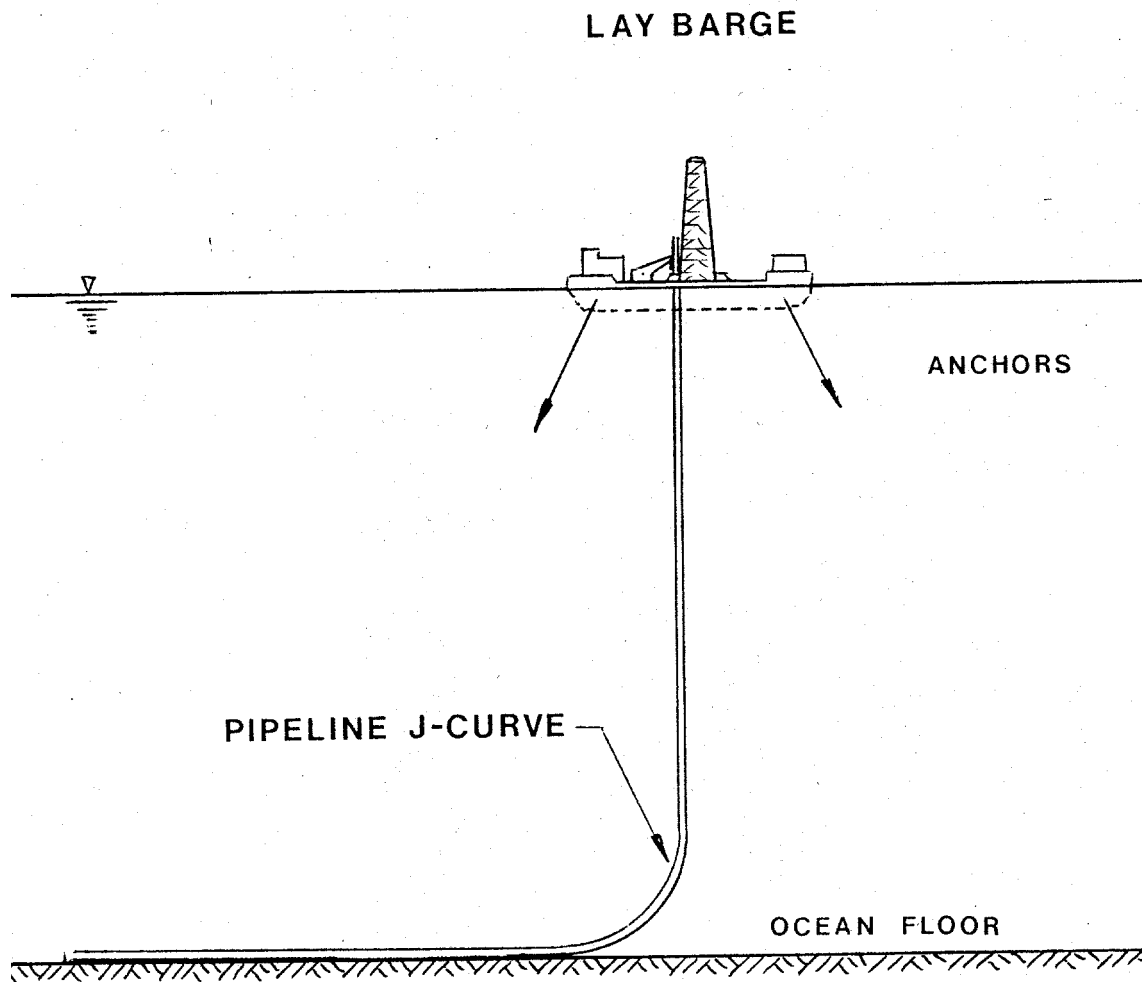


Figure 2.2 Illustration of the J curve pipelaying system (Fennel 1986).

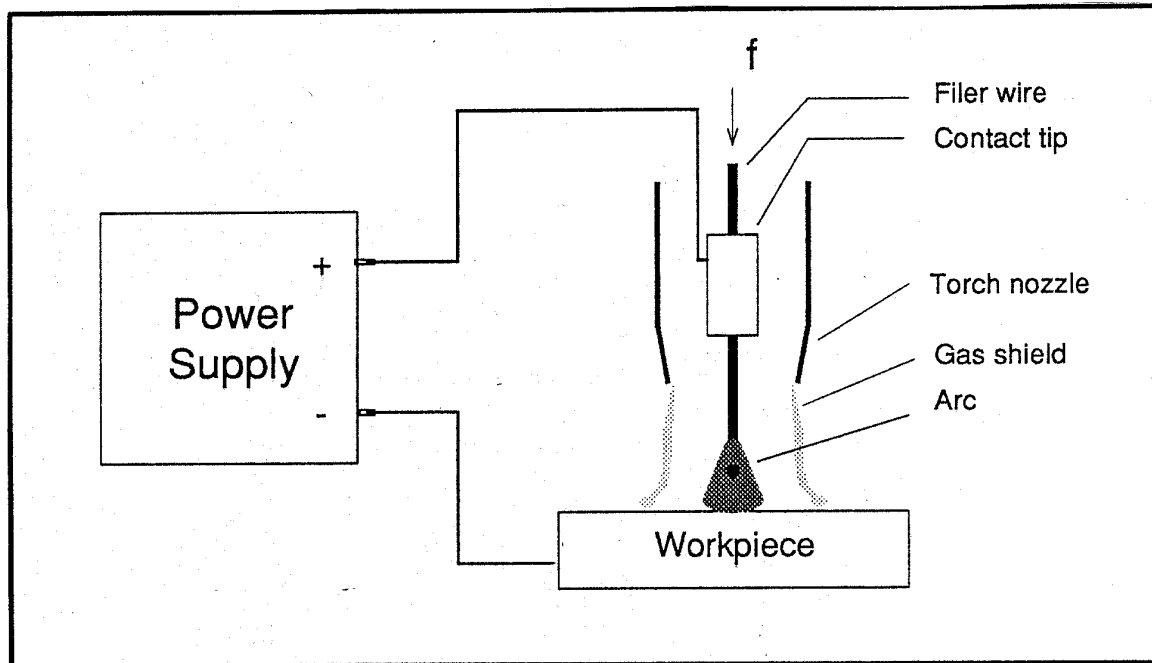


Figure 2.3 Schematic representation of the GMAW process.

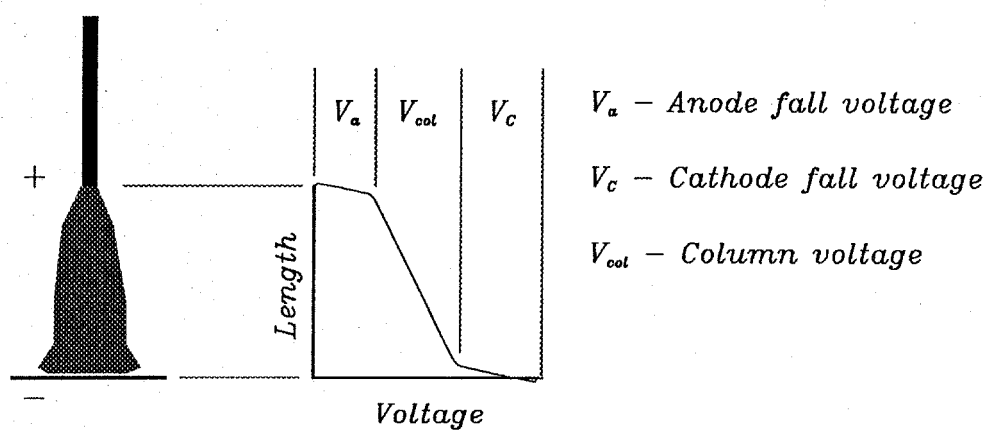


Figure 2.4 Voltage distribution along an arc shown schematically.

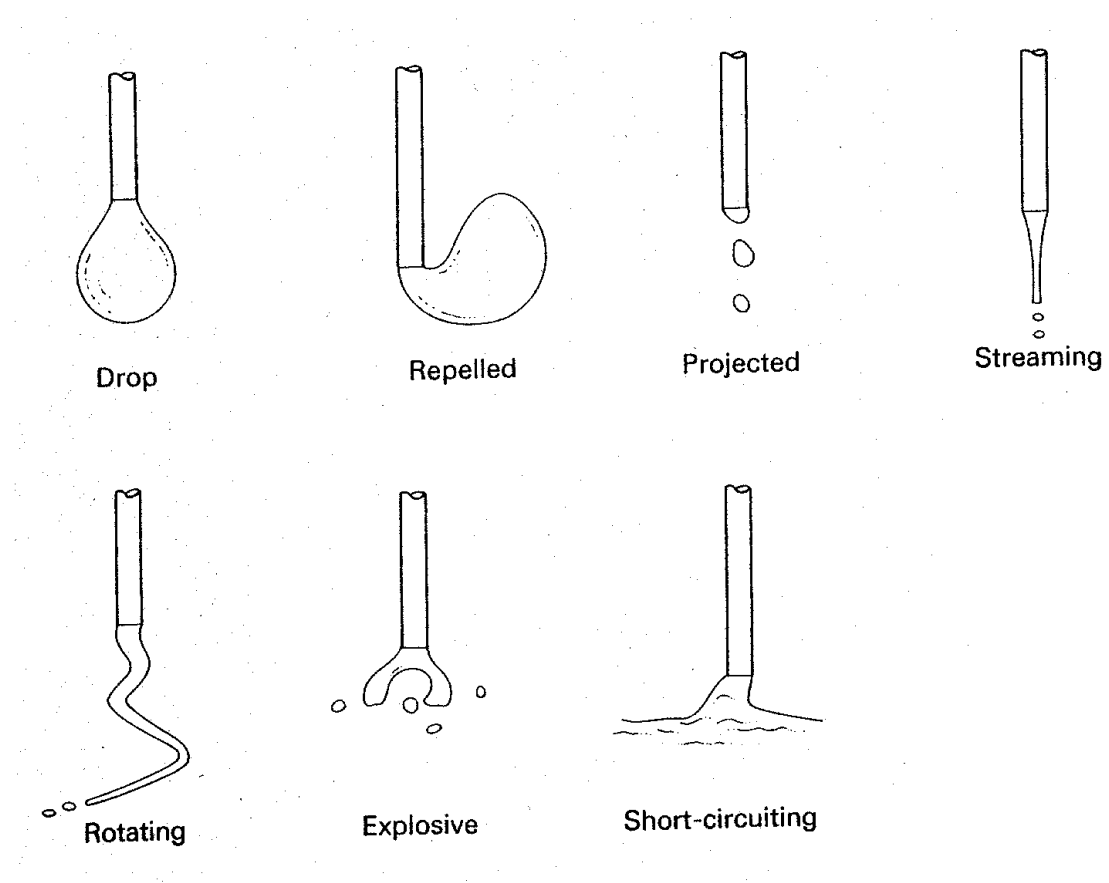


Figure 2.5 Common transfer modes in GMAW.

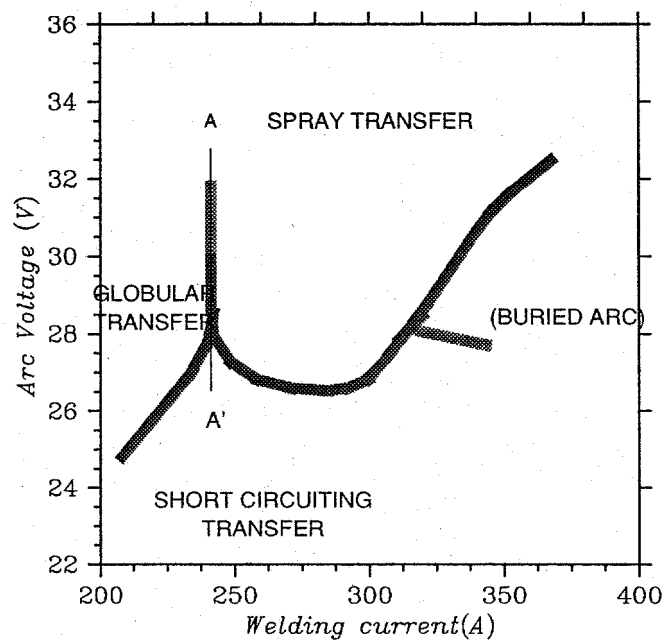


Figure 2.6 Idealised representation of the effect of current and voltage on metal transfer mode (based on Matumoto 1982).

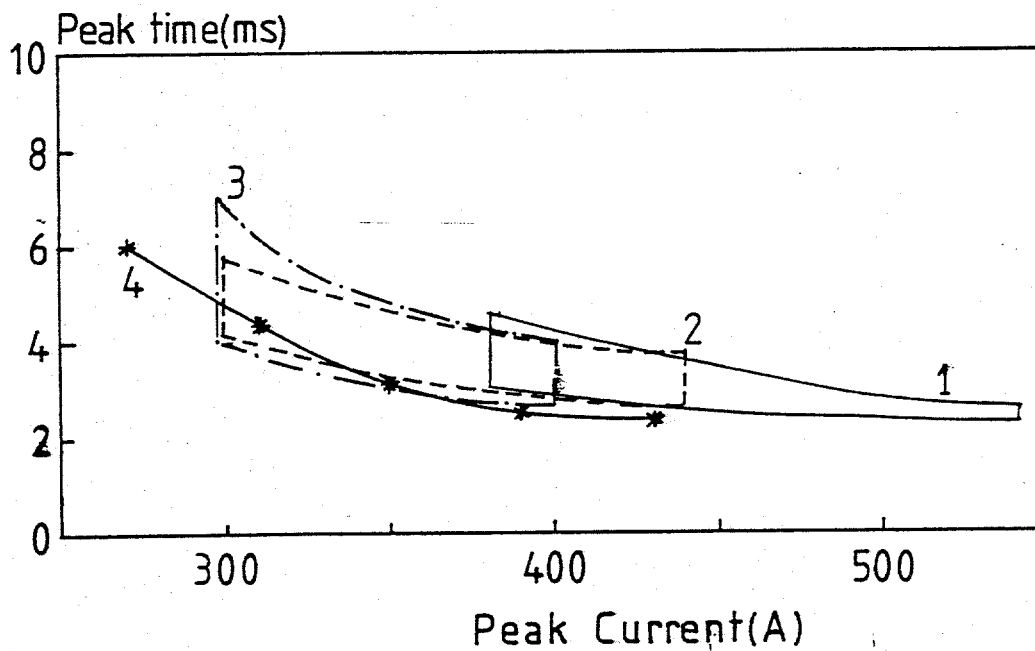


Figure 2.7 Conditions for one pulse-one drop obtained from different authors: (1)Ueguri (1985), (2) Allum (1983), (3) Foote (1986) and (4) Smati (1986).

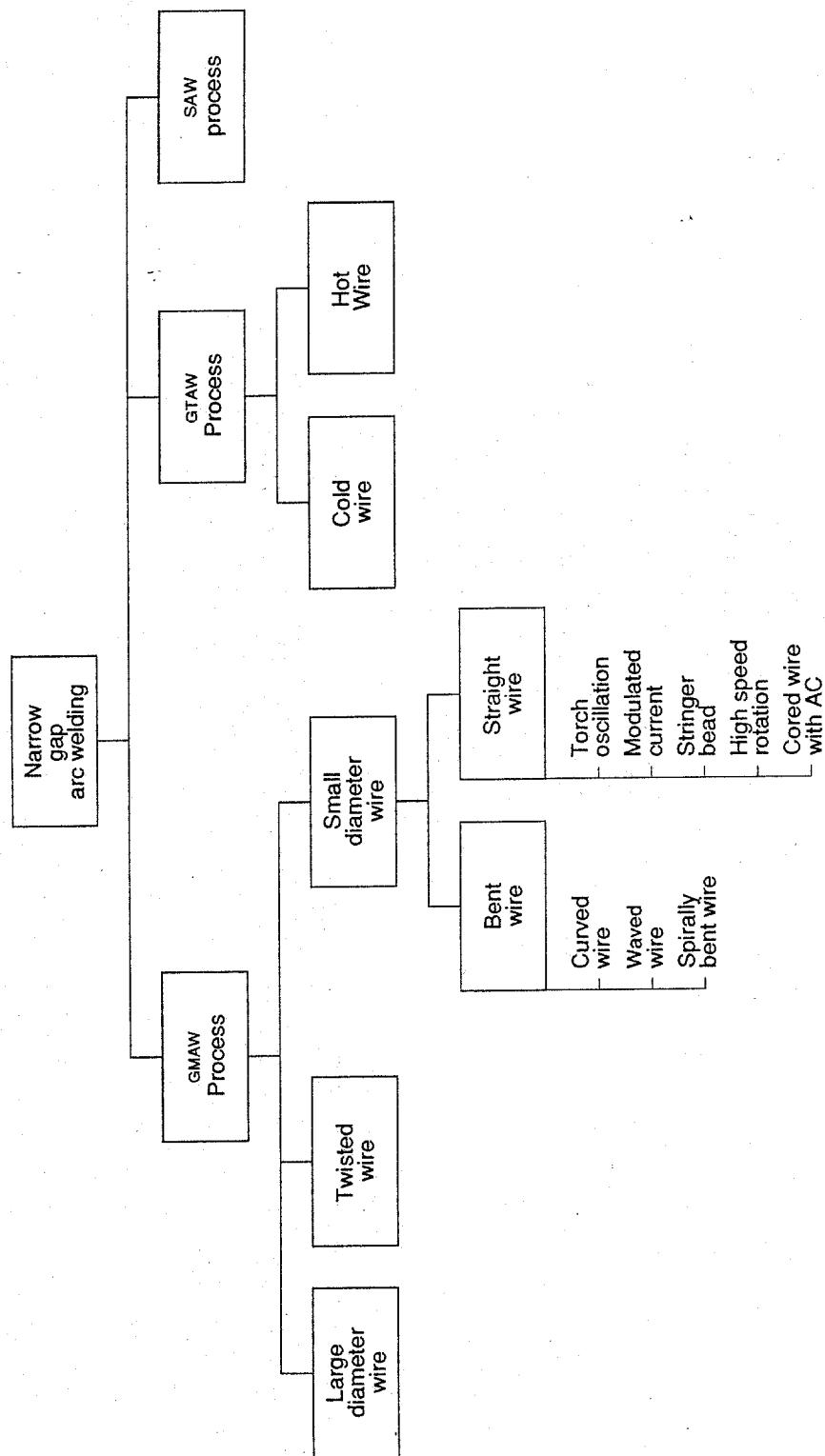


Figure 2.8 Classification of NGW processes in Japan (Nomura and Sugitani 1984).

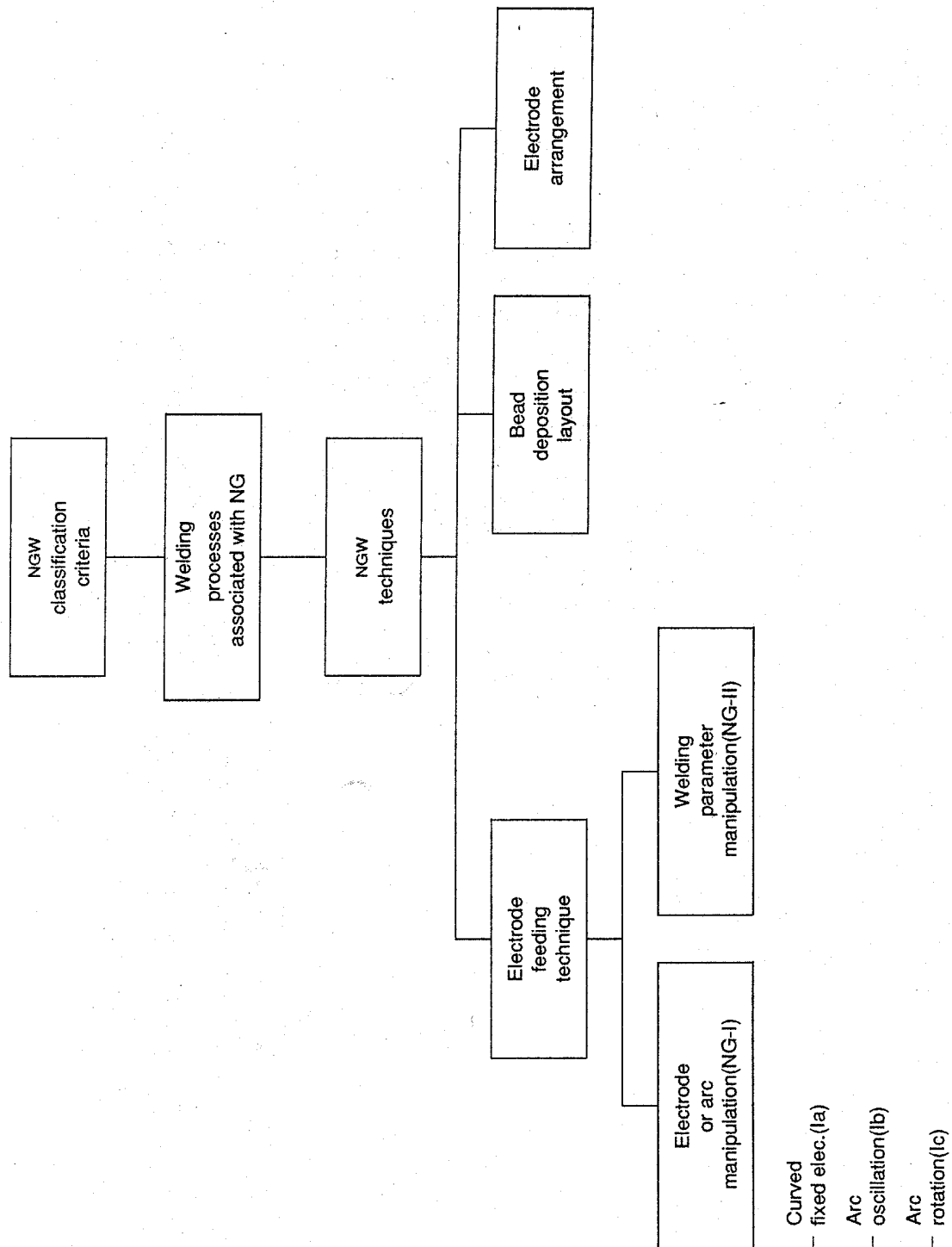


Figure 2.9 Classification of NGW processes (Malin 1987).

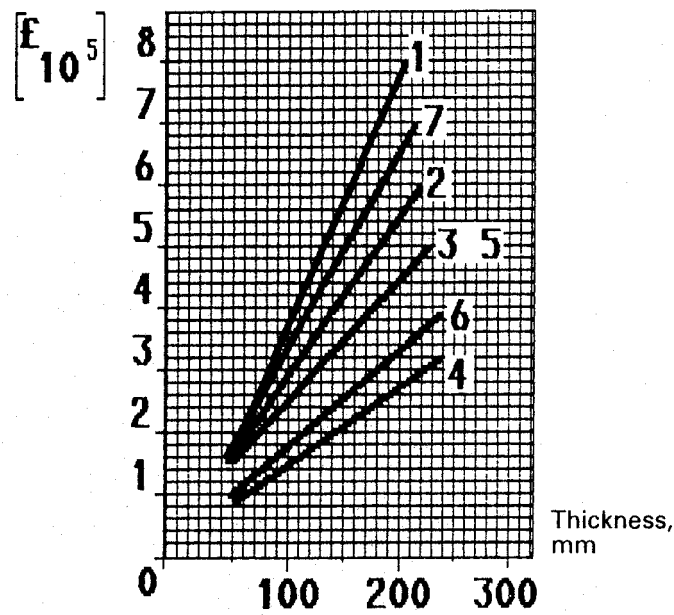


Figure 2.10 Welding costs as a function of joint thickness for different welding processes: (1)Single wire SAW, (2)single wire SAW-NG, two passes per layer, (3) same technique but with tandem wires, (4)tandem wires SAW-NG, one pass per layer, (5)single wire SAW-NG, one pass per layer, (6)GMAW-NG, and (7)ESW (Manzoli and Caccia 1989).

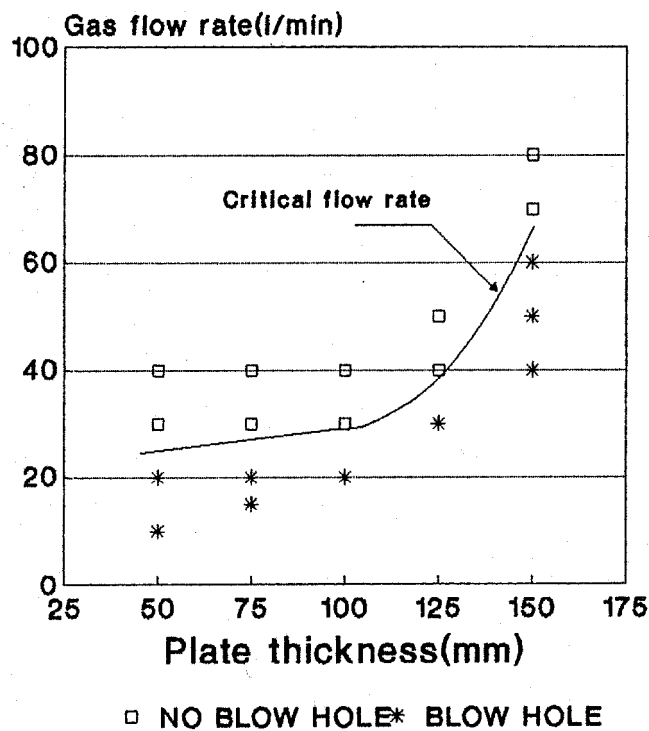


Figure 2.11 Effect of gas flow rate and plate thickness on blow hole formation (Kurokawa et al. 1966).

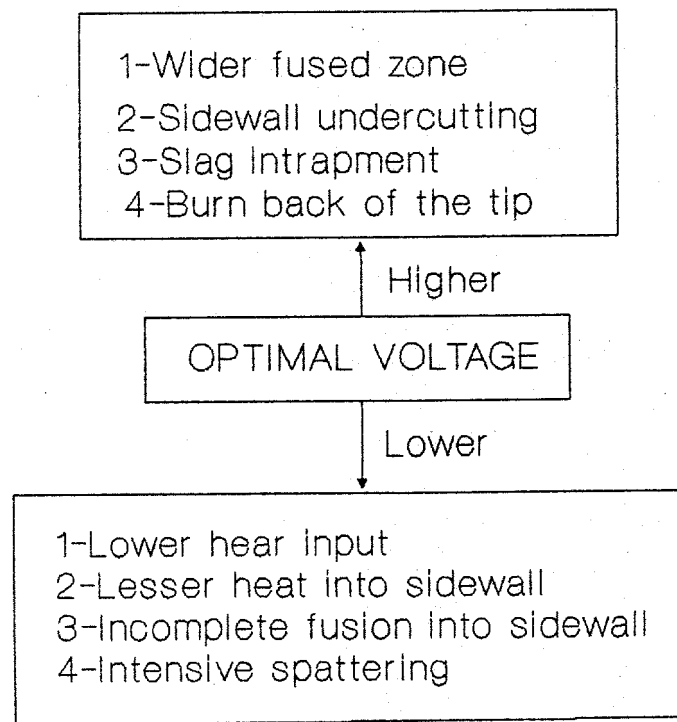


Figure 2.12 Effect of voltage on process stability and bead formation (Malin 1987).

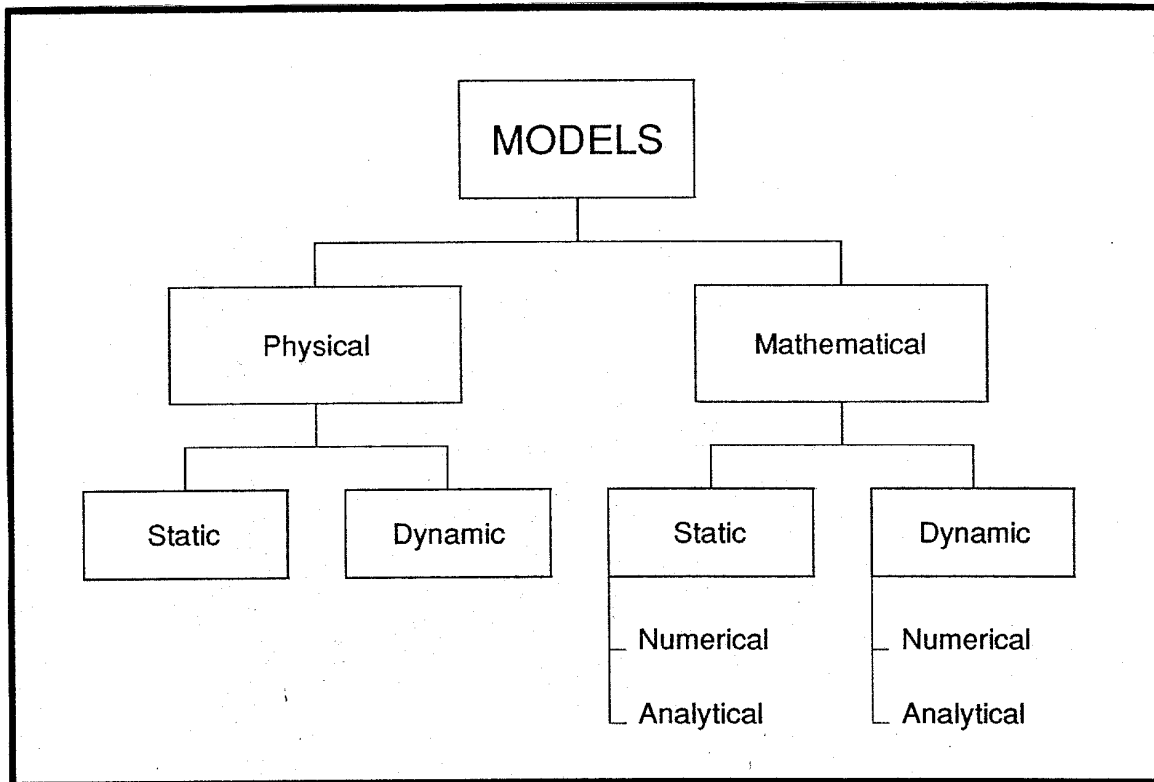


Figure 2.13 Classification of models (Gordon 1978).

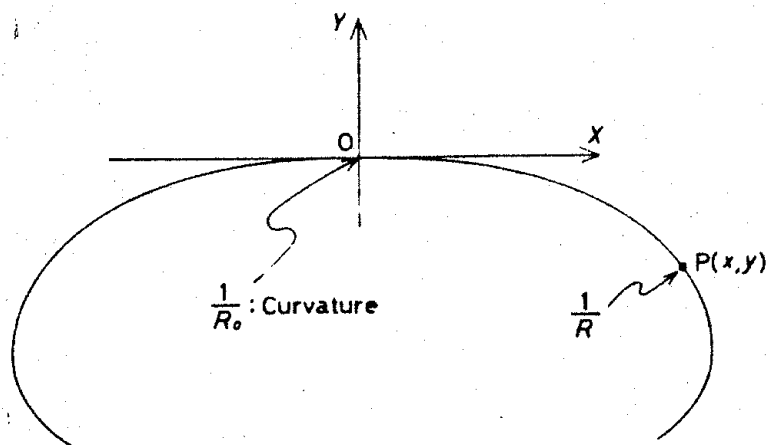


Figure 2.14 Two dimensional model of the weld pool (Nishiguchi et al. 1975).

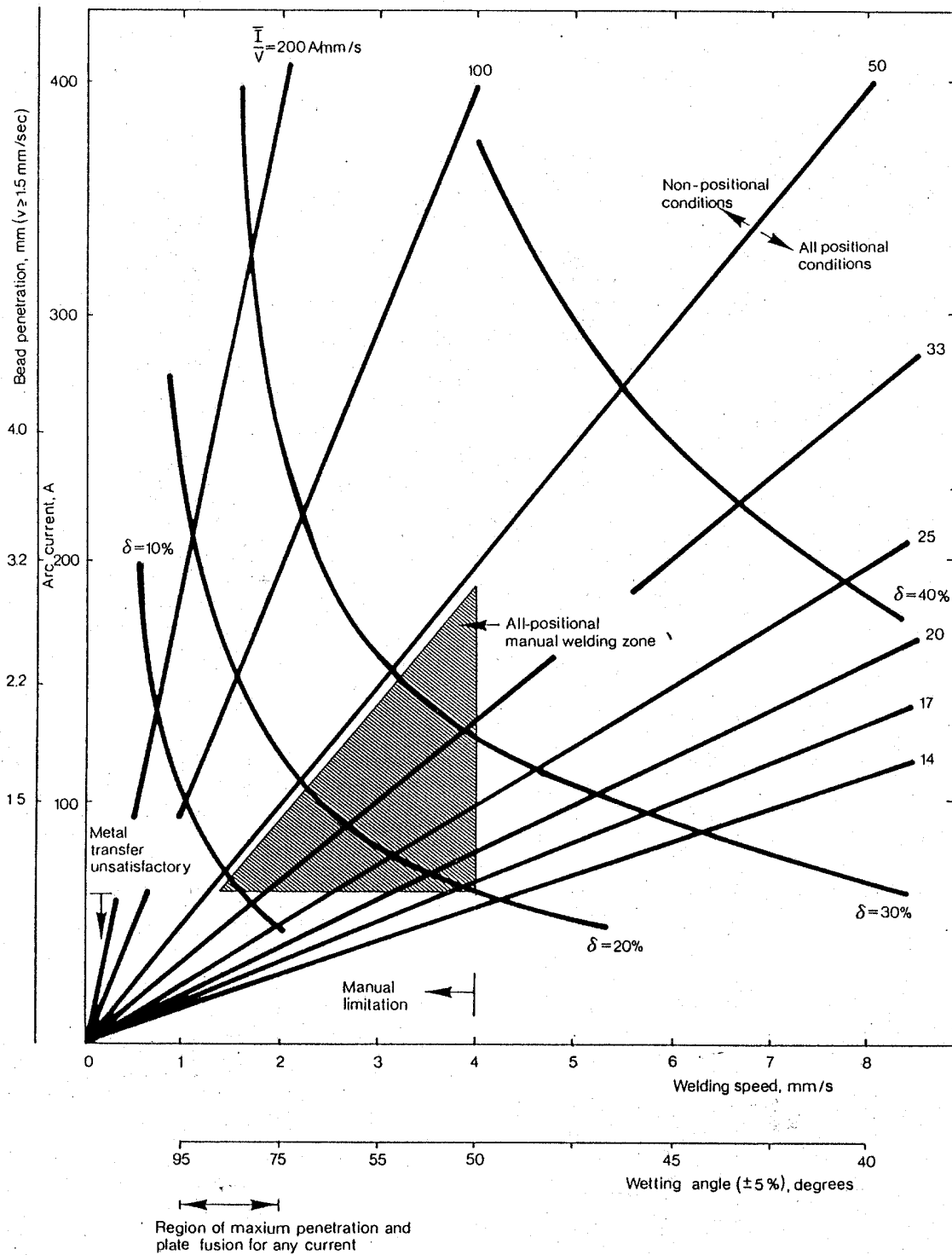


Figure 2.15 Generalised representation of fusion characteristics in pulsed welding (Quintino 1986).

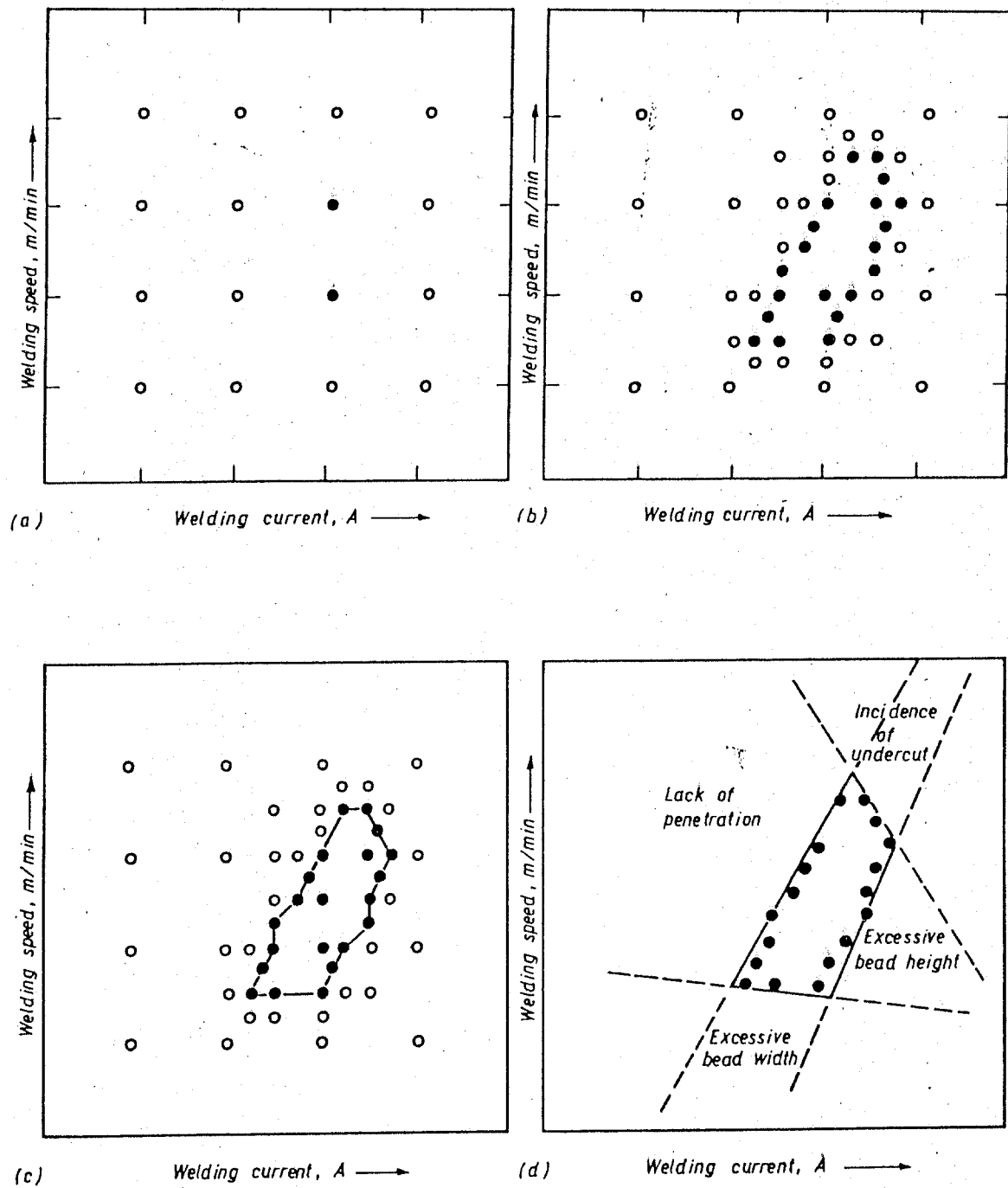


Figure 2.16 Outline of the experimental method for tolerance box technique: (a) Initial factorial lattice (acceptable welds: dark circles); (b) focused experimental lattice; (c) experimentally determined boundary positions; (d) boundary lines and associated defects (McGlove 1980).

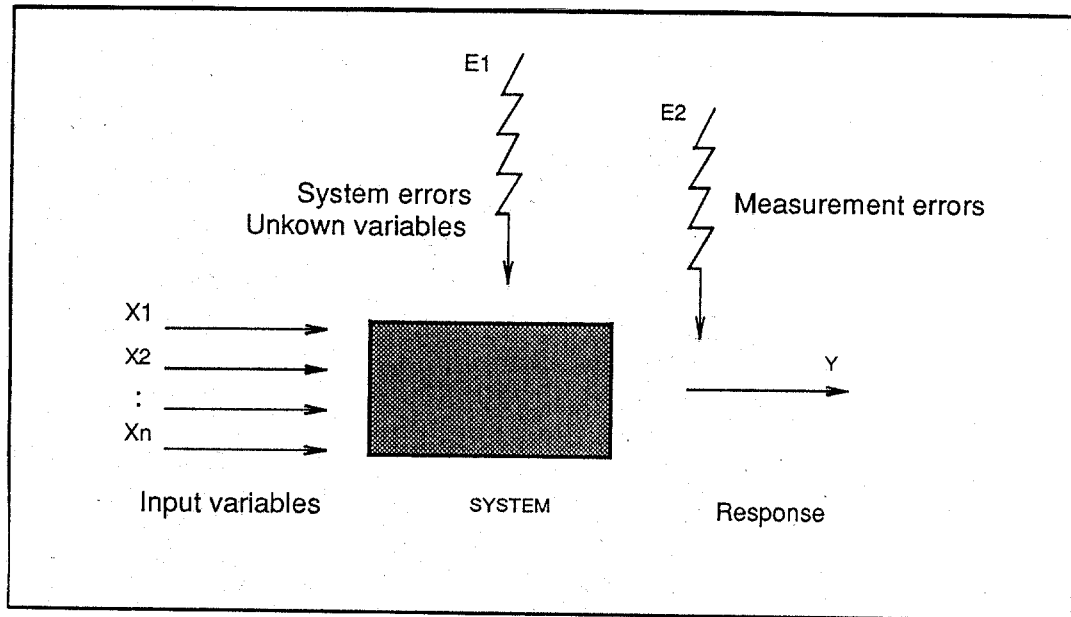


Figure 2.17 Schematic representation of an experiment.

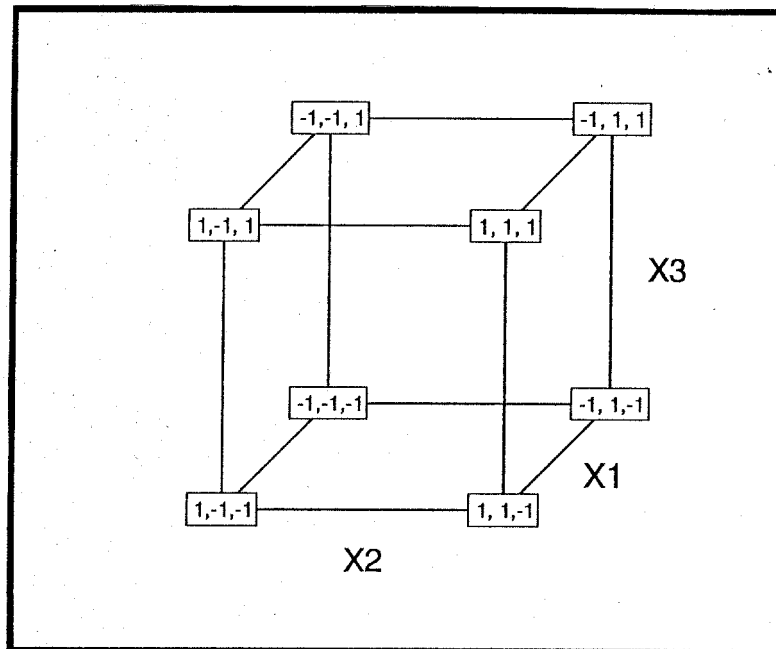


Figure 2.18 Geometric representation of a two-level factorial.

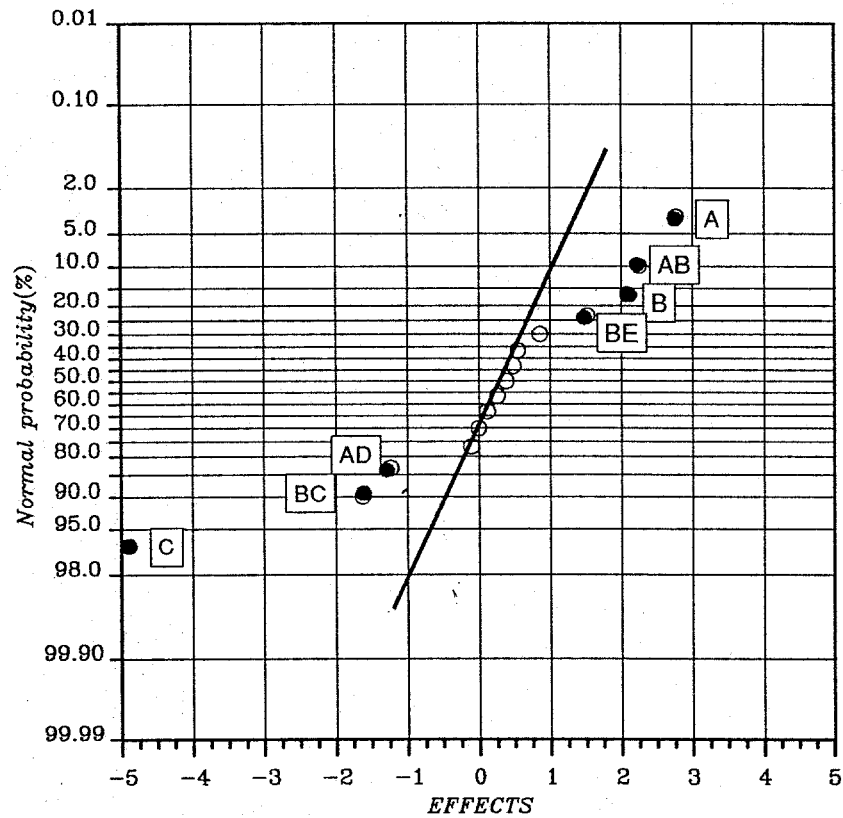


Figure 2.19 Example of application of the normal distribution plot to assess the significant factors in a 2^{5-1} factorial experiment. Data from Raveendra and Parmar (1987). A, voltage, B, current, C, welding speed, D, groove angle, and E, standoff. Response: bead width in SAW.

CHAPTER 3

3. EQUIPMENT AND MATERIALS

3.1. Power supplies

Two electronic power supplies were used during most of the experimental work: a TPS Fronius 500 and a GEC (AWP) M500. A special GEC series regulator power supply commissioned by the Cranfield Institute of Technology was used for a few trials in the hyperbaric chamber.

3.1.1. TPS Fronius 500

The TPS Fronius 500 is a high frequency (25 KHz) primary inverter power supply. It is a highly flexible machine that uses microprocessor control and is based on a modular system structure. Different control boxes provide different operation modes including several synergic GMAW programmes and CVCC operation. In the present work, the Tr-17 control box which allows independent control of all pulse parameters was used. This power supply was used for pulsed current welding.

3.1.2. GEC (AWP) M500

This is a series regulator type power supply. Its main technical characteristics are listed in table 3.1. This power supply was used for constant current (non-pulsing) welding.

3.2. Wire feed unit

A Fronius Vr 130 wire feeder was used in conjunction with the TPS Fronius 500 power supply. It provides a wire feed speed continuously adjustable between 0-18 m/min. A digital display with a resolution of 0.1 m/min indicates the selected wire feed speed.

An ESAB A10-MEC44 feeder was used in conjunction with the GEC (AMP) M500 power supply. Originally, the wire speed was selected and indicated by a low resolution and unreliable marked dial. This was improved by using the voltage signal from the speed control potentiometer of the wire feeder to indicate the wire speed. For both wire feeders, the actual wire speeds were calibrated against the selected values (figure 3.1).

3.3. Welding torch

An AW 500 torch was used with the Fronius power supply. Approximately 3 mm was machined from the gas shroud to expose the contact tip for narrow gap welding. A Union Carbide ST12 water cooled torch was used with the GEC (AWP) M500 power supply.

3.4. Test rig

The welding rig consisted of a table that could be moved in the horizontal direction while the torch was kept fixed. A simple support was built and attached to the table for positional welding (figure 3.2). The horizontal position and height of the torch were controlled by means of manually adjustable lead screws. The welding position was changed by rotating the torch along an axis parallel to the welding direction. The travel speed of the welding table was calibrated before its use (figure 3.3). A schematic diagram of the welding rig and measuring equipment is shown in figure 3.4. The video equipment shown in this figure was used for measuring the arc length in some welding trials.

3.5. Gas mixer and analyser

Two gas mixing devices were used throughout the project to add different proportions of oxygen to commercial shielding gases: a Witt gas mixer was used in the initial stages of the project (shielding gas optimization) and a Cranfield built mixer (figure 3.5) was employed in the modelling of narrow gap welding with the optimized mixture. Both mixers operated using similar principles, i. e., the gases are supplied from high pressure cylinders with a controlled flow and mixed in a chamber before being fed into the welding torch. The composition of the output mixture was defined by the composition and relative flow of the n input gases:

$$c_i = \sum_{j=1}^n (f_j c_{ij}) / \sum_{j=1}^n f_j \quad [3.1]$$

where c_i is the content of component i in the output mixture,
 f_j is the flow of the input mixture j , and
 c_{ij} is the content of i in the input mixture j .

The flow of the input gases was monitored and controlled by tapered tube and float devices placed at the entrances of the mixing chamber. As different commercial gas mixtures were used with flowmeters calibrated for either argon or helium, the actual gas flow (f_{act}) was calculated from the measured flow (f_{meas}) by:

$$f_{act} = f_{meas} \cdot (\sigma_{ref} / \sigma_{act})^{0.5} \quad [3.2]$$

where σ_{ref} and σ_{act} are the densities of the reference and actual gases respectively. The densities of gases relevant to the present work are shown in table 2.4.

A Servomex 1420 oxygen analyser (Servomex 1987) was used with the Witt mixer to check the oxygen concentration in the output gas mixture. The same analyser was utilized to calibrate the Cranfield built mixer.

3.6. Photography

The equipment and some weld beads were photographed with ordinary 35 mm black and white film. Weld bead macro-photographs were taken using a Vickers microscope using 100x120 mm negatives. Metal transfer and arc shape were photographed using both an "Imacon" image converter camera (time between exposures of 0.100 msec) with back flash illumination and Polaroid film, and an ordinary reflex 35 mm camera with 1/2000 shutter speed, 210 mm lens and extension tube. Neutral density filters were used to reduce the arc glare.

3.7. Current and voltage measurement

Mean current and voltage were measured using the built-in digital meters in the power supplies. These meters presented a resolution of 1A and 0.1 V in both power supplies and their calibration was checked against other meters previously calibrated with a precision power supply.

For the analysis of the pulse structure in pulsed current welding and the study of welding current and voltage transient phenomena, a digital data logger (VELA) was used to register signals from these parameters. The VELA is a simple to operate and flexible 8-bit data logger with 4k of RAM memory and 1 or 4 channels manufactured by Data Harvest. The data stored in the VELA can be transferred to a BBC microcomputer by a programme supplied by Data Harvest and called Vela Analysis which can also plot graphs, measure instantaneous values and store the data on disk for further analysis.

3.8. Metallographic equipment

Macrographic specimens were sectioned on a band saw and prepared using rotating silicon carbide papers up to 1200 mesh. Nital 10% (nitric acid in alcohol) was used as etchant. A Vickers projection microscope was used to produce magnified tracings (4-7X) of the specimens.

3.9. Weld bead measurement

Two methods were used to determine the weld bead dimensions:

- A planimeter and a ruler were used to measure areas and linear dimensions respectively in magnified tracings of the weld bead.

- An IBM/AT compatible microcomputer equipped with a video frame store and digitiser card was connected to a video camera. This system could be used to input the magnified image of the actual specimens. An inspection and image processing software package supplied by Integral Vision was then used to measure the weld bead dimensions.

3.10.Data analysis

A programme written in BBC BASIC (appendix A) was used to convert the binary data files from the VELA into ASCII format which could be transferred to an IBM compatible microcomputer or the mainframe computer system at Cranfield. The pulse current structure was calculated from the data files by means of a FORTRAN programme (appendix B). Current and voltage traces were also plotted by this programme using BIZPAK and RASPAK libraries (UNIRAS). Interactive UNIRAS programmes, UNIMAP and UNIEDIT, were used for surface mapping and plot preparation. Multiple linear regression analysis of all data generated was performed by programmes written for the SPSS-X statistical package (SPSS 1988) at the mainframe. A sample programme and printout are shown in appendix C.

3.11.Materials

3.11.1.Filler wire

All welding was carried out using grade A18 wire of 1.2 mm diameter. The nominal composition of this wire is shown in table 3.2, according to the specification BS 2901.

3.11.2.Base metal

Cold rolled mild steel bars of 20x50 mm were used to prepare the narrow gap welding specimens. Backing bars for the specimens for horizontal welding were cut from an A36 plate (14 mm thick).

3.11.3.Shielding gases

The following gases were used alone or mixed: argon (Ar), helium (He), oxygen, argon-25%helium (Ar-25%He), argon-75%helium (Ar-75%He), Argoshield 5 (Ar-5), Argoshield 20 (Ar-20), Argonox 1 (Ar-1%O₂), Argonox 2 (Ar-2%O₂), Argonox 5 (Ar-5%O₂), Helishield 1 (He-1), Helishield 2 (He-2), and Helishield 101 (He-101). The nominal composition of the commercial gas mixtures is shown in table 3.3.

3.12. Narrow gap welding specimen preparation

Linear specimens were used throughout the experimental programme since they are cheaper and easier to prepare, and simulate closely a short length of a tubular joint. Additionally, positioning of the welding torch in the joint and controlling its position during welding are simpler when using a linear specimen.

The mild steel bars were degreased, cut into pieces approximately 250 mm and 280 mm long (for the specimen's sides and backing bar respectively), and bright ground. A diagram of the specimen is presented in figure 3.6. Machined spacers were placed into the groove during specimen assembly in order to ensure the correct gap width required for each specimen. Thinner backing bars (15 mm) with holes drilled at its extremities were used in specimens for the horizontal-vertical welding trials.

Table 3.1 Technical specifications of the M500 power supply (Foote 1986).

Input:

Voltage:	380/400 V - 3 phase
Frequency:	50 Hz

Output:

Open circuit voltage:	55 V
-----------------------	------

Characteristics:

- Output current/voltage relationship infinitely variable between constant current and constant voltage.
 - Current level variable between 0 - 500 A in 1A steps.
 - Current rise time variable between 0.1 - 10 ms in 0.1 ms steps.
 - Short circuit current variable between 0 - 499 A with variable short circuit detect voltage.
 - Peak and background levels between 0 - 500 A in 1 A steps.
 - Accuracy $\pm 0.5\%$.
 - Peak and background duration between 0 - 999.9 ms in 0.1 ms steps.
 - Reproducibility and accuracy:
 - current: $\pm 1\%$ at full scale setting,
 - timing: $\pm 0.5\%$ for each control.
-

Table 3.2 Chemical composition of the filler wire (nominal).

C	Mn	Si	S	P
0.12 max	0.60-0.90	0.70-1.20	0.04max	0.040max

Table 3.3 Composition of commercial gas mixtures.

Mixture	Nominal composition
Argoshield 5	Ar-5% CO ₂ -up to 2% O ₂
Argoshield 20	Ar-20% CO ₂ -up to 2% O ₂
Argonox 1	Ar-1% O ₂
Argonox 2	Ar-2% O ₂
Argonox 5	Ar-5% O ₂
Helishield 1	Ar-85% He-1.5% CO ₂ -250Vpm O ₂
Helishield 2	Ar-75% He
Helishield 101	Ar-38% He-2% CO ₂

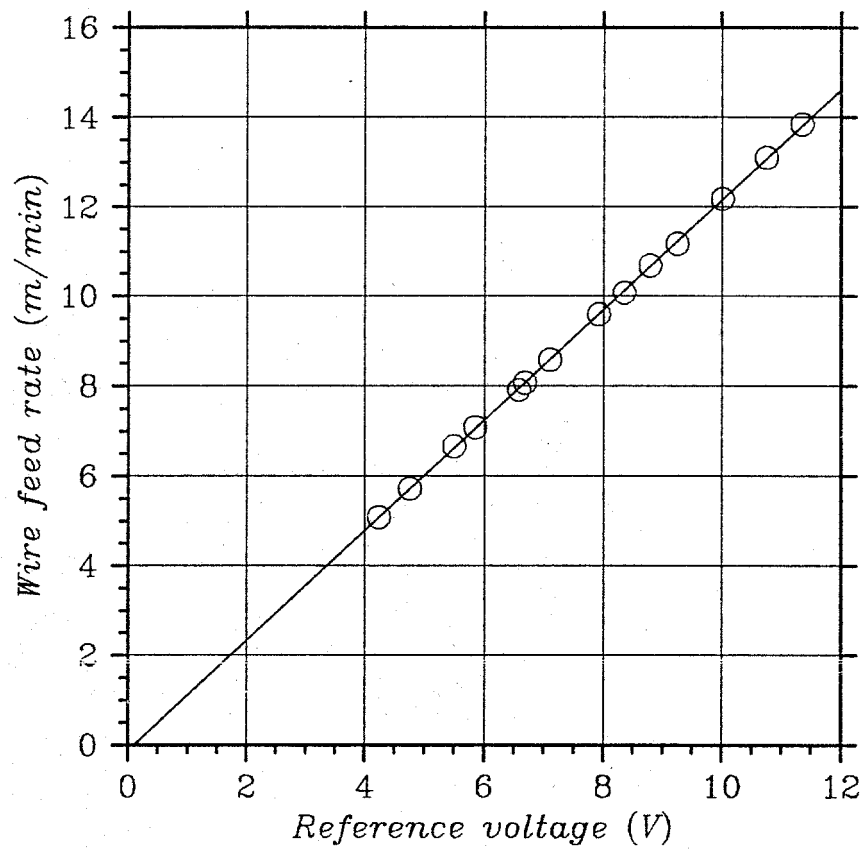


Figure 3.1 Calibration curve for the ESAB A10-MEC44 wire feeder.

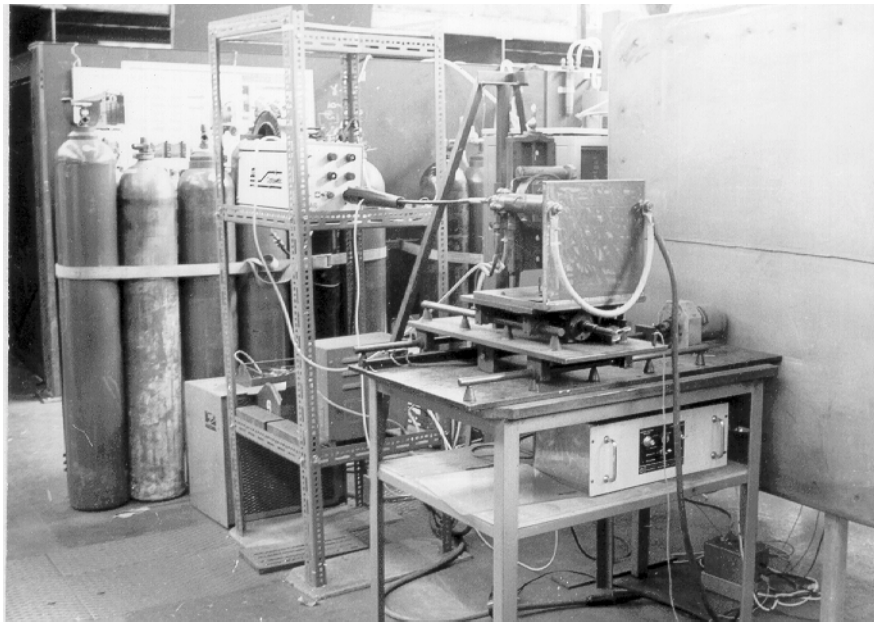


Figure 3.2 Welding rig (used with the GEC (AWP) M500 power supply).

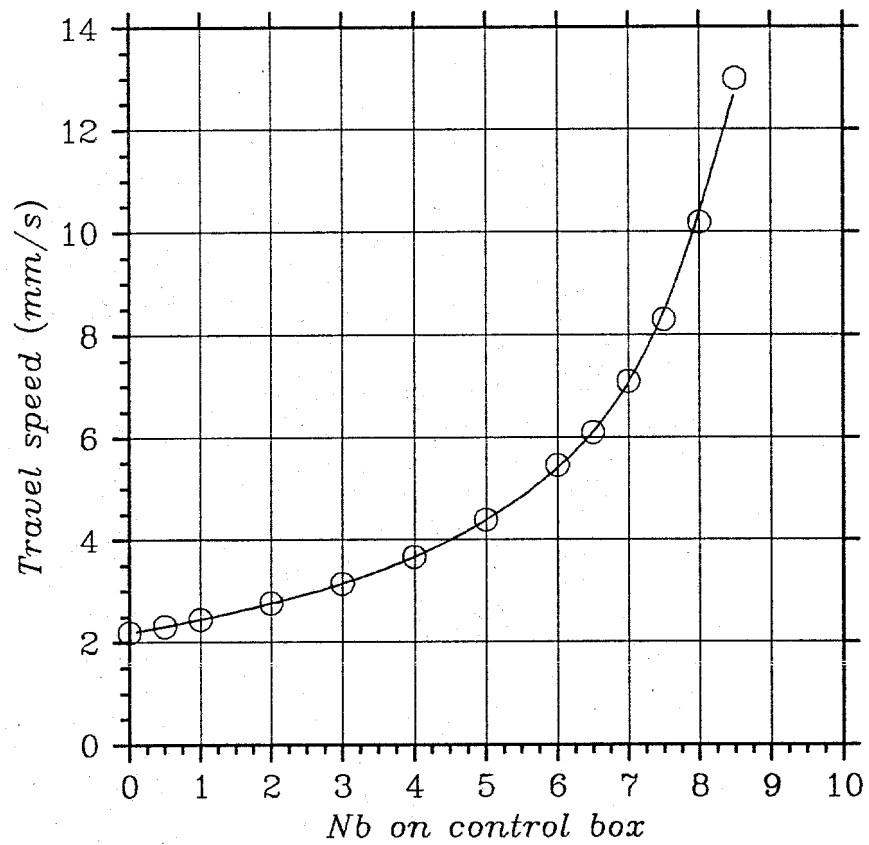


Figure 3.3 Calibration curve for the welding table.

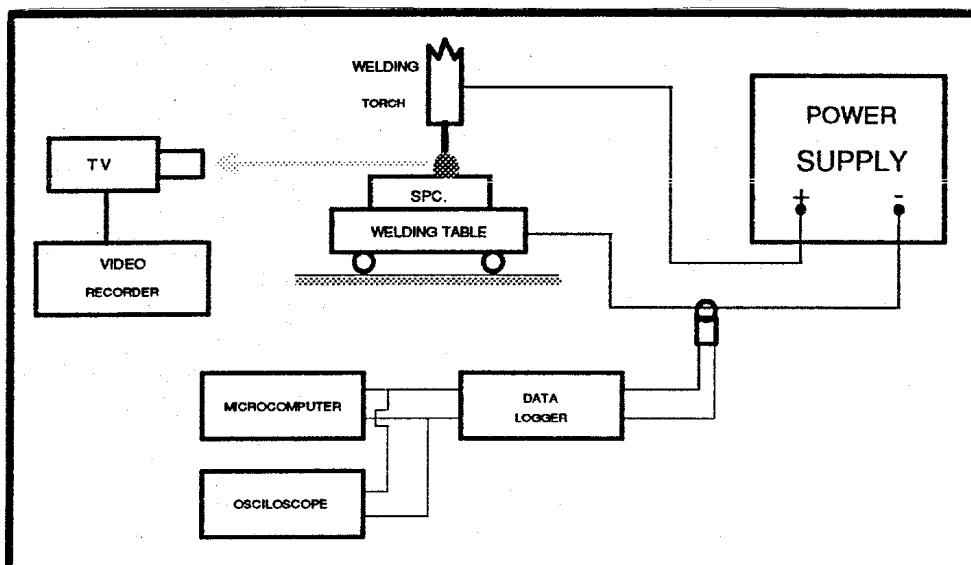


Figure 3.4 Schematic diagram of the welding rig.

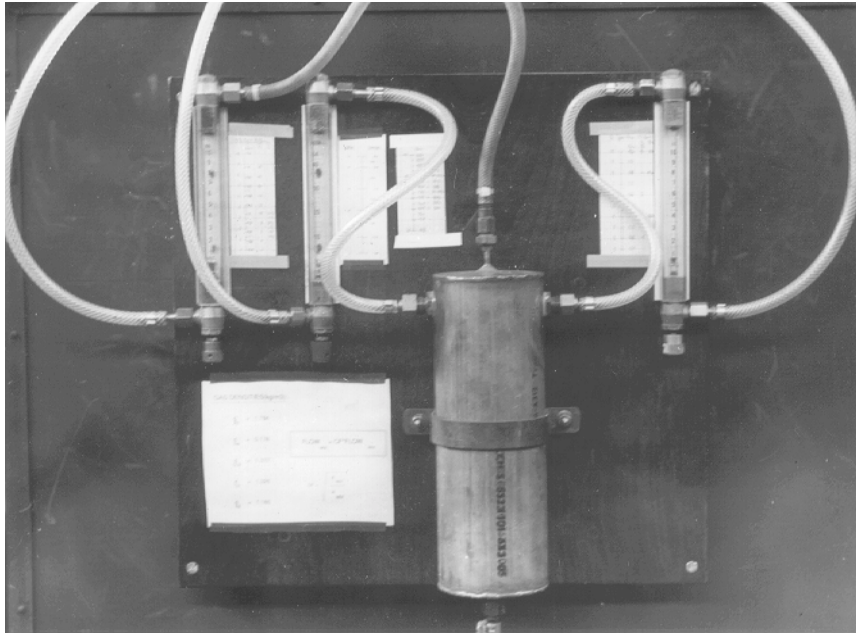


Figure 3.5 Gas mixer.

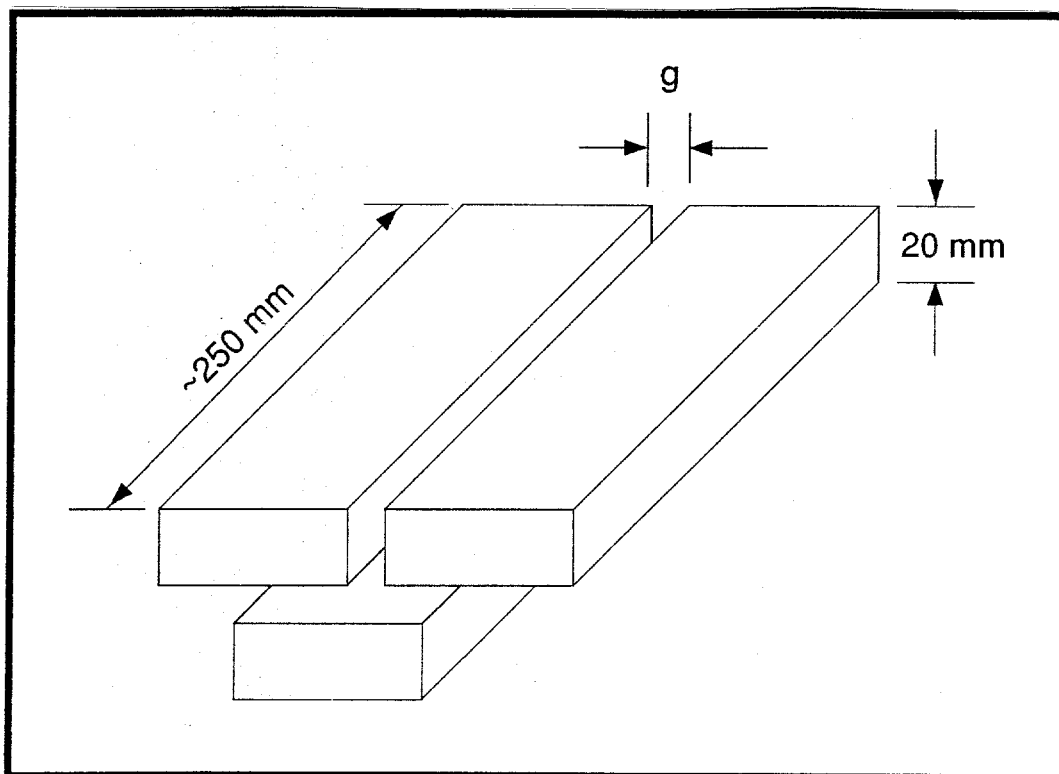


Figure 3.6 Diagram of the narrow gap welding specimen.

CHAPTER 4

4. RESEARCH PROGRAMME

The J-laying technique for the construction of offshore pipelines requires a fast welding process that can produce sound welds in the horizontal-vertical position. A previous project at the Cranfield Institute of Technology (Fennel 1986) demonstrated for that application the suitability of a NG-GMAW process with the following characteristics:

- NGW II technique (§2.31),
- reduced gap width (under 9mm),
- thin wire diameter,
- DC+ pulsed current operation, and
- high welding speed.

However, an extensive study which could provide a better understanding of the relationship between process variables and the physical processes involved in the formation of the weld bead in this process had not been carried out. Previous work in narrow gap welding is generally associated with the NGW I technique or with wire diameters and current levels much higher than those which can be used in the horizontal-vertical position. This study should provide valuable information to help establishing improved welding conditions for the process in terms of minimizing the likelihood of defect formation and optimizing the welding time.

As a result, the basic aims of the experimental programme were as:

- to investigate the influence of welding parameters on bead characteristics in a narrow gap GMAW process to be applied to the welding of pipelines in the J-curve pipelaying technique,
- to establish a set of optimal welding conditions for this process based on some criteria and to determine the sensitivity of these conditions to small variations in process parameters, and
- to determine the most significant parameters that control bead shape in a narrow gap process.

Statistical modelling of the welding process was used throughout the programme in order to accomplish these aims. Statistical principles were used for both design of the experimental work, data analysis and modelling. This approach was considered more efficient than either the classical "one-variable-at-a-time" experimental approach or purely theoretical modelling to cope with the complexity and large number of variables of the process.

Results from initial experimental work indicated arc instability problems associated with the commercial helium based shielding mixture. These problems tended to occur only for the

relatively short arc normally used in the narrow gap welding situation. Consequently additional aims were introduced, i. e.:

- Optimization of a shielding gas mixture for NGW in terms of both process stability and weld bead shape, and,
- Investigation of arc length dependent instability phenomena.

A flowchart of the experimental programme is shown in figure 4.1. A step-by-step strategy was adopted to determine the influence of the large number of variables that could affect the process. Each step consisted of one or more blocks of welding trials based on the results of previous tests. The results of the first experimental blocks (step S1) suggested that shielding gas composition plays a major factor in controlling weld bead shape. Consequently, an extensive study was also performed to optimize the gas mixture composition in terms of process stability and weld bead characteristics in narrow gap welding.

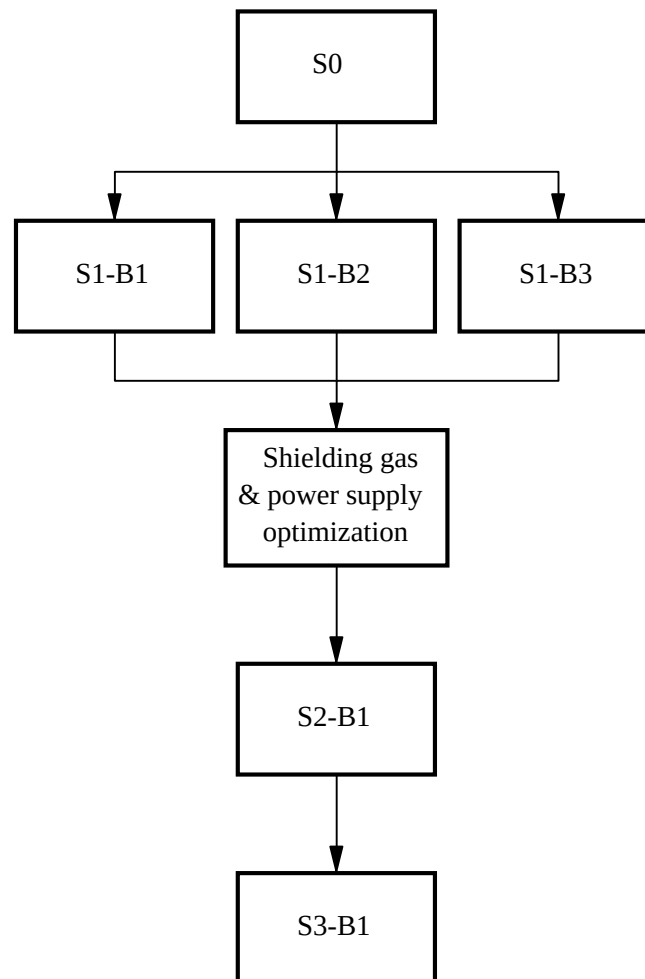


Figure 4.1 Flowchart of the experimental programme.

CHAPTER 5

5. PROCESS MODELLING

5.1. Experimental procedure

5.1.1. Design of the experiments

The experimental programme was intended to produce data for statistical modelling of the narrow gap GMAW process. Whereas theoretical model building is based mainly on considerations about basic physical or chemical principles, statistical modelling depends solely on information contained in the experimental data it is being applied to. Therefore a properly designed and conducted experiment is crucial for the modelling exercise to succeed. Definition and statement of the problem, gathering of expertise and the execution of exploratory trials to define system behaviour are an essential initial stage.

The present programme was run as a set of experimental steps. Each step was formed by one or more experimental blocks which, in turn, were constituted by a number of welding trials. A sequential approach was used so that the results from one step could influence the design of the following step. A certain bias between experimental steps can result from this approach, but it was considered the most flexible to cope with the large number of variables involved in the study and with the exploratory nature of the optimization process.

An extensive list of factors that can have some influence on bead shape in a narrow gap II process is shown in table 5.1. Not all of the factors listed there are independent of each other and different relationships may exist between two or more of them. Some relationships are quite obvious, such as (table 5.1):

$$h = s + l_a \quad [5.1]$$

or

$$I_{\text{mean}} = (I_p t_p + I_b t_b) / (t_p + t_b) \quad [5.2]$$

Others, however, can be much less obvious and more difficult to detect. Several welding parameters, such as wire feed rate, welding current, voltage and shielding gas composition, must be inter-related in order to guarantee an acceptably stable operation for the process. Such constraint restricts the combinations of independent variable levels that can be possibly used for studying the process and tend to introduce a certain level of dependency amongst predictors. The division of the modelling and optimization problem into smaller units (steps

and blocks), as adopted in the present work, can reduce the problem by allowing fewer parameters to be analysed in each step and, therefore, reducing the quantity of constraints on the experiment.

It was initially intended to design the experimental blocks as 2^k factorial experiments with central points. This design was selected because it provides an efficient way to investigate the effects and interactions of many variables with a relatively small number of experimental trials. A limitation of 2^k factorial design is that no second or higher order effect can be obtained from it. However, as the experimental blocks were performed on a small region of the predictors space (i. e., only relatively small changes in the predictor variables were used in each experimental block), an approximately linear relationship between predictors and response may be expected. Furthermore, if, after processing the data, the necessity of a more complicated model becomes apparent, the factorial experiment can be easily augmented to more sophisticated designs.

However, results from the first experimental blocks indicated that, due to the strong inter-relationship amongst process variables, stable welding conditions were difficult to achieve for all experimental points when a factorial approach was used. Therefore the experimental design was modified and a certain dependency between some of the predictor variables allowed in the last two experimental steps.

5.1.2. Initial welding trials

An initial experimental step (figure 4.1, step S0) was performed to study the consistency of weld bead shape along the length of a pass and amongst welds executed under similar conditions. The welding parameters used in this step were based on results from a previous work (Fennel 1986) and are shown in table 5.2. A two pass weld was deposited on each specimen: the root pass extended along the entire length of the joint whereas the second pass was restricted to the first half of the joint. The welded specimen was cut into several transverse slices which were prepared for macrographic examination and measurement of weld bead characteristics. The thickness of each slice was measured so that its position along the joint could be calculated approximately.

5.1.3. Modelling steps

The main body of the experimental part of the modelling work comprised three experimental steps (S1, S2 and S3, figure 4.1). The primary goal of step S1 was to study the process

response to changes in welding conditions around the initial points used in step S0 for three commercial shielding gas mixtures (Ar-5, He-1 and Ar-20). Consequently, three experimental blocks were designed as 2^k factorial experiments with central points. Wire feed rate, welding speed, gap width and a pulse parameter (either pulse frequency or background current level) were used as input factors (tables 5.3, 5.4 and 5.5).

A "customised factorial" experiment was adopted in step S2 in order to allow some correlation between wire feed rate and welding current. Based on results of experimental step S1 and the shielding gas/process optimization step (chapter 7), step S2 used an experimental shielding mixture together with a constant current (DC+) power supply. The predictor variables in this step were welding current, wire feed rate, welding speed and gap width (table 5.6). When unmodulated arc current was used in this experimental block, its value was always kept above the globular-spray transition (230-250A for a 1.2mm mild steel wire).

The same shielding mixture and power supply characteristic were employed in step S3 (table 5.7) in which the effect of the force of gravity (horizontal-vertical welding) was considered.

5.1.4.Complementary trials

A number of trials were performed after completion of blocks S2-B1 and S3-B1 in order to either study the effect of some variables not included in the blocks, or to obtain multipass specimens (table 5.8).

5.2.Experimental results

Many different dependent variables were considered at some stage of this programme in order to explore different characteristics of the welding process (table 5.9).

5.2.1.Pulsed current parameters

In experimental steps S0 and S1, the current structure was calculated from data files recorded by VELA (§3.7) using a specially designed FORTRAN programme (appendix b). In some cases the current trace could include a significantly high noise level due to the current control mechanism of the power supply, and the data was filtered in the software before being used

to calculate pulse parameters. A method was developed in which each data point was substituted by the weighted mean of this point and nf of its right and left neighbours:

$$yf_i = p_0 y_i + \sum_{j=1}^{nf} [p_j y_{i+j} + p_j y_{i-j}] \quad [5.3]$$

where yf_i is the filtered datum,

y_i is the unfiltered point,

$p_0, \dots, p_{nf}$ are the weighting factors based on a binomial random variable with parameters $(nf, 0.5)$, and

nf is the filter factor.

A constant filter factor value of two was used in this work. The effect of the software filter on a current trace is demonstrated in figure 5.1.

The peak and background times for each pulse period and the number of pulses in a data file were calculated by determining the points in which the current trace intercepted a reference current level set at 300A (figure 5.2). For each peak and background period, the peak and background current values were defined as their maximum and minimum values respectively. These data were then used to calculate mean and standard deviation values of peak and background current. Finally, pulse frequency was defined as:

$$F = \frac{\text{Number of cycles}}{\text{Total time}} \quad [5.4]$$

Tables 5.10, 5.11, 5.12 present the electrical parameters obtained in experimental blocks S1-B1, S1-B2 and S1-B3 respectively. Measured pulse frequencies in S1-B1 and S1-B2 showed some variance from the planned values for these experimental blocks (tables 5.3 and 5.4) and resulted from the low sensitivity of the power supply control at the frequency level that was used. In later trials, this limitation was overcome by measuring and calibrating the signal from the frequency control potentiometer of the power supply.

5.2.2.Arc length

In experimental step 1, the arc image was recorded using a TV camera with neutral density (ND) filtering of the arc glare. The arc length was then determined by playing back the recorded sequence, freezing the image at random and measuring the length directly on the

screen. A minimum of ten measurements were undertaken for each trial. However, apart from experimental block S1-B1 where the welding process was very stable, the smoke level generated during welding tended to obscure the arc image. Therefore, arc length results in S1-B2 and S1-B3 were considered less reliable. Table 5.13 shows the results for S1-B1.

5.2.3. Weld bead characteristics

Weld bead parameters were either measured directly from transverse sections of the weld bead or calculated from other measured parameters.

The definitions of bead area (A_t), deposited area (A_d), lateral penetration area (A_p) and axial penetration area (A_a) for weld beads that did not present appreciable undercutting are shown in figure 5.3. When undercutting level was significant, deposited and lateral penetration areas were recalculated as:

$$A_{cor} = A_{meas} + kA_{und} \quad [5.5]$$

where A_{cor} is the corrected area, A_{meas} is its measured value, A_{und} is the undercutting area (figure 5.4) and k is 1 for lateral penetration area and -1 for deposited area.

The direct use of undercutting area to model the occurrence of undercutting in a welding operation can be problematic because, if the welding conditions are such that only a few welds are defective, undercutting area will be nought for all but a few points. Under this condition, a significant regression model can hardly be obtained and, if used, it will tend to overestimate the threshold of undercutting (figure 5.5). Similar limitations apply when crack length is used to define centreline cracking susceptibility. In order to study undercutting tendency, a new parameter, undercutting factor, was defined as:

$$f_u = (h_{max} - h_{mean})/g \quad [5.6]$$

where g is the gap width,

h_{max} is defined in figure 5.4, and

h_{mean} , the mean bead height, is given by:

$$h_{mean} = A_d/g^* \quad [5.7]$$

where g^* is the gap width measured after welding.

The motivation for using the f_u parameter was purely empirical and based on the observation that, in a narrow gap welding joint in the downhand position, undercutting is generally caused by the arc reaching a point in the sidewall much higher than the mean height of the bead. In the presence of undercutting, the highest point in the joint reached by the arc may be estimated by $h_{\max}$ while, in the absence of undercutting, $h_{\max}$ may estimate this point well or overestimate it slightly. Finally, the difference between $h_{\max}$ and h_{mean} was divided by gap width on the simple intuitive assumption that a larger gap would accommodate more easily a given difference between $h_{\max}$ and h_{mean} .

To study the susceptibility to centre-line cracking, the usual height/width ratio parameter (figure 5.3.) was used.

Figure 5.3 shows how lateral lack of fusion (l_f) was measured in beads presenting positive lack of fusion. When no real lack of fusion was detected, a negative value for l_f was defined based on the conventions shown in figure 5.6.

In order to study the welding time, a parameter, production time, was defined as the time necessary to complete a 1 m long weld in a H mm thick narrow gap joint, and was calculated as:

$$t_{\text{prod}} = 10^3(H.g)/(A_d.v) \quad [5.8]$$

where H was assumed to be equal to 20 mm in this programme.

In the horizontal-vertical trials, no serious evidence of weld pool sagging could be observed from the surface profile of the bead. The beads, however, tended to present a strong asymmetrical shape, particularly, for the low welding speed trials (figure 5.7). Therefore, additional parameters were defined to characterize this asymmetrical characteristic. These included the ratio between the lateral penetration areas in the lower and upper sides of the joint, and the ratio between the lower and upper halves of the axial penetration area (figure 5.8a and b). Once the reduced lateral fusion in the lower wall side made it difficult to directly measure lack of fusion, an alternative approach was used to define it in this particular case (figure 5.8c).

Figures 5.9 shows the variability of some bead characteristics along of the weld bead length obtained in step S0. A relatively good reproducibility of results holds between welding trials performed at similar conditions. However, for the experimental set-up used, some variability associated, possibly, with inconsistent wire feeding may be present. In an attempt to reduce

variability effects, bead parameters for each experimental trial were measured on three different sections of the welded specimen.

The measured bead characteristics for all modelling experimental steps are shown in tables 5.14-5.18.

5.2.4.Complementary trials

Table 5.19 presents the welding bead parameters of complementary trials of block S3-B1. The macrosection of the multipass downhand and horizontal-vertical specimens are shown in figure 5.10.

5.3.Modelling procedure

The experimental results of the previous sections were used for developing modelling equations for different aspects of the welding process, particularly, those related to the weld geometry. The basic objective of modelling was to extract the useful part of the information contained in the experimental data and to summarize it in mathematical expressions for easier interpretation and handling.

The basic tool used in this programme of data analysis and model building was multiple linear regression. Different modelling formulations were attempted. The most commonly used form was (MODEL A):

$$y_{trans} = a_0 + \sum_{i=1}^p a_i x_i \quad [5.9]$$

where $y_{trans} = y^t$ (equation [2.35]) is a power transformation of the response y ,

x_i 's are p predictor variables from a initial set of k predictor candidates (k_p) that were included in the model based on some criteria, and

a_0 and a_i 's are coefficients to be determined by multiple linear regression.

Transformation of the dependent variable was used to improve nonnormality, to reduce heterogeneous variance of errors and to accommodate non-linear trends in the model. This procedure was preferred over adding second or higher order predictor interactions because it can result in simpler models of easier interpretation. As these equations were to be used not

only for mapping the welding process response but also to provide a base for a better understanding of its behaviour, simpler models were considered more desirable.

Adopting a model format such as equation [5.9] implies accepting that a linear relationship exists between the predictor variables and some transformed form y^t of the response. Such an assumption is obviously an oversimplification of the complex processes taking place in welding. However, by investigating a relatively restricted region in the process operational space, one can expect that a linear model can provide a reasonably close description of the true unknown, and possibly not linear, relationship (figure 5.11).

The modelling procedure included the following steps:

- . Transformation of the response using equation [2.35]. Values between -1 and 2, with intervals of 0.5, were generally used for the exponent t . For a nought value of t , a logarithmic transformation, $y_{\text{trans}} = \ln(y)$, was employed.
- . Selection of the "best" set of predictors for y_{trans} . Usually, the initial set of predictor candidates included welding current, wire feed speed, welding speed and gap width. The selection of predictors was performed by backward elimination (§2.4.3.3). A significance level higher than 0.1 (the default value taken by the SPSS^x programme) for the partial F ratios was used as the criterion to drop variables from the model.
- . Selection of the best transformation factor t for a given response y . Following the procedure devised by Box and Cox (1964), the optimum t was considered that which provided the minimum value for the mean square error (MSe_t) in the family of transformations [2.37] (see §2.4.3.3). The 95% confidence interval on the transformation factor t was obtained by calculating MSe^* (equation [2.38]) and finding the interception points between the MSe^* horizontal line and the MSe_t curve (figure 5.12). Residual plots and predicted value plots were carefully examined at this stage and possible outliers considered for exclusion from the data matrix before a final value of t was accepted.
- . Model diagnosis. In order to assess the model adequacy, residuals plot, predicted values plot and the statistics R^2 and F ratio were considered. No rigid criteria were set to define model adequacy. Generally, significance of F lower than about 0.001 coupled with reasonable residual plots were considered sufficient. However, even when the statistics of a given equation were not favourable, it could be considered

satisfactory for comparative analysis, when it showed a similar trend with similar equations of other experimental blocks.

Other alternative model forms that were also considered, included: (a) linear model with second order interactions (MODEL B)

$$y_{trans} = a_0 + \sum_{i=1}^p a_i x_i + \sum_{i=1, j>i}^{p-1, p} a_{ij} x_i x_j \quad [5.10]$$

and (b) logarithmic model (MODEL C):

$$\ln(y) = a_0 + \sum_{i=1}^p a_i \ln(x_i) \quad [5.11]$$

Equation [5.10] was considered and used only when no satisfactory form of the basic model (equation [5.9]) could be fitted to a particular response.

Meanwhile, equation [5.11] was used as an alternative model form in those cases in which a similar theoretical model could be developed based on the balance of mass between the metal fed by the wire and the resulting bead volume. If metal losses can be considered negligible, this relationship can be expressed as:

$$\pi (d_w^2/4)w = A_d \cdot v \quad [5.12]$$

or

$$A_d = [k' \pi (d_w^2/4)].w/v \quad [5.13]$$

where k' can be a factor that depends on the units of measuring used. The theoretical expressions for mean bead height and production time can be easily derived from equations [5.7], [5.8] and [5.13]:

$$h_{mean} = A_d/g \approx k'.w/(v.g), \text{ and} \quad [5.14]$$

$$t_p = (10^3 H/k').(g/w) \quad [5.15]$$

Equations [5.13], [5.14] and [5.15] are readily transformed into the equation [5.11] format by taking logarithms of both sides of each expression.

5.4. Modelling results

Graphs of R^2 , F ratio and corrected mean square error (MSe_t) against transformation factor (t) are presented in figures 5.13 to 5.16 for some of the studied responses. In most cases, the "best" transformation factor, which corresponded to a minimum for MSe_t , could be found inside the (-1,2) interval. When it was located outside this interval, the outmost t value that corresponded to the smallest MSe_t was considered to be the "best" t. An "optimum" transformation factor that was common to as many experimental blocks as possible was selected by comparing the 95% confidence intervals on t. Table 5.20 summarizes the information regarding transformation factors that was used to develop MODEL A type equations (tables 5.21 and 5.22).

Predicted value plots for some responses of blocks S1-B1, S1-B2 and S2-B1 are shown in figures 5.17 to 5.19 for model A type equations. The points that were considered outliers and were not included in the linear regression process are marked by the number of their experimental trial. Most of these points could be associated with some operational problem or with an welding condition that strongly affected the response considered. For instance, trials #1 and #14 in block S1-B2 presented serious control problems, probably associated with inconsistent wire feeding. Consequently, only a fraction of the resulting beads turned out to be satisfactory and the validity of measurement could not be guaranteed. Hence, data from these trials were excluded from model building whenever the diagnosis stage provided an indication for that. Points #3 in S1-B1 and #2 in S1-B2 presented abnormally small axial penetration areas in comparison with other trials and tended to influence strongly the A_a equation. Analysis of their macrosections and welding parameters indicated that, in one case, an excessively high wire feed rate associated with low current and welding speed in a very narrow gap resulted in a thick liquid layer between the arc and base metal which may have impaired axial fusion. In the other trial, the arc seems to have deflected almost completely to the sidewalls not reaching the bottom of the joint. These beads showed evidence of either high undercutting or lack of fusion levels and these would certainly prevent their use for production welding, and so it was decided to exclude their A_a values from modelling. Finally, many measured values from trial #18 of S2-B1 tended to stand clearly as an outlier in residuals plots. Although no apparent abnormality could be associated with this trial, these data were excluded from regression analysis based only on the results of model diagnosis.

Tables 5.23 and 5.24 present those cases in which a MODEL B type equation resulted in some improvement, in terms of R^2 and significance of F ratio, when compared with previous equations.

MODEL C type equations do not appear to improve significantly on the previous results for A_d , h_{mean} , and t_p (tables 5.25 and 5.26). However, their theoretical background is an important advantage. These equations can be used, for instance, to check the validity of the experimental conditions against the theoretical model.

Table 5.1 List of independent variable candidates without considering possible relationships among some of them.

Independent variable candidates	
Welding current (I)	
Polarity (DC+/DC-)	
Current structure (if pulsed):	
	Peak current (I_p)
	Peak time (t_p)
	Base current (I_b)
	Frequency (F)
Arc voltage (V)	
Power supply characteristics	
Wire feed speed (w)	
Wire diameter (d_w)	
Wire composition	
Standoff distance (h)	
Electrode stickout (s)	
Arc length (l_a)	
Welding speed (v)	
Gap width (g)/other joint details	
Shielding gas composition	
Shielding gas flow rate (f)	
Welding position	
Torch/joint angle	

Table 5.2 Welding parameters for the initial experimental step.

CONSTANT FACTORS				
Power supply:	Fronius TPS500	Wire feed rate:	12 m/min	
Operation mode:	CVCC pulsed	Wire diameter:	1.2 mm	
Peak voltage:	40 V	Gas flow rate:	20/35 l/min	
Peak time:	2 ms	Welding speed:	7 mm/s	
Frequency:	200 Hz	Gap width:	7 mm	
Weld. position:	Downhand			
Test plate	Shielding gas	Base current(A)	Mean current(I)	Mean voltage(V)
S0-1	Ar-5	50	260	28.5
S0-2	Ar-5	50	260	29.0
S0-3	He-1	140	277	32.2
S0-4	He-1	140	277	32.2

Table 5.3 Experimental design of the first experimental block, step 1.

Run Nb	Pulse frequency (Hz)	Wire feed rate (m/min)	Welding speed (mm/s)	Gap width (mm)
1	180	11	6	6
2	220	11	6	6
3	180	13	6	6
4	220	13	6	6
5	180	11	8	6
6	220	11	8	6
7	180	13	8	6
8	220	13	8	6
9	180	11	6	8
10	220	11	6	8
11	180	13	6	8
12	220	13	6	8
13	180	11	8	8
14	220	11	8	8
15	180	13	8	8
16	220	13	8	8
17	200	12	7	7
18	200	12	7	7
CONSTANT FACTORS				
Power supply:	Fronius TPS500	Peak voltage:	40 V	
Operation mode:	CVCC pulsed	Peak time:	2 ms	
Gas flow rate:	20 l/min	Base current:	50 A	
Wire diameter:	1.2 mm	Weld. position:	Downhand	

Table 5.4 Experimental design of the second experimental block, step 1.

Run Nb	Base current (A)	Wire feed rate (m/min)	Welding speed (mm/s)	Gap width (mm)
1	100	11	6	6
2	165	11	6	6
3	100	13	6	6
4	165	13	6	6
5	100	11	8	6
6	165	11	8	6
7	100	13	8	6
8	165	13	8	6
9	100	11	6	8
10	165	11	6	8
11	100	13	6	8
12	165	13	6	8
13	100	11	8	8
14	165	11	8	8
15	100	13	8	8
16	165	13	8	8
17	140	12	7	7

CONSTANT FACTORS

Power supply:	Fronius TPS500	Peak voltage:	40 V
Operation mode:	CVCC pulsed	Peak time:	2 ms
Gas flow rate:	35 l/min	Frequency:	200 Hz
Wire diameter:	1.2 mm	Weld. position:	Downhand

OBS: Trials #1 and #14 presented strong arc length variations.

Table 5.5 Experimental design of the third experimental block, step 1.

Run Nb	Base Current (A)	Wire feed rate (m/min)	Welding speed (mm/s)
1	50	11	6
2	100	11	6
3	50	13	6
4	100	13	6
5	50	11	8
6	100	11	8
7	50	13	8
8	100	13	8
9	75	12	7
10	75	12	7

CONSTANT FACTORS

Power supply:	Fronius TPS500	Peak voltage:	40 V
Operation mode:	CVCC pulsed	Peak time:	2 ms
Gas flow rate:	20 l/min	Frequency:	200 Hz
Wire diameter:	1.2 mm	Weld. position:	Downhand
Gap width:	7 mm		

Table 5.6 Experimental design of the only experimental block of step 2.

Run Nb	Wire feed rate (m/min)	Welding speed (mm/s)	Gap width (mm)	Welding current (A)
1	10	6	6	260
2	11	6	6	260
3	10	8	6	260
4	11	8	6	260
5	10	6	8	260
6	11	6	8	260
7	10	8	8	260
8	11	8	8	260
9	11	6	6	290
10	12	6	6	290
11	11	8	6	290
12	12	8	6	290
13	11	6	8	290
14	12	6	8	290
15	11	8	8	290
16	12	8	8	290
17	12	7	7	260
18	10	7	7	290
19	11	7	5	275
20	11	7	9	275
21	11	5	7	275
22	11	9	7	275
CONSTANT FACTORS				
Power supply:	GEC (AWP) M500	Short cir. det.:	15V	
Operation mode:	Constant current	Gas flow rate:	35 l/min	
Wire diameter:	1.2 mm	Weld. position:	Downhand	

Table 5.7 Experimental design of the only experimental block of step 3.

Run Nb	Wire feed rate (m/min)	Welding current (A)	Welding speed (mm/s)
1	11	260	6
2	12	260	6
3	11	280	6
4	13	280	6
5	12	300	6
6	13	300	6
7	11	260	8
8	12	280	8
9	12	280	8
10	13	300	8
11	11	260	10
12	12	260	10
13	11	280	10
14	13	280	10
15	12	300	10
16	13	300	10
CONSTANT FACTORS			
Power supply:	GEC (AWP) M500 Short cir. det.:		15V
Operation mode:	Constant current	Gas flow rate:	35 l/min
Wire diameter:	1.2 mm	Gap width: 7 mm	
Weld. position:	Horizontal-vertical		

Table 5.8 Welding parameters of the complementary trials.

Trial #	Exp. block	I (A)	w (m/min)	v (mm/s)	g (mm)	OBS.
C1	S2-B1	260	11	7	7	Multipass (4 runs)
C2	S2-B1	280	12	8	7	Multipass (5 runs)
C3	S3-B1	280	12	8	7	1 pass
C4	S3-B1	280	12	8	7	1 pass
C5	S3-B1	280	12	8	6	1 pass
C6	S3-B1	280	12	8	8	1 pass
C7	S3-B1	280	12	8	9	1 pass
C8	S3-B1	260	10	8	5-7*	Multipass (5 runs)

* Tapered edge specimen (5 mm root gap, 7 mm face gap).

Table 5.9 List of measured parameters.

Dependent variables

(a)Electrical parameters:

- . Mean current (I)
- . Mean voltage (V)
- . Pulse structure (pulsed welding):
 - . Peak current (I_p)
 - . Standard deviation of I_p (s_p)
 - . Peak time (t_p)
 - . Base current (I_b)
 - . Frequency (F)

(b)Arc parameters:

- . Arc length (l_a)

(c)Bead parameters:

- . Bead area (A_t)
- . Deposited area (A_d)
- . Lateral penetration area (A_p)
- . Axial penetration area (A_a)
- . Undercutting area (A_{und})
- . Lateral lack of fusion (lf)
- . Maximum axial penetration (p_a)
- . Mean bead height (h_{mean})
- . Centre-line crack length (l_{ck})
- . Gap contraction (d_g)
- . Height/width ratio (R)
- . Undercutting factor (f_u)
- . Production time (t_{prod})

(d)Bead parameters (horizontal-vertical welding):

- . Upper side lateral penetration area (A_{pu})
- . Lower side lateral penetration area (A_{pl})
- . A_{pl}/A_{pu} ratio (R_{plu})
- . Upper axial penetration area (A_{au})
- . Lower axial penetration area (A_{al})
- . A_{al}/A_{au} ratio (R_{alu})

Table 5.10 Current structure for welding trials of experimental block S1-B1.

Nb	I_{mean} (A)	I_{peak} (A)	s_{peak} (A)	t_{peak} (ms)	I_{base} (A)	Frequency (Hz)
1	240	-	-	-	-	-
2	275	509	9	2.25	-	207
3	270	514	5	2.38	60	168
4	285	506	5	2.28	60	206
5	240	501	4	2.26	50	166
6	280	500	5	2.22	60	217
7	270	510	5	2.42	55	172
8	290	496	1	2.26	60	216
9	235	506	6	2.21	45	166
10	270	506	8	2.06	60	207
11	260	503	12	2.31	65	169
12	280	504	5	2.28	50	207
13	235	502	5	2.20	45	167
14	270	491	7	2.06	60	220
15	250	505	5	2.29	55	172
16	285	497	1	2.22	60	216
17	268	503	4	2.22	50	195
18	268	502	3	2.28	60	191

Obs: (1)Reference current: 300A

(2)Base current was measured graphically

Table 5.11 Current structure for welding trials of experimental block S1-B2.

Nb	I_{mean} (A)	I_{peak} (A)	s_{peak} (A)	t_{peak} (ms)	I_{base} (A)	Frequency (Hz)
1	265	493	23	2.15	105	202
2	300	463	7	2.25	165	219
3	270	506	33	2.18	105	200
4	285	499	48	2.26	165	193
5	260	499	12	2.17	95	196
6	295	499	25	2.33	165	204
7	270	519	14	2.17	100	204
8	305	523	6	2.37	165	205
9	245	459	26	1.93	100	194
10	275	456	3	2.23	160	200
11	255	474	38	2.09	100	199
12	285	449	60	2.10	165	209
13	235	437	26	1.93	95	198
14	265	449	5	2.21	160	193
15	265	503	26	2.16	100	200
16	290	480	3	2.28	160	200
17	277	491	18	2.19	120	203

Obs: (1)Reference current: 300A

(2)Base current was measured graphically

(3)Trials nb 1 and 14 presented stability problems (see text.)

Table 5.12 Current structure for welding trials of experimental block S1-B3.

Nb	I_{mean} (A)	I_{peak} (A)	s_{peak} (A)	t_{peak} (ms)	I_{base} (A)	Frequency (Hz)
1	245	438	7	2.08	45	203
2	260	435	7	2.11	105	199
3	260	480	20	-	65	-
4	275	463	8	2.13	105	204
5	240	466	7	2.03	45	202
6	250	402	7	1.99	105	200
7	255	459	13	2.00	60	200
8	270	439	36	2.01	110	201
9	255	468	8	2.11	75	202
10	260	443	10	2.01	85	204

Obs: (1)Reference current: 300A

(2)Base current was measured graphically

Table 5.13

Arc length measurements for the experimental block S1-B1.

Nb	Arc length (mm)	Standard deviation (mm)	Number of measurements
1	2.7	0.6	30
2	4.5	1.8	15
3	1.2	0.8	16
4	3.2	0.4	27
5	2.0	0.4	27
6	6.5	0.5	16
7	1.7	0.7	35
8	2.8	0.2	14
9	2.3	0.5	43
10	3.2	0.3	26
11	1.3	0.4	41
12	1.9	0.2	23
13	2.1	0.3	28
14	4.0	0.3	21
15	1.3	0.3	24
16	2.1	0.2	17
17	2.3	0.2	19
18	2.1	0.3	16

Mean: 2.6
St. deviation: 1.3

Table 5.14 Weld bead characteristics of the first experimental block, step S1 (M - mean, SD -standard deviation).

RUN NB	A_t (mm²)	A_d (mm²)	A_p (mm²)	A_{und} (mm²)	A_a (mm²)	h_{mean} (mm)	R -	Lf (mm)	f_u -
1	46.3	33.0	3.9	0.0	9.4	5.9	1.38	0.47	0.14
2	54.7	32.6	10.7	1.1	11.5	6.1	1.14	-0.04	0.34
3	42.3	37.9	1.7	0.0	2.7	6.8	1.25	3.08	0.06
4	52.5	39.5	4.4	0.0	8.6	7.1	1.53	1.61	0.09
5	35.7	23.6	2.4	0.0	9.8	4.2	1.14	0.00	0.09
6	43.5	23.2	12.8	3.4	7.5	4.9	0.93	-0.07	0.61
7	36.8	27.9	1.7	0.0	7.7	5.0	1.18	1.50	0.07
8	47.0	29.0	6.2	0.0	11.9	5.3	1.25	0.00	0.14
9	47.1	33.2	1.1	0.0	12.9	4.4	0.96	1.40	0.07
10	54.2	32.4	4.8	0.0	17.1	4.3	0.91	1.25	0.13
11	50.2	38.7	1.3	0.0	10.2	5.2	1.03	3.04	0.07
12	57.9	39.2	1.8	0.0	16.9	5.3	1.12	2.50	0.11
13	35.8	24.1	1.1	0.0	10.6	3.2	0.74	0.75	0.02
14	41.4	22.8	3.5	0.7	15.1	3.2	0.82	-0.14	0.23
15	42.3	28.9	1.0	0.0	13.1	3.7	0.94	0.93	0.05
16	47.2	29.2	2.0	0.0	16.0	4.0	0.96	0.36	0.07
17	46.0	28.8	3.1	0.0	14.1	4.5	1.15	0.40	0.11
18	45.2	30.3	1.7	0.0	13.2	4.7	1.20	1.11	0.09
M	45.9	30.7	2.6		11.6	4.9	1.09	1.10	0.14
SD	6.4	5.5	3.3		3.7	1.1	0.20	1.12	0.14

Table 5.15 Weld bead characteristics of the second experimental block, step S1 (M - mean, SD -standard deviation).

RUN NB	A _t (mm ²)	A _d (mm ²)	A _p (mm ²)	A _{und} (mm ²)	A _a (mm ²)	h _{mean} (mm)	R -	Lf (mm)	f _u -
1	54.5	35.2	11.6	0.0	7.7	5.5	1.08	0.32	0.21
2	55.9	30.1	23.2	9.4	2.6	7.2	0.98	1.50	1.15
3	54.1	35.6	11.2	0.2	7.7	6.5	1.14	0.47	0.33
4	55.9	37.7	10.7	0.1	7.5	6.9	1.15	0.57	0.19
5	38.9	22.7	9.1	1.3	7.1	4.1	0.88	0.15	0.43
6	44.1	22.4	15.5	5.5	6.2	4.1	0.88	0.88	0.79
7	40.7	27.1	5.5	0.0	8.1	4.9	1.08	0.36	0.17
8	48.3	28.5	7.3	0.0	12.5	5.1	1.11	-0.06	0.13
9	46.2	30.2	4.7	0.0	11.3	4.1	0.80	0.80	0.09
10	52.6	31.8	5.5	0.0	15.3	4.3	0.89	0.15	0.20
11	50.0	34.9	3.9	0.0	11.2	4.7	0.90	0.53	0.05
12	58.3	37.3	7.7	0.0	13.3	5.1	0.89	0.14	0.10
13	35.4	23.4	1.7	0.0	10.3	3.1	0.72	0.75	0.11
14	39.4	20.9	3.8	0.3	14.7	2.8	0.66	-0.29	0.45
15	42.2	27.7	2.1	0.0	12.4	3.7	0.86	0.18	0.05
16	44.3	26.1	2.3	0.2	15.9	3.5	0.84	0.36	0.18
17	45.8	28.7	5.5	0.0	11.6	4.5	0.95	0.47	0.19
M	47.4	29.4	7.7		10.3	4.8	0.93	0.38	0.28
SD	6.9	5.4	5.5		3.6	1.3	0.14	0.38	0.29

Table 5.16 Weld bead characteristics of the third experimental block, step S1 (M - mean, SD -standard deviation).

RUN NB	A_t (mm²)	A_d (mm²)	A_p (mm²)	A_{und} (mm²)	A_a (mm²)	h_{mean} (mm)	R -	Lf (mm)
1	46.5	32.0	2.9	0.0	11.6	4.9	1.13	0.93
2	50.1	31.5	3.8	0.0	14.8	4.9	1.18	0.57
3	47.7	37.9	2.5	0.0	7.3	5.9	1.21	2.32
4	54.5	37.9	3.9	0.0	12.7	5.8	1.21	1.40
5	37.7	23.8	1.6	0.0	12.3	3.5	0.93	0.11
6	39.2	23.5	2.9	0.0	12.8	3.6	0.92	0.00
7	40.3	26.8	2.4	0.0	11.1	4.1	1.08	0.57
8	41.7	28.0	2.4	0.0	11.3	4.2	1.07	0.75
9	43.4	29.4	2.3	0.0	11.7	4.5	1.15	0.68
10	46.8	29.7	4.0	0.0	13.1	4.6	1.08	0.75
M	44.8	30.0	2.9		11.9	4.6	1.10	0.81
SD	5.3	5.0	0.8		1.9	0.8	0.10	0.66

Table 5.17 Weld bead characteristics of S2-B1.

RUN NB	A_t (mm²)	A_d (mm²)	A_p (mm²)	A_{und} (mm²)	A_a (mm²)	h_{mean} (mm)	R -	Lf (mm)	f_u -
1	52.6	29.9	13.3	>0.	9.4	5.6	0.89	-0.39	0.25
2	54.3	32.9	11.2	0.	10.2	6.0	1.08	-0.25	0.09
3	39.7	20.8	6.5	0.	12.4	3.7	0.88	-0.54	0.19
4	41.1	23.8	5.9	0.	11.4	4.1	0.96	-0.32	0.09
5	55.1	29.1	10.1	>0.	15.9	3.9	0.66	-0.24	0.19
6	57.1	32.1	8.9	0.	16.1	4.2	0.74	-0.43	0.09
7	42.0	21.2	4.3	0.	16.5	2.8	0.69	-0.07	0.18
8	44.8	23.0	4.4	0.	17.4	3.1	0.71	-0.11	0.10
9	67.0	32.8	18.9	>0.	15.3	6.1	1.11	-0.96	0.33
10	64.2	35.2	16.4	0.	12.6	6.5	1.11	-0.50	0.15
11	52.2	24.7	11.9	0.55	15.6	4.5	1.01	-0.97	0.37
12	50.6	26.5	9.3	0.	14.8	4.8	1.05	-0.57	0.15
13	64.0	33.2	11.4	0.45	19.4	4.5	0.85	-0.25	0.47
14	70.1	35.4	11.5	0.	23.2	4.7	0.88	-0.14	0.16
15	50.7	23.5	5.3	>0.	22.0	3.1	0.79	-0.21	0.19
16	51.3	25.0	5.2	0.	21.1	3.4	0.85	+0.18	0.15
17	49.6	28.7	5.6	0.	15.3	4.4	0.98	-0.14	0.05
18	44.1	20.3	11.1	3.0	12.7	3.7	0.76	-0.50	0.66
19	52.1	28.3	14.5	0.	9.3	5.9	1.09	-0.82	0.13
20	55.9	28.0	6.2	0.	21.7	3.2	0.63	-0.24	0.09
21	74.2	41.6	19.2	>0.	13.4	6.3	0.87	-0.26	0.18
22	43.3	19.9	5.3	0.	18.1	3.0	0.81	-0.68	0.16
M	53.9	28.0	9.8	-	1.73	4.4	0.88	-0.43	0.20
SD	9.6	5.8	4.6	-	0.47	1.2	0.15	0.30	0.14

Table 5.18 Weld bead characteristics of S3-B1.

RUN NB	A _t (mm ²)	A _d (mm ²)	A _{pu} (mm ²)	A _{pl} (mm ²)	A _a (mm ²)	R _{lu} -	h _{mean} (mm)	R -	l _{fu} (mm)	l _{fd} (mm)	tp (s/m)
1	52.8	33.9	5.8	0.4	12.8	0.659	5.3	1.11	-0.93	0.90	689
2	54.9	36.2	4.5	1.1	13.1	0.621	5.5	1.14	-1.12	1.23	645
3	53.6	32.8	4.2	0.9	15.8	0.585	5.1	1.16	-1.06	0.10	712
4	58.0	39.5	6.0	1.2	11.3	0.551	6.0	1.05	-0.59	0.71	591
5	62.6	36.0	6.0	0.8	19.9	0.766	5.5	1.31	-2.21	1.37	649
6	66.1	40.4	5.7	1.7	19.3	0.604	6.2	1.30	-1.42	0.30	578
7	41.4	25.6	2.7	0.3	12.9	0.557	3.8	0.92	-0.45	0.89	685
8	45.0	26.9	2.8	0.3	15.1	0.653	4.2	-	-1.16	1.02	651
9	45.9	27.7	2.5	0.4	15.3	0.614	4.2	-	-0.66	0.89	632
10	55.3	30.8	1.4	0.3	22.7	0.564	4.7	1.49	-0.23	2.12	568
11	33.7	20.0	0.8	0.3	12.7	0.553	3.0	0.86	-0.20	0.36	702
12	33.8	21.95	0.4	0.5	11.0	0.534	3.3	0.91	+0.22	0.55	638
13	35.3	20.1	0.4	0.3	14.5	0.527	3.0	0.94	-0.10	0.28	698
14	37.5	23.3	0.7	0.2	13.4	0.554	3.5	0.96	-0.55	0.88	601
15	-	-	-	-	-	-	-	-	-	-	-
16	42.3	24.3	1.0	0.2	17.5	0.607	3.6	1.18	-0.20	0.77	576

Table 5.19 Weld bead characteristics of some of the complementary trials.

Trial	A _t #	A _d (mm ²)	A _{pu} (mm ²)	A _{pd} (mm ²)	h _{mean} (mm ²)	L _{fu} (mm)	L _{fd} (mm)	R (mm)	-
C3	44.1	26.8	1.8	0.8	4.1	-	-	1.07	
C4	45.1	26.7	2.8	0.8	4.2	-	-	1.06	
C5	41.3	26.3	3.2	1.8	4.8	-1.0	0.0	1.10	
C6	44.8	26.7	1.0	0.3	3.5	-0.1	1.0	0.89	
C7	48.8	28.0	0.8	0.5	3.3	-0.2	1.1	0.86	

Table 5.20 Transformation factor values (t_m) for minimum MSe_t , 95% confidence interval on t and "optimum" t values (t_{op}).

Response	Exp. step	t_m	Confidence interval			t_{op}
A_t	S1-B1	0.0	?	..	?	.
	S1-B2	-0.5	?	..	1.1	.
	S1-B3	-1.0	?	..	1.3	0.0
	S2-B1	0.0	?	..	1.1	.
	S3-B1	0.0	-0.7	..	0.7	.
A_d	S1-B1	0.5	-0.5	..	1.0	.
	S1-B2	0.0	?	..	1.1	.
	S1-B3	-0.5	?	..	0.3	0.0
	S2-B1	-0.5	-0.9	..	0.2	.
	S3-B1	-0.5	-0.7	..	0.1	.
A_p	S1-B1	-0.5	-0.8	..	0.2	0.0
	S1-B2	0.0	-0.3	..	0.6	0.0
	S2-B1	0.0	-0.5	..	0.5	0.0
	S3-B1	0.0	-0.2	..	0.6	0.0
h_{mean}	S1-B1	0.0	-0.6	..	0.8	.
	S1-B2	0.0	-0.6	..	0.9	.
	S1-B3	0.0	-0.8	..	0.4	0.0
	S2-B1	0.0	-0.6	..	0.3	.
	S3-B1	0.0	-0.6	..	0.3	.
R	S1-B1	0.0	?	..	1.7	1.0
	S1-B2	1.0	-0.7	..	?	1.0
	S1-B3	2.0	-0.7	..	?	1.0
	S2-B1	0.5	-0.7	..	?	1.0
	S3-B1	-1.0	?	..	1.0	-1.0

Cont.

OBS: ? - Limit outside explored interval for t .

Table 5.20(cont) Transformation factor values (t_m) for minimum MSe_t , 95% confidence interval on t and "optimum" t values (t_{op}).

Response	Exp. step	t_m	Confidence interval			t_{op}
Lf	S1-B1	0.0	-0.6	..	0.7	0.0
	S1-B2	1.5	0.7	..	?	1.5
	S1-B3	0.0	-0.4	..	0.5	0.0
	S2-B1	0.0	?	..	0.7	0.0
A_a	S1-B1	2.0	?	..	?	1.0
	S1-B2	1.0	-0.8	..	?	1.0
	S1-B3	2.0	0.4	..	?	1.0
	S2-B1	0.5	-0.2	..	1.4	1.0
	S3-B1	-1.0	?	..	0.6	-1.0
t_p	S1-B1	0.0	-0.8	..	0.8	.
	S1-B2	1.0	-0.5	..	1.8	.
	S1-B3	2.0	?	..	?	0.5
	S2-B1	1.0	0.2	..	1.9	.
	S3-B1	1.5	?	..	?	.
f_u	S1-B1	-0.5	?	..	-0.2	-0.5
	S1-B2	0.0	-0.6	..	0.3	0.0
	S2-B1	0.0	-0.6	..	0.2	0.0

OBS: ? - Limit outside explored interval for t.

Table 5.21 Optimized modelling equations (MODEL A).

Resp.	Exp. step	Modelling equations
A_t	S1-B1	$\ln(y) = 3.113 + 0.0044I - 0.106v + 0.041g$ <u>(0.303) (0.0009) (0.016) (0.017)</u>
	S1-B2	$\ln(y) = 3.533 + 0.0036I + 0.0184w - 0.126v$ <u>(0.134) (0.0004) (0.0078) (0.007)</u>
	S1-B3	$\ln(y) = 3.334 + 0.0045I - 0.098v$ <u>(0.248) (0.0009) (0.010)</u>
	S2-B1	$\ln(y) = 3.119 + 0.0040I + 0.0636w - 0.132v$ <u>(0.247) (0.0010) (0.0206) (0.0103)</u>
	S3-B1	$\ln(y) = 3.111 + 0.0041I + 0.0397w - 0.1113v$ <u>(0.152) (0.0007) (0.0124) (0.0046)</u>
A_d	S1-B1	$\ln(y) = 3.428 + 0.0922w - 0.161v$ <u>(0.081) (0.0058) (0.0058)</u>
	S1-B2	$\ln(y) = 3.325 + 0.0878w - 0.145v$ <u>(0.117) (0.0083) (0.0083)</u>
	S1-B3	$\ln(y) = 3.501 + 0.0812w - 0.155v$ <u>(0.079) (0.0057) (0.0057)</u>
	S2-B1	$\ln(y) = 3.541 + 0.0883w - 0.172v$ <u>(0.119) (0.0100) (0.0061)</u>
	S3-B1	$\ln(y) = 3.273 + 0.0899w - 0.128v$ <u>(0.072) (0.0057) (0.0027)</u>
A_p	S1-B1	$\ln(y) = 0.954 + 0.0345I - 0.580w - 0.309g$ <u>(1.332) (0.0047) (0.085) (0.076)</u>
	S1-B2	$\ln(y) = 5.889 + 0.0137I - 0.208w - 0.316v - 0.446g$ <u>(1.342) (0.0037) (0.062) (0.059) (0.067)</u>
	S2-B1	$\ln(y) = 3.272 + 0.0145I - 0.111w - 0.338v - 0.215g$ <u>(0.583) (0.0020) (0.041) (0.023) (0.023)</u>
	S3-B1	$\ln(y) = 4.732 - 0.483v$ <u>(0.231) (0.029)</u>

cont

- OBS: (1) In blocks S1-B3 and S3-B1, gap width is not used as a variable.
 (2) Numbers in brackets are the standard deviation estimate of the regression coefficients.

Table 5.21(cont) Optimized modelling equations (MODEL A).

Resp.	Exp. step	Modelling equations	
A _a	S1-B1	$y = -20.7 + 0.0581I$	$+ 2.463g$
		<u>(9.06) (0.028)</u>	<u>(0.539)</u>
	S1-B2	$y = -33.4 + 0.0825I$	$+ 3.091g$
		<u>(7.68) (0.0224)</u>	<u>(0.409)</u>
h _{mean}	S2-B1	$y = -48.8 + 0.137I$	$+ 0.796v + 3.083g$
		<u>(5.39) (0.018)</u>	<u>(0.225) (0.225)</u>
	S3-B1	$y^{-1} = 0.2497 - 7.1E-4I$	$+ 1.87E-3v$
		<u>(0.0232) (8E-5)</u>	<u>(7E-4)</u>
Lf	S1-B1	$\ln(y) = 2.749 + 0.0783w - 0.1488v - 0.1558g$	
		<u>(0.162) (0.0104) (0.0104) (0.0104)</u>	
	S1-B2	$\ln(y) = 3.526 + 0.0471w - 0.2014v - 0.1634g$	
		<u>(0.276) (0.018) (0.0177) (0.0177)</u>	
	S1-B3	$\ln(y) = 1.677 + 0.0833w - 0.1664v$	
		<u>(0.068) (0.0048) (0.0048)</u>	
	S2-B1	$\ln(y) = 2.740 + 0.0983w - 0.1773v - 0.1621g$	
		<u>(0.141) (0.0111) (0.0072) (0.0072)</u>	
	S3-B1	$\ln(y) = 1.470 + 0.0880w - 0.1352v$	
		<u>(0.075) (0.0059) (0.0059)</u>	
	S1-B1	$\ln(y+0.5)=1.070 - 0.0258I + 0.0696w - 0.337v$	
		<u>(1.495) (0.0055) (0.102) (0.089)</u>	
	S1-B2	$(y+0.5)^{3/2}=2.212 - 0.0134I + 0.176w$	
		<u>(1.225) (0.0053) (0.095)</u>	
	S1-B3	$\ln(y+0.5)=0.771 - 0.0115I + 0.4347w - 0.411v$	
		<u>(1.390) (0.0067) (0.072) (0.052)</u>	
	S2-B1	$\ln(0.5-y)=-0.569 + 0.0115I - 0.125w - 0.199g$	
		<u>(0.719) (0.0025) (0.051) (0.029)</u>	

cont

OBS: (1) In blocks S1-B3 and S3-B1, gap width is not used as a variable.
 (2) Numbers in brackets are the standard deviation estimate of the regression coefficients.

Table 5.21(cont) Optimized modelling equations (MODEL A).

Resp.	Exp. step	Modelling equations
R	S1-B1	$y = 1.755 + 0.0781w - 0.0844v - 0.144g$ <u>(0.366) (0.0235) (0.0235) (0.0235)</u>
	S1-B2	$y = 1.231 + 0.0675w - 0.0500v - 0.109g$ <u>(0.177) (0.0113) (0.0113) (0.011)</u>
	S1-B3	$y = 1.129 + 0.0514w - 0.0924v$ <u>(0.178) (0.0128) (0.0128)</u>
	S2-B1	$y = 0.806 + 0.0969w - 0.0220v - 0.119g$ <u>(0.171) (0.0134) (0.0087) (0.009)</u>
	S3-B1	$y^{-1} = 2.282 - 0.0060w + 0.0407v$ <u>(0.369) (0.0013) (0.0113)</u>
t_p	S1-B1	$y^{1/2} = 23.03 - 0.980w + 1.926g$ <u>(1.74) (0.125) (0.125)</u>
	S1-B2	$y^{1/2} = 26.99 - 1.146w + 1.879g$ <u>(1.40) (0.100) (0.099)</u>
	S1-B3	$y^{1/2} = 38.80 - 1.059w$ <u>(1.01) (0.084)</u>
	S2-B1	$y^{1/2} = 26.00 - 1.204w + 2.031g$ <u>(2.19) (0.184) (0.113)</u>
	S3-B1	$y^{1/2} = 38.80 - 1.134w$ <u>(0.79) (0.65)</u>
f_u	S1-B1	$y^{-0.5} = 2.965 - 0.0370I + 0.831w$ <u>(1.679) (0.0065) (0.114)</u>
	S1-B2	$\ln(y) = 3.062 + 0.0175I - 0.524w - 0.454g$ <u>(2.455) (0.0066) (0.118) (0.129)</u>
	S2-B1	$\ln(y) = -4.826 + 0.0403I - 0.730w$ <u>(1.080) (0.0041) (0.082)</u>
l_a	S1-B1	$\ln(y) = 1.065 + 0.0199I - 0.456w$ <u>(0.718) (0.0029) (0.054)</u>

OBS: (1) In blocks S1-B3 and S3-B1, gap width is not used as a variable.
 (2) Numbers in brackets are the standard deviation estimate of the regression coefficients.

Table 5.22 Statistical parameters and comments related to MODEL A equations (table 5.21).

Resp.	Exp. block	R ² (%)	MSE	DF	SigF	Comments
A _t	S1-B3	S1-B1	82.5	4.1E-3	3/14	0.0000
		S1-B2	96.7	8.9E-4	3/13	0.0000
		96.1	6.9E-4	2/7	0.0000	
		S2-B1	92.9	2.6E-3	3/17	0.0000
		S3-B1	98.5	9.1E-4	3/12	0.0000
A _d	S1-B3	S1-B1	98.6	5.4E-4	2/15	0.0000
		S1-B2	97.2	9.6E-4	2/12	0.0000
		99.3	2.6E-4	2/7	0.0000	Points 1 and 14 dropped from model.
		S2-B1	97.9	9.0E-4	2/18	0.0000
		S3-B1	99.51	3.3E-4	2/13	0.0000
A _p	S1-B3	S1-B1	88.1	8.6E-2	4/13	0.0000
		S1-B2	92.0	5.6E-2	4/12	0.0000
		-	-	-	-	NO SIGNIFICANT EQUATION
		S2-B1	95.3	1.3E-2	4/17	0.0000
		S3-B1	88.8	3.6E-2	2/12	0.0000
A _a	S1-B2	S1-B1	61.4	4.16	2/14	0.0013
		81.6	2.12	2/13	0.0000	Point 3 dropped from model.
		S2-B1	93.8	1.22	3/17	0.0000
		S3-B1	88.8	2.2E-5	2/12	0.0000
h _{mean}	S1-B3	S1-B1	97.2	1.7E-3	3/14	0.0000
		S1-B2	94.2	4.9E-3	3/13	0.0000
		99.5	1.9E-4	2/7	0.0000	Point 2 dropped from model.
		S2-B1	98.5	1.2E-3	3/18	0.0000
		S3-B1	99.5	3.5E-4	2/13	0.0000

Cont.

OBS: DF - Degrees of freedom (Regression/Residuals).
 SigF - Significance of F statistic.
 MSE - Mean square sum of errors.

Table 5.22(cont) Statistical parameters and comments related to MODEL A equations (table 5.21).

Resp.	Exp.	R ² block	MSE (%)	DF	SigF	Comments
Lf	S1-B3	S1-B1	82.0	0.126	3/14	0.0000
		S1-B2	35.4	8.4E-2	2/12	0.0727
		95.1	1.8E-2	3/6	0.0003	NOT STATISTICALLY SIGNIFICANT AT 7.3% !
		S2-B1	81.0	1.9E-2	3/15	0.0000
R	S1-B3	S1-B1	83.1	6.9E-3	3/14	0.0000
		S1-B2	91.9	2.1E-3	3/13	0.0000
		90.8	1.3E-3	2/7	0.0002	
		S2-B1	93.2	1.8E-3	3/18	0.0000
		S3-B1	80.1	5.5E-3	2/10	0.0003
t _p	S1-B3	S1-B1	98.3	0.105	3/14	0.0000
		S1-B2	97.6	0.138	2/12	0.0000
		95.2	5.7E-2	1/8	0.0000	Points 1 and 14 dropped from model.
		S2-B1	95.3	0.304	3/17	0.0000
		S3-B1	95.6	4.3E-2	1/14	0.0000
f _u	S1-B2	S1-B1	81.2	0.155	2/14	0.0000
		82.8	0.175	3/11	0.0002	Point 13 dropped from model.
		S2-B1	86.6	5.4E-2	2/19	0.0000
l _a	S1-B1	84.4	3.5E-2	2/15	0.0000	

OBS: DF - Degrees of freedom (Regression/Residuals).

SigF - Significance of F statistic.

MSE - Mean square sum of errors.

Table 5.23 MODEL B type equations.

RESP.	EXP. STEP	MODELLING EQUATIONS
At	S1-B1	$\ln(y) = 10.584 - 0.955w - 0.413v + 0.0016Iw - 0.0019Ig + 0.0255wv + 0.046wg$ (1.335) (0.188) (0.123) (0.0003) (0.0005) (0.0100) (0.012)
Ap	S1-B1	$y = -2.87 + 0.701I - 14.28w - 0.0798Ig + 1.664wg$ (3.39) (0.078) (1.71) (0.0108) (0.238)
	S2-B1	$\ln(y) = -7.413 + 0.0458I - 0.137w + 1.31g - 0.0043Ig - 0.0482vg$ (2.745) (0.0100) (0.034) (0.39) (0.0014) (0.0025)
Aa	S1-B2	$y = 52.4 - 0.467I + 0.0194Iw + 0.0460Ig - 0.780wg$ (22.7) (0.166) (0.0070) (0.0120) (0.269)
	S2-B1	$y^2 = -2609. + 22.4I - 256.w + 349.w - 2.67Iv + 29.0wv$ (1973.) (5.3) (57.) (138.) (0.77) (8.3)
R	S1-B2	$y = 2.049 - 0.277v + 0.0189wv - 0.0092wg$ (0.080) (0.018) (0.0013) (0.0007)
Lf	S1-B1	$y = -37.9 + 4.30w + 3.85v - 0.0028Iw - 0.365wv$ (8.6) (0.74) (1.21) (0.0005) (0.100)
	S1-B3	$\ln(y + 0.5) = 20.336 - 0.0873I - 2.464v + 0.0017Iw + 0.0080Iv$ (6.032) (0.0237) (0.841) (0.0002) (0.0033)
	S2-B1	$\ln(0.5 - y) = -1.930 + 0.0165I - 0.126w - 0.00073Ig$ (0.662) (0.0025) (0.049) (0.00010)
fu	S1-B1	$y^{1/2} = -3.43 + 0.0294I - 0.0012Iw + 0.0014Iv - 0.0028Ig - 0.0297wv + 0.0587wg$ (1.05) (0.0079) (0.0003) (0.0005) (0.0005) (0.0089) (0.0060)
	S1-B2	$\ln(y) = 8.996 + 1.598w - 4.906g - 0.0053Iw + 0.0117Ig - 0.110wv + 0.186vg$ (1.080) (0.627) (1.086) (0.0021) (0.0035) (0.038) (0.067)

OBS:Numbers in brackets are the standard deviation estimates of the regression coefficients.

Table 5.24 Statistical parameters and comments related to MODEL B equations (table 5.23).

Resp.	Exp. block	R ² (%)	MSE	DF	SigF	Comments
A _t	S1-B1	94.6	1.7E-3	6/11	0.0000	
A _p	S1-B1	94.8	0.75	4/13	0.0000	
	S2-B1	97.7	7.2E-3	5/15	0.0000	Point 18 dropped from model.
A _a	S1-B2	89.9	1.37	4/11	0.0000	Point 2 dropped from model.
	S1-B3	94.3	233.	5/4	0.0130	
R	S1-B2	95.9	1.0E-3	3/13	0.0000	
Lf	S1-B2	S1-B1 72.2	90.1 2.3E-2	0.16 5/7	4/13 0.0600	0.0000 MODEL NOT STATISTICALLY SIGNIFICANT AT 6% !
		S1-B3 97.8	1.0E-2	4/5	0.0003	
		S2-B1 82.1	1.8E-2	3/15	0.0000	Points 6, 16 and 22 dropped from model.
f _u	S1-B1	94.2	1.9E-3	6/10	0.0000	Point 13 dropped from model.
	S1-B2	94.6	7.6E-2	6/8	0.0001	Points 1 and 14 dropped from model.

OBS: DF - Degrees of freedom (Regression/Residuals).

SigF - Significance of F statistic.

MSE - Mean square sum of errors.

Table 5.25 Optimized modelling equations (MODEL C).

Resp.	Exp. step	Modelling equations
A_d	S1-B1	$\ln(y) = 2.838 + 1.103\ln(w) - 1.118\ln(v)$ <u>(0.182) (0.066) (0.039)</u>
	S1-B2	$\ln(y) = 2.710 + 1.050\ln(w) - 1.008\ln(v)$ <u>(0.273) (0.099) (0.057)</u>
	S1-B3	$\ln(y) = 3.064 + 0.973\ln(w) - 1.078\ln(v)$ <u>(0.182) (0.067) (0.039)</u>
	S2-B1	$\ln(y) = 3.210 + 0.995\ln(w) - 1.175\ln(v)$ <u>(0.234) (0.093) (0.036)</u>
	S3-B1	$\ln(y) = 2.710 + 1.073\ln(w) - 0.993\ln(v)$ (0.176) (0.067) (0.021)
h_{mean}	S1-B1	$\ln(y) = 3.336 + 0.936\ln(w) - 1.035\ln(v) - 1.084\ln(g)$ <u>(0.354) (0.120) (0.070) (0.070)</u>
	S1-B2	$\ln(y) = 3.028 + 1.025\ln(w) - 1.045\ln(v) - 1.057\ln(g)$ <u>(0.261) (0.103) (0.049) (0.049)</u>
	S1-B3	$\ln(y) = 1.272 + 0.999\ln(w) - 1.156\ln(v)$ <u>(0.171) (0.063) (0.036)</u>
	S2-B1	$\ln(y) = 3.388 + 1.082\ln(w) - 1.224\ln(v) - 1.119\ln(g)$ <u>(0.298) (0.114) (0.044) (0.044)</u>
	S3-B1	$\ln(y) = 0.993 + 1.053\ln(w) - 1.051\ln(v)$ (0.199) (0.077) (0.024)
t_p	S1-B1	$\ln(y) = 6.635 - 0.936\ln(w) + 0.981\ln(g)$ <u>(0.319) (0.117) (0.068)</u>
	S1-B2	$\ln(y) = 7.210 - 1.050\ln(w) + 1.001\ln(g)$ <u>(0.273) (0.100) (0.057)</u>
	S1-B3	$\ln(y) = 8.936 - 0.973\ln(w)$ <u>(0.195) (0.079)</u>
	S2-B1	$\ln(y) = 6.925 - 0.993\ln(w) + 1.053\ln(g)$ <u>(0.348) (0.139) (0.053)</u>
	S3-B1	$\ln(y) = 9.126 - 1.074\ln(w)$ (0.161) (0.065)

OBS: (1) In blocks S1-B3 and S3-B1, gap width is not used as a variable.
(2) Numbers in brackets are the standard deviation estimates of the regression coefficients.

Table 5.26 Statistical parameters and comments related to MODEL C equations (table 5.21).

Resp.	Exp. block	R ² (%)	MSE	DF	SigF	Comments
A _d	S1-B3	S1-B1	98.7	5.0E-4	2/15	0.0000
		S1-B2	97.2	9.6E-4	2/12	0.0000
		99.3	2.5E-4	2/7	0.0000	Points 1 and 14 dropped from model.
		S2-B1	98.5	6.5E-4	2/18	0.0000
		S3-B1	99.5	3.1E-4	2/13	0.0000
h _{mean}	S1-B3	S1-B1	97.4	1.6E-3	3/14	0.0000
		S1-B2	98.2	1.1E-3	3/11	0.0000
		99.5	2.2E-4	2/7	0.0000	Points 1 and 14 dropped from model.
		S2-B1	98.9	7.3E-4	3/18	0.0000
		S3-B1	99.4	4.2E-4	2/13	0.0000
t _p	S1-B3	S1-B1	95.5	5.2E-4	3/14	0.0000
		S1-B2	97.2	9.6E-4	2/12	0.0000
		95.0	2.5E-4	2/7	0.0000	Points 1 and 14 dropped from model.
		S2-B1	96.1	4.0E-4	3/17	0.0000
		S3-B1	95.2	2.9E-4	1/14	0.0000

OBS: DF - Degrees of freedom (Regression/Residuals).

SigF - Significance of F statistic.

MSE - Mean square sum of errors.

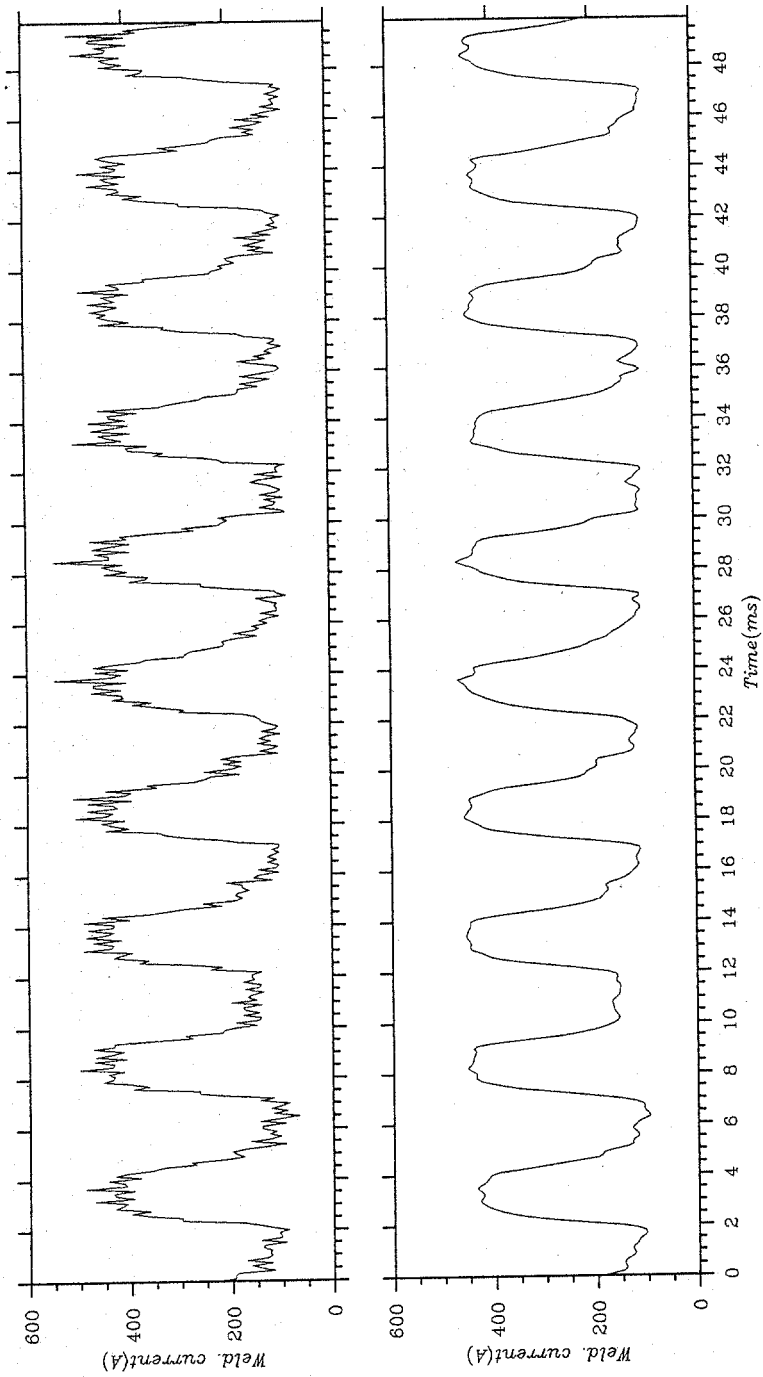


Figure 5.1

Effect of the software filtering routine on the welding current trace. Top: original data. Bottom: filtered data.

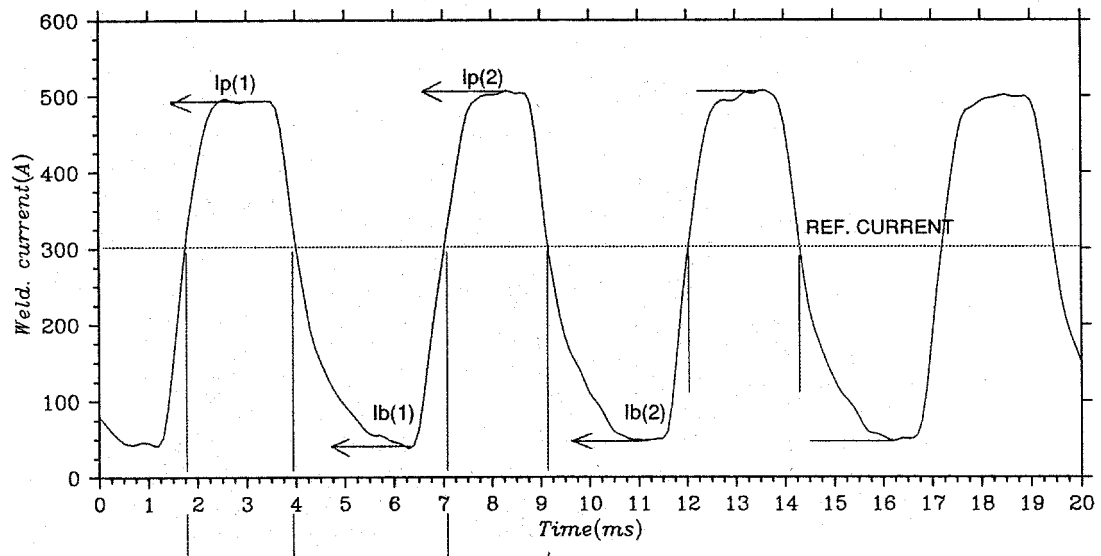


Figure 5.2 Procedure used in the software to calculate current peak and base parameters.

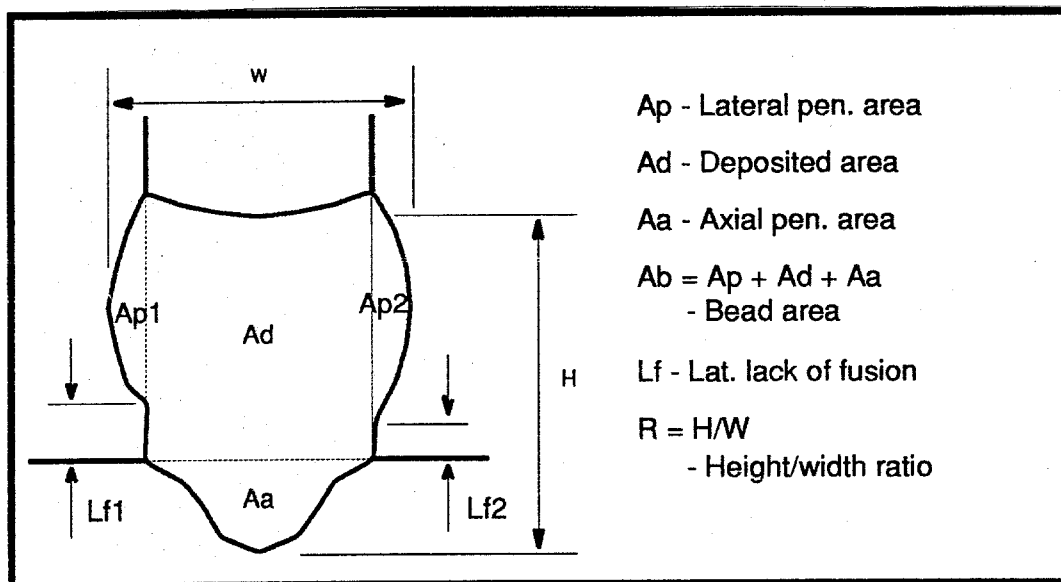


Figure 5.3 Definition of bead, deposited, lateral penetration and axial penetration areas.

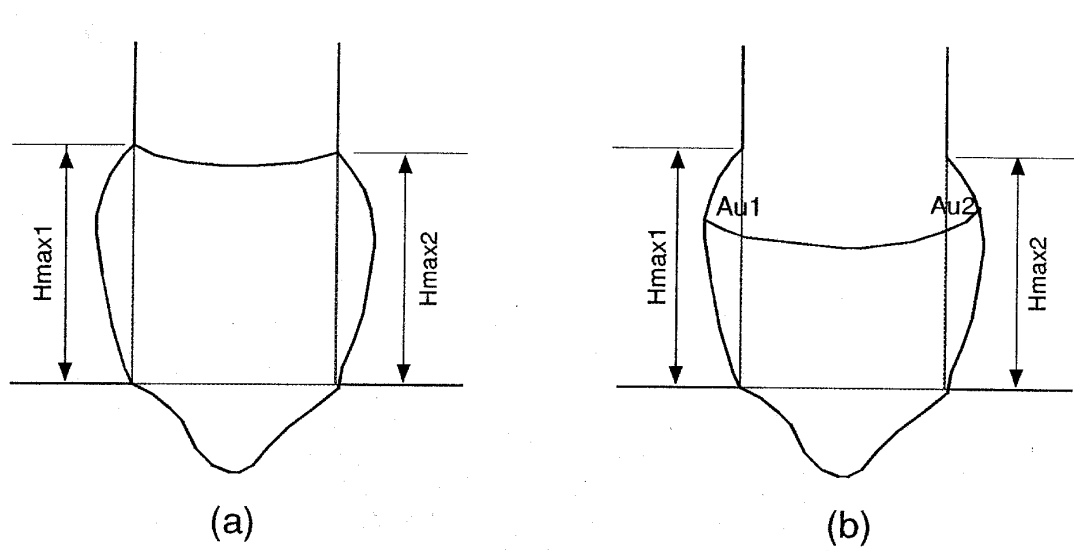


Figure 5.4 Definition of maximum arc action height (h_{max}) for weld beads with (a) and without (b) undercutting. Undercutting area (A_u) is also shown in (b).

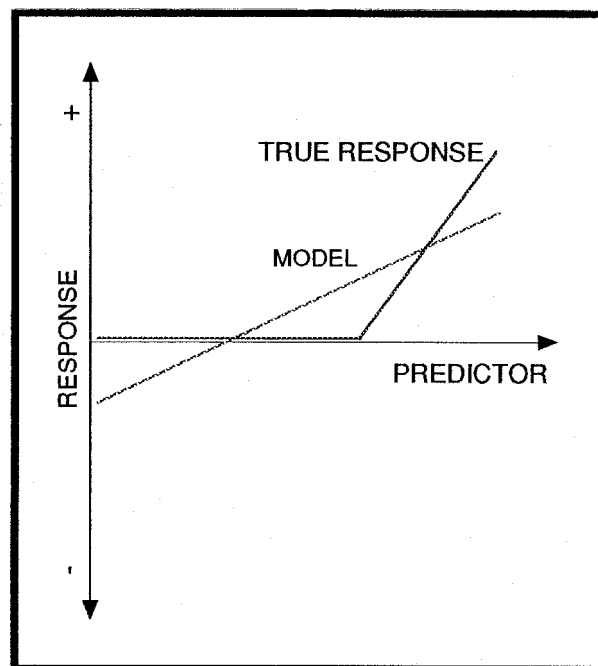


Figure 5.5 Schematic representation of the inconvenience in using undercutting area to directly model the undercutting tendency in a weld process.

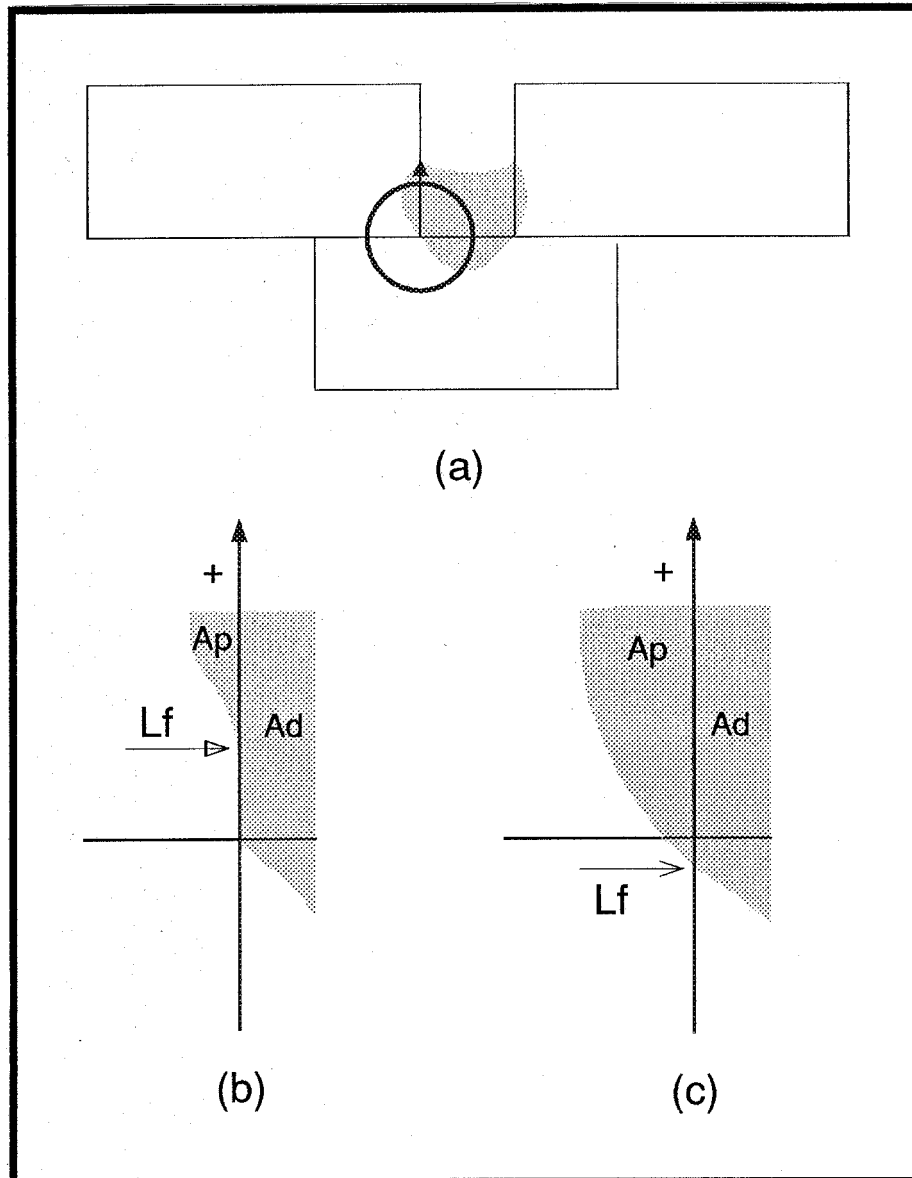
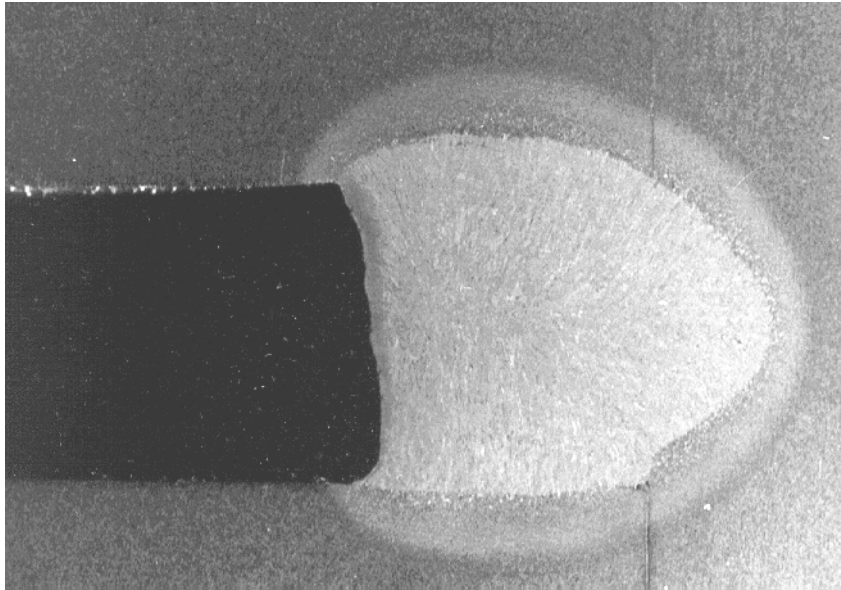
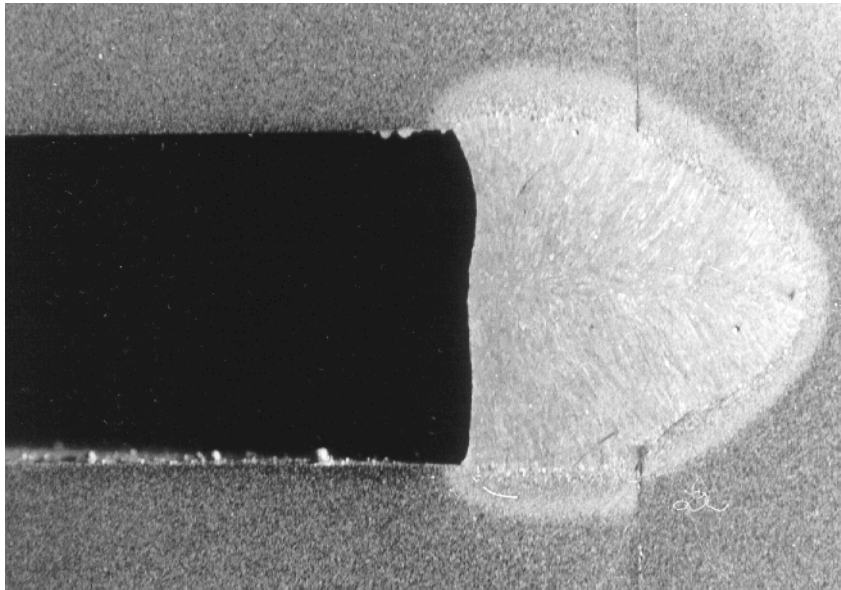


Figure 5.6 Convention adopted to define and measure lateral lack of fusion. (a) Transverse section of a welded specimen. Magnified views of the region enclosed by the circle in (a), with the estimated values of l_f , are shown in (b) and (c), for weld beads with positive and negative lack of fusion respectively.



(a)



(b)

Figure 5.7 Weld bead macrosections of horizontal-vertical welds performed with welding speeds of (a) 6mm/s and (b) 10mm/s. Magnification: 6X.

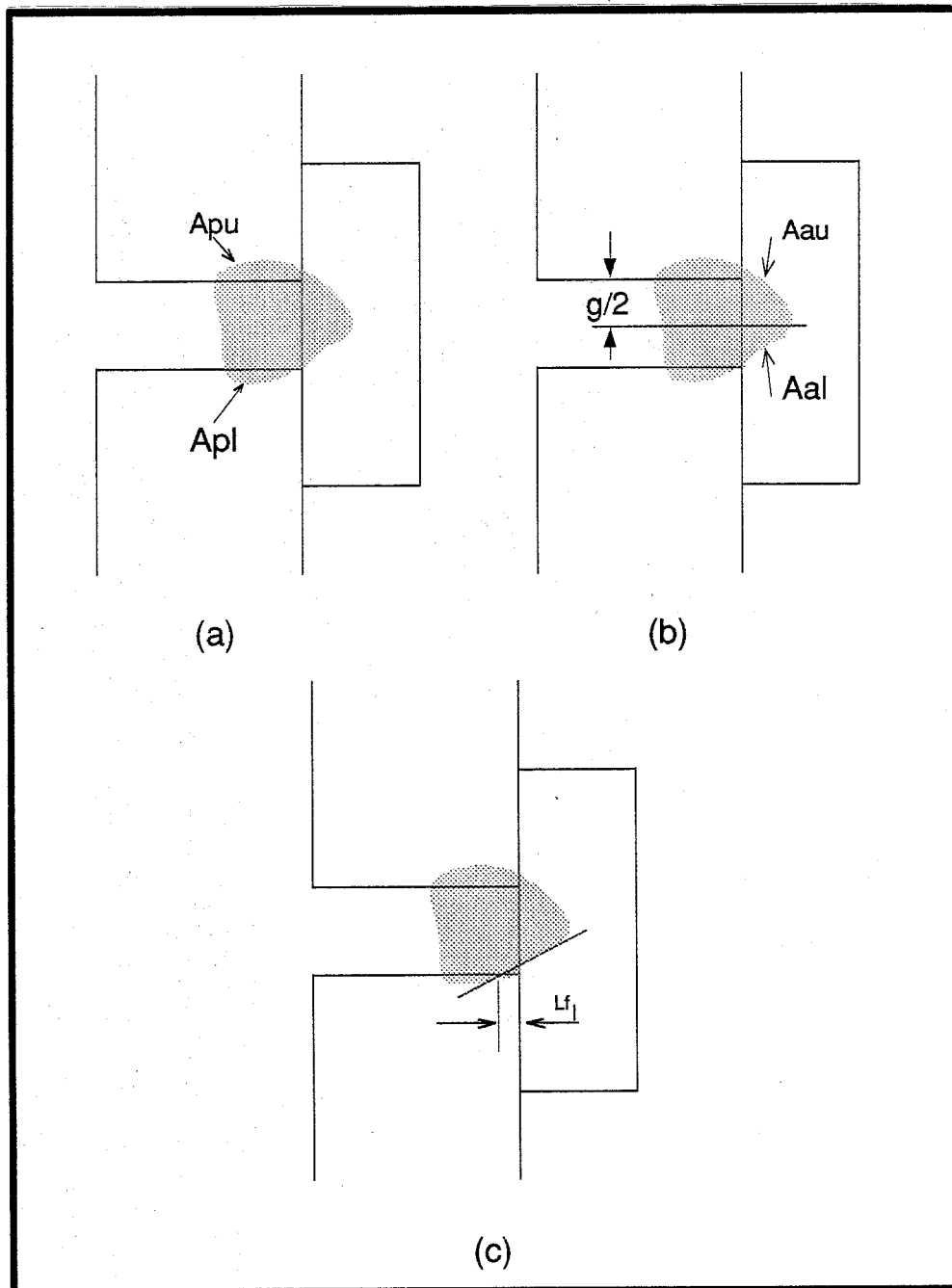


Figure 5.8 Definitions of upper and lower side lateral penetration areas (a), upper and lower axial penetration area (b), and lateral lack of fusion in the lower side wall (c).

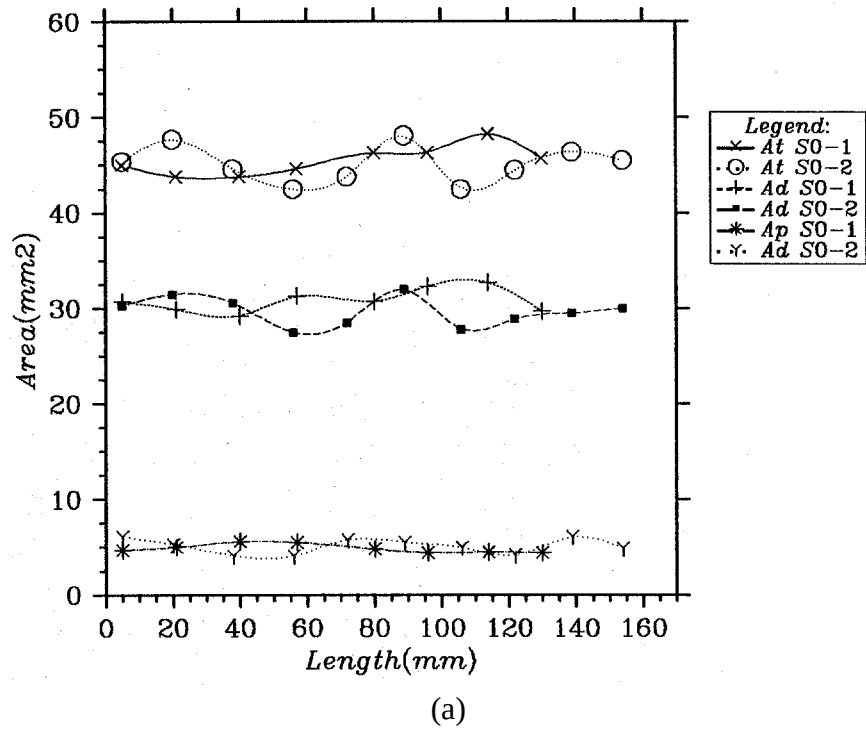
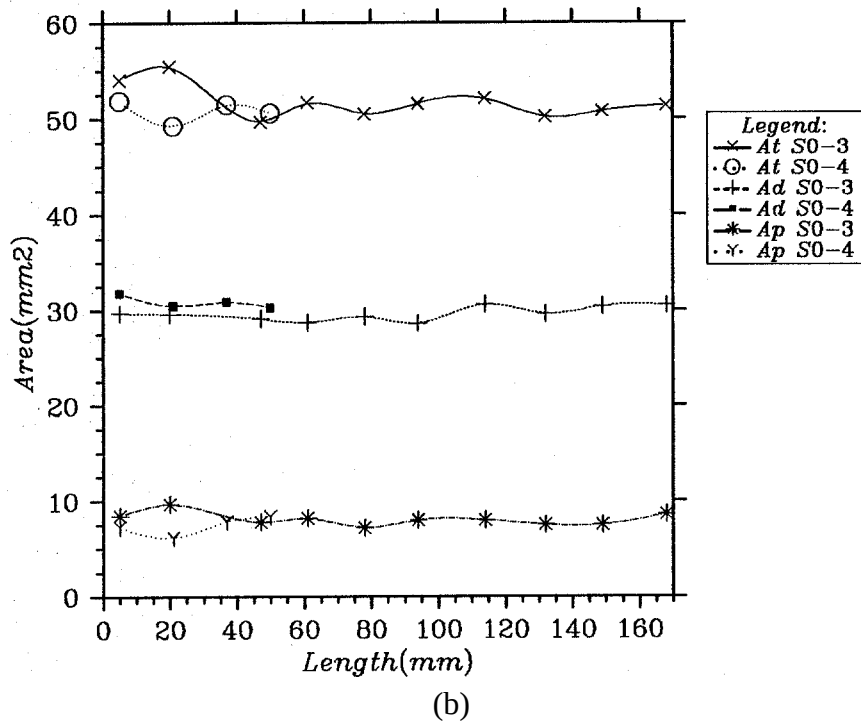
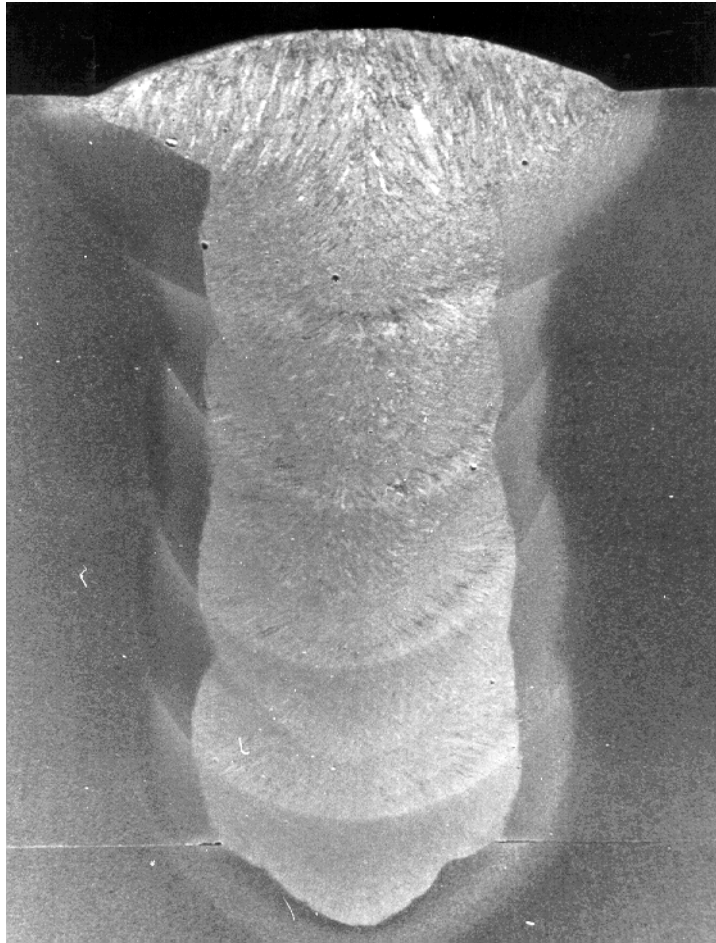
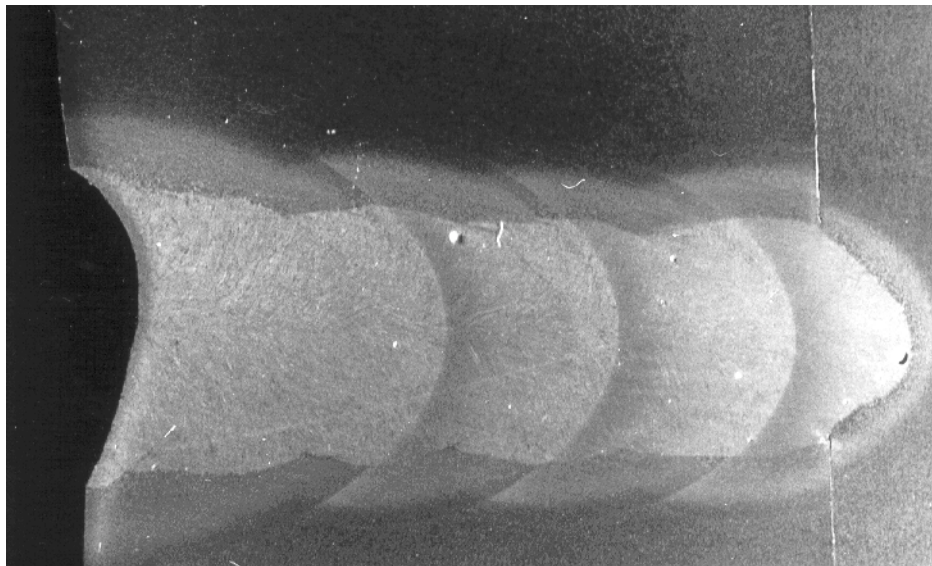


Figure 5.9

Variability of bead area (A_t), deposited area (A_d) and lateral penetration area (A_p) along the bead length for narrow gap specimens welded with Ar-5 (a) and He-1 (b), experimental step S0.



(a)



(b)

Figure 5.10 Macrosections of multipass downhand (a) and horizontal-vertical (b) welds. 5X.

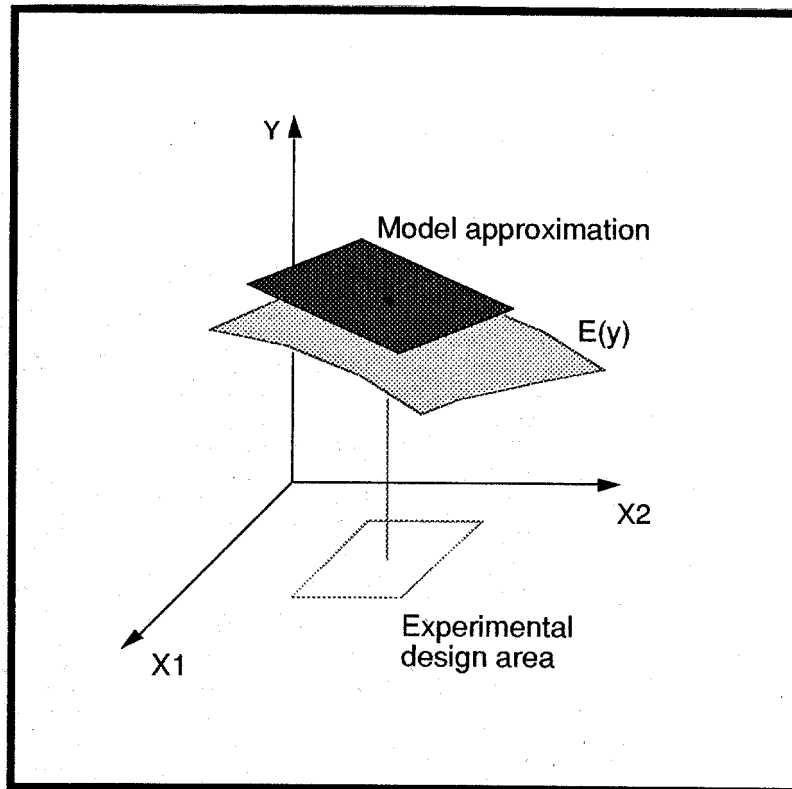


Figure 5.11 Schematic representation of a linear model being used to represent locally a more complex relationship $E(y)$ between a response y and the predictors x_1 and x_2 .

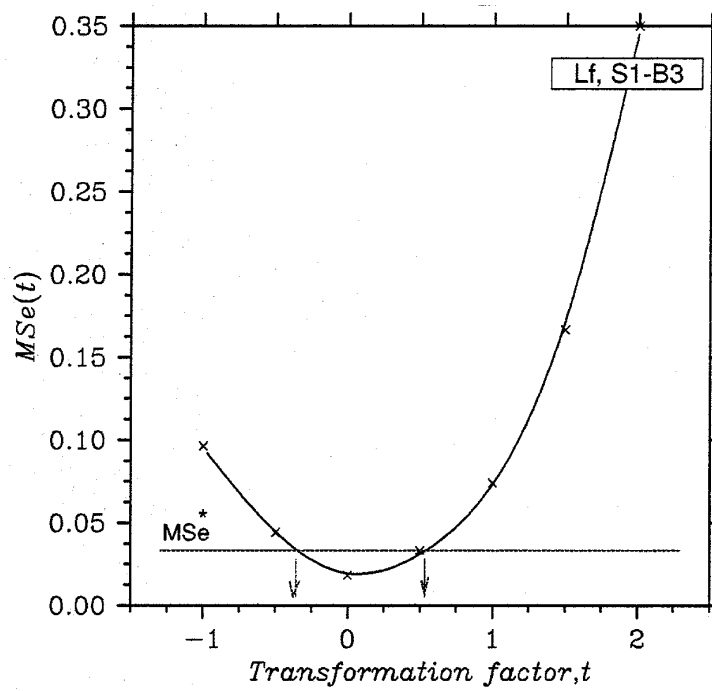


Figure 5.12 Graphical procedure to determine the confidence interval of t .

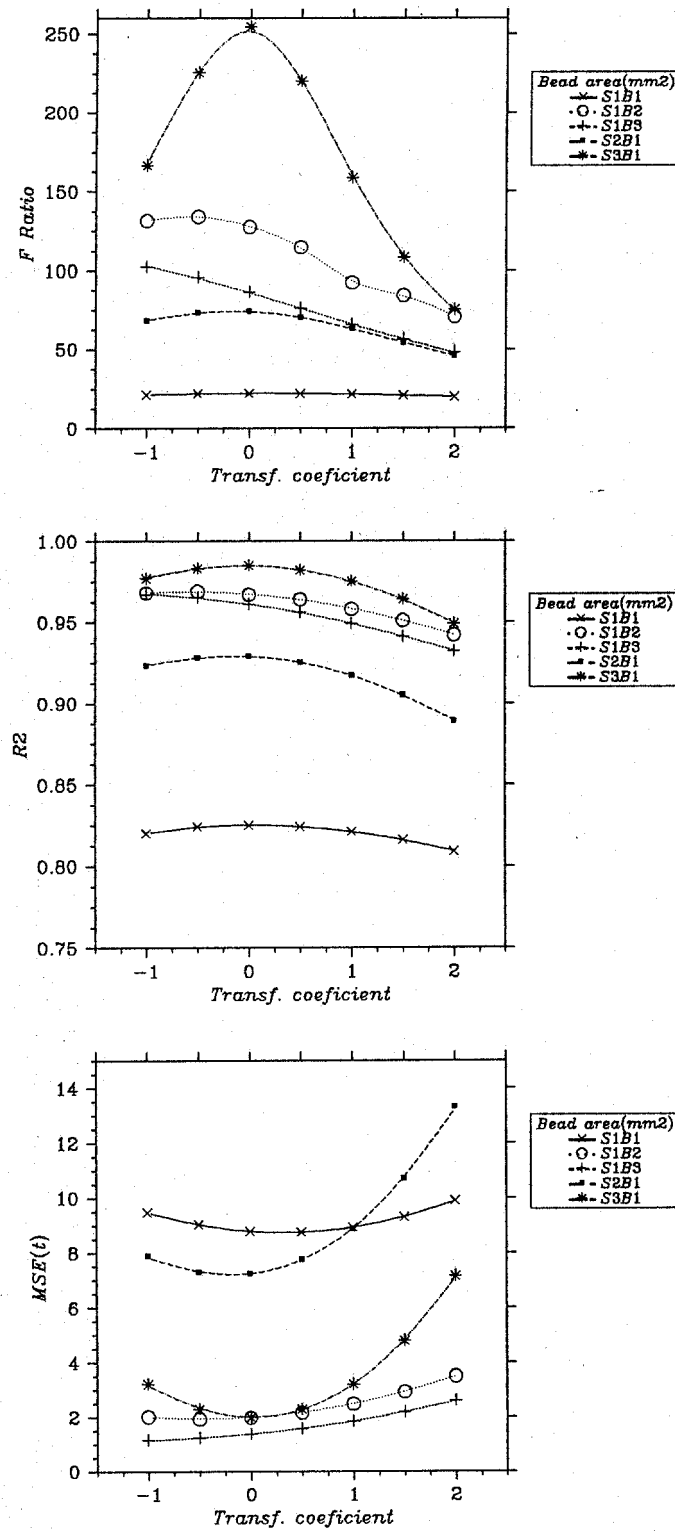


Figure 5.13

Variation of the F ratio, R^2 and MSE_t statistics with the transformation factor t for bead area models.

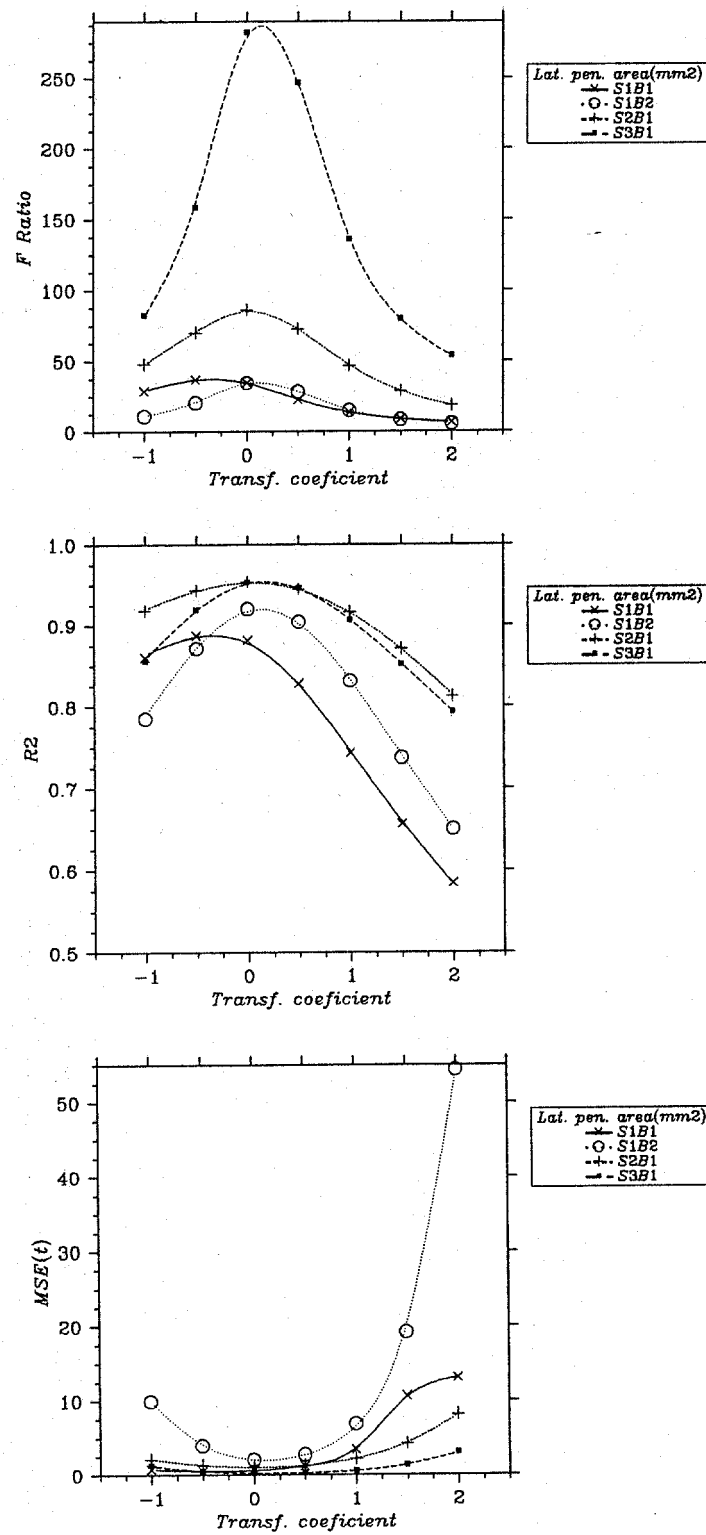


Figure 5.14

Variation of the F ratio, R^2 and MSE_t statistics with the transformation factor t for lateral penetration area models.

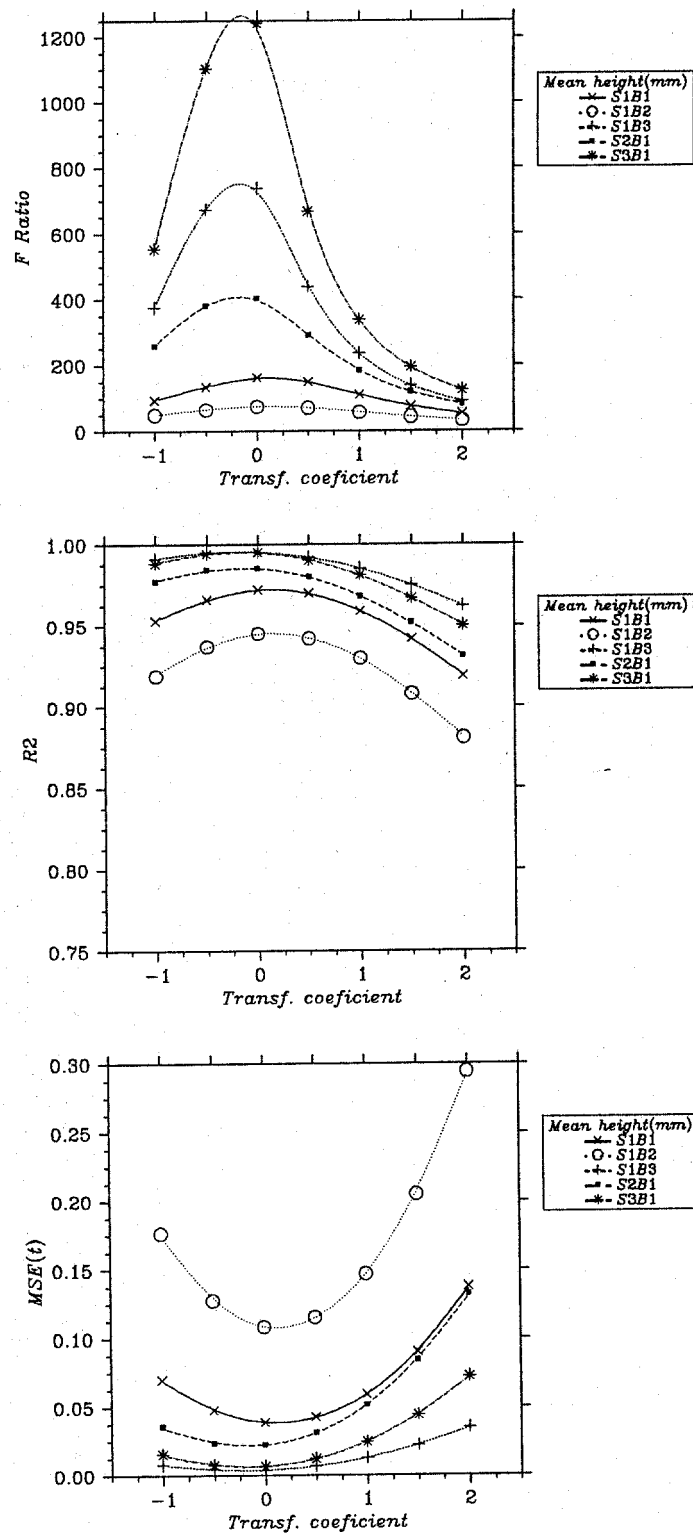


Figure 5.15 Variation of the F ratio, R^2 and MSE_t statistics with the transformation factor t for mean bead height models.

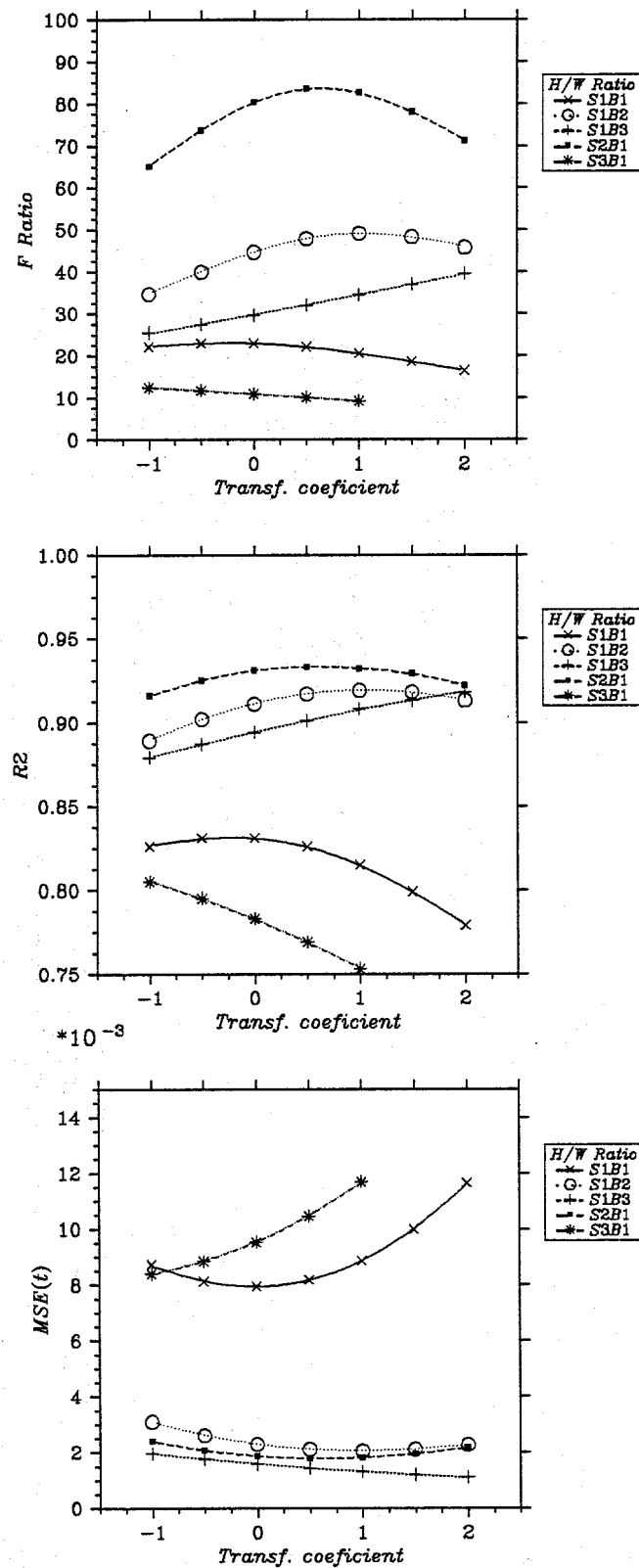


Figure 5.16

Variation of the F ratio, R^2 and MSE_t statistics with the transformation factor t for H/W ratio models.

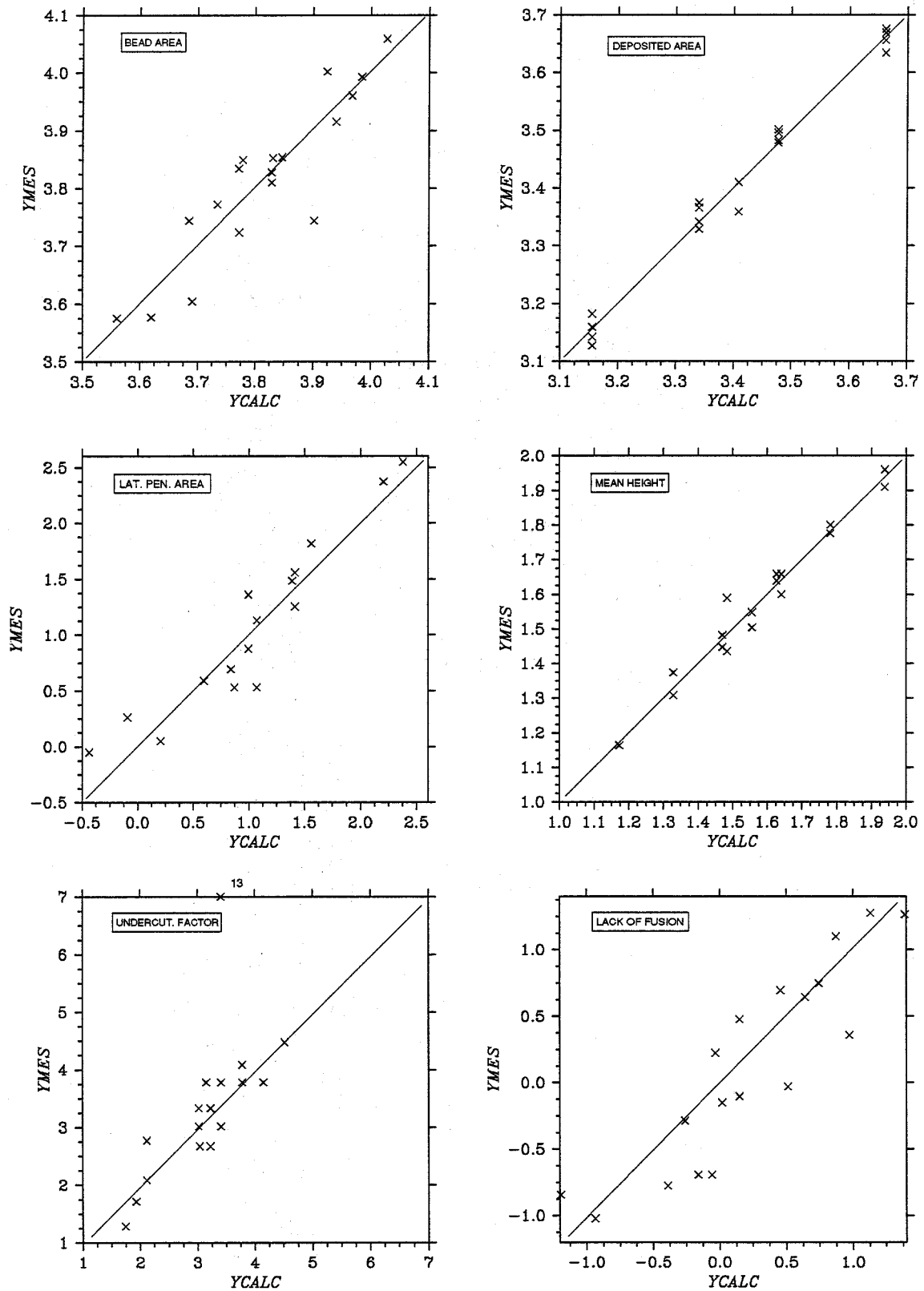


Figure 5.17 Predicted value plots of MODEL A equations for some responses of S1-B1.

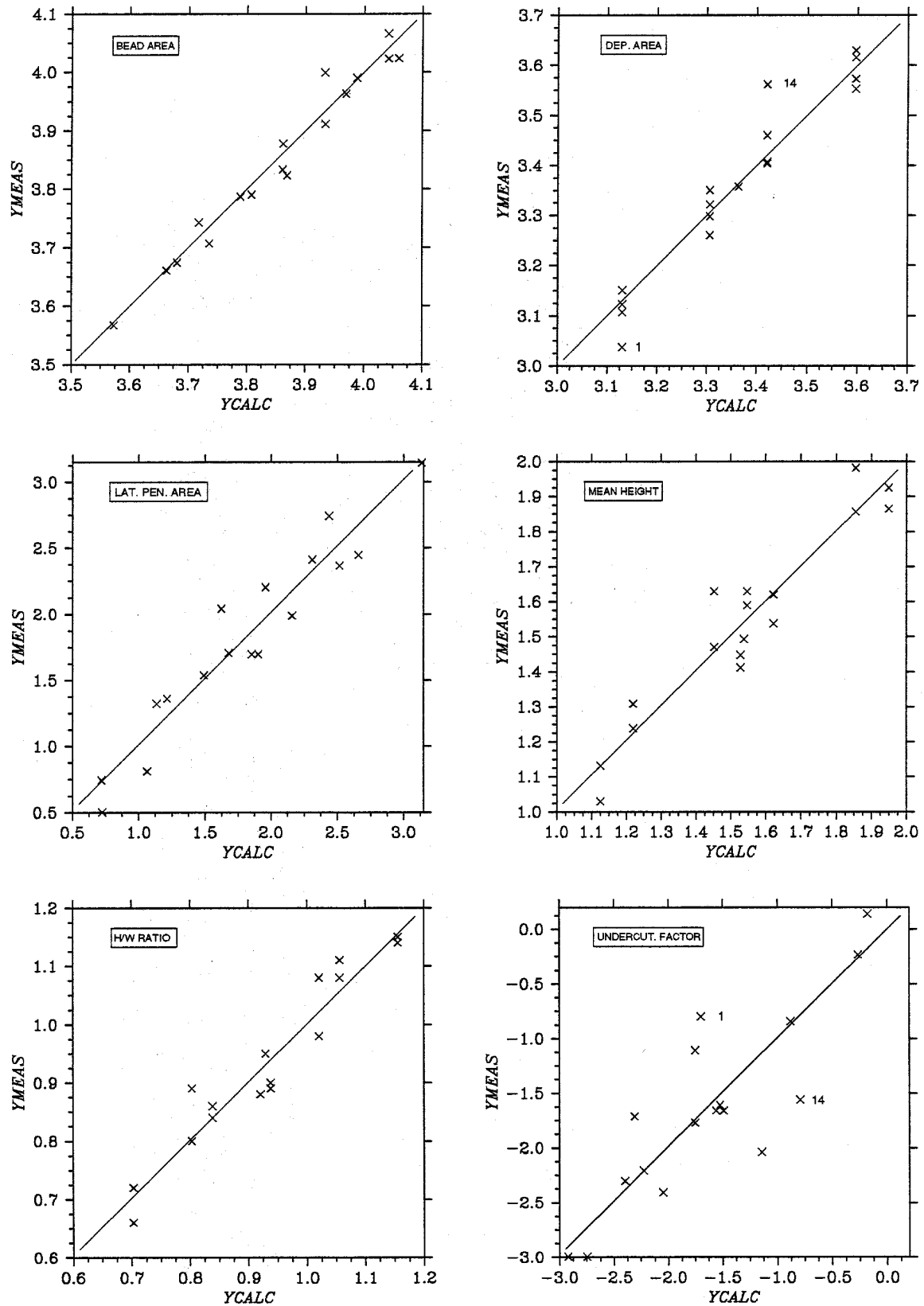


Figure 5 18 Predicted value plots of MODEL A equations for some

Figure 5.18 Predicted value plots of MODEL A equations for some responses of S1-B2.

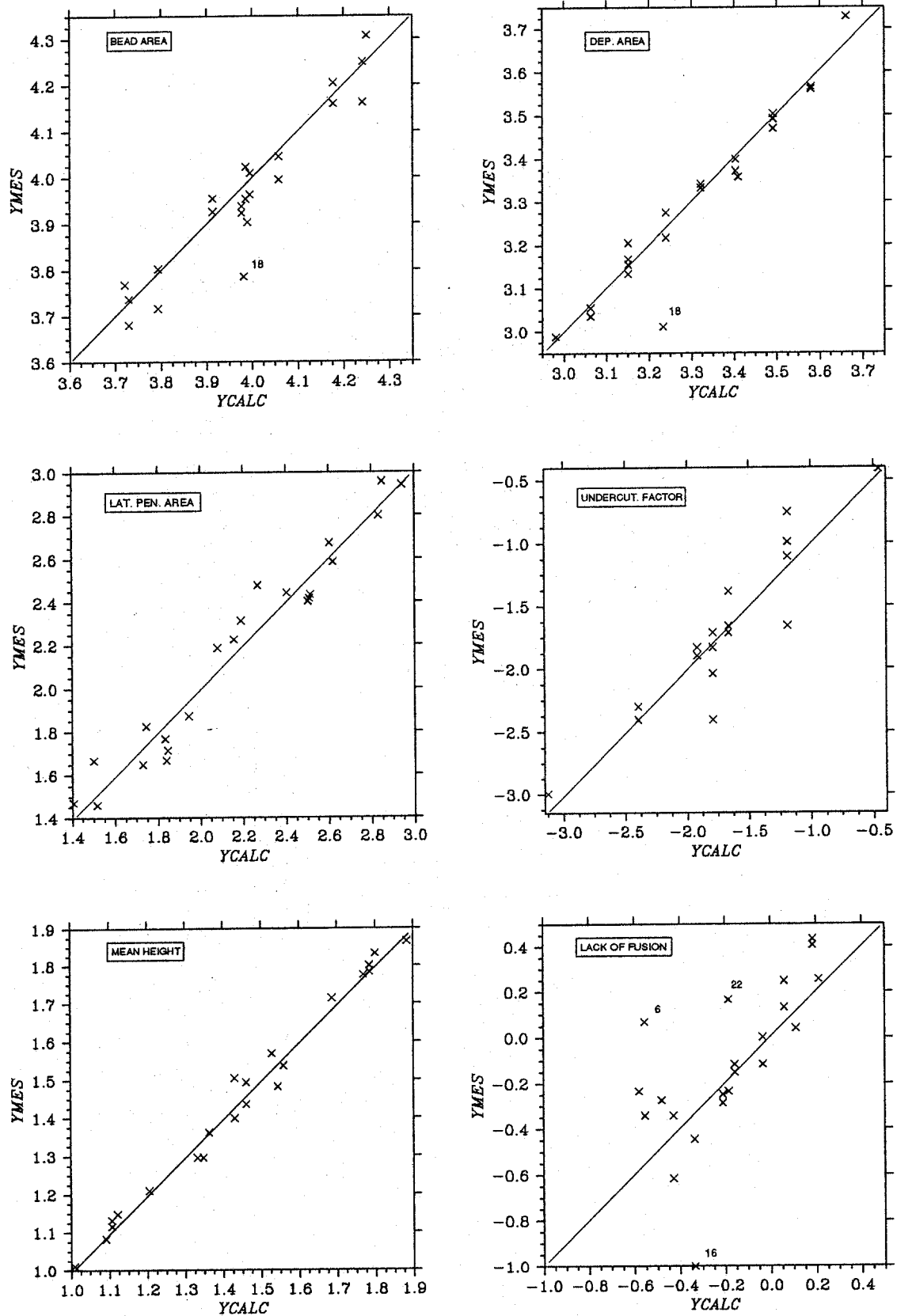


Figure 5.19 Predicted value plots of MODEL A equations for some responses of S2-B1.

CHAPTER 6

6. Analysis of results and discussion

6.1. Assessment of experimental and modelling techniques

6.1.1. Experimental design

In general, the expected value of a response considered of interest for welding or any other process can be often described by some sort of function F that depends on a number of input variables or parameters:

$$y = F(x_1, x_2, \dots, x_t) \quad [6.1]$$

Where x_i , $i=1, t$, is a subset of an ideal collection of "all possible parameters of the process". Unfortunately, both F and the subset x_i are often partially or completely unknown and their determination may not be simple, or even possible, in some cases. In order to find F , basic physical principles should be applied to the situation encountered in the welding system and a solution found. However, developing such a model in a comprehensive way for a complex welding process can be a rather difficult task. Compromise solutions can be frequently worked out by making simplifications of the initial assumptions. Although such approach has greatly helped the understanding of physical phenomena in welding processes and despite enormous recent progress in this area, direct application of theoretical principles to a welding system is still mainly limited to general aspects of the process and has found only partial success in modelling a concrete welding application.

Empirical model building has been used as an alternative to the theoretical approach to study welding processes, particularly if it is desired to approximate the response only over limited ranges of the input variables. By assuming that the corrected form of F is unknown, this approach attempts to develop a model of the form:

$$y = G(x_1, x_2, \dots, x_p) \quad [6.2]$$

Where G is an arbitrary function that is generally much simpler than F and x_i , $i=1, p$, is a set of input variables not necessarily identical to the one associated with F . Often, the model above is based almost completely on information contained in data from actual welding trials. Consequently, an empirical model actually represents the data it is derived from, and adopting it to represent a system implies assuming that the available data represent that system well.

Therefore, a close link should exist between data collection and model formulation. In this sense, statistical techniques provide a powerful tool for both model building and design of the experiment. The former use of statistics has been applied to welding problems for a long time while the latter has only recently been more commonly applied. A properly designed experiment can greatly help to reduce confusing effects from experimental error, detect the presence of complex effects of input variables on the response and provide a more sound basis for deducing cause-and-effect relationships from the experimental data. Factorial design is a statistical experimental technique that is extensively used in industrial experimentation and has recently proven suitable to the study of welding problems (§2.4.3.2).

In the present programme, the experimental work was initially intended to be designed as factorial experiments. However, due to the complex interaction that can exist between input variables, including joint geometry and power supply characteristics, this approach soon presented difficulties in terms of guaranteeing stable welding conditions for all experimental trials within a factorial block. This represented a limitation of the technique because the whole experiment is run as a block and the presence of one or more abnormal points can strongly affect and distort the data analysis step. Therefore, a proper selection of input variable levels that provide representative welding conditions is extremely important but a frequently difficult or even impossible task. The knowledge necessary for this selection is not always completely available at the moment of design and, in many situations, this is one of the goals of the experiment. Running an initial set of experimental trials can provide valuable guidance to establish the experimental area, however, this will inevitably add more steps to the experimental programme and increase its cost.

Furthermore, stable welding conditions will often be naturally linked with a strong interdependence between some of the input variables and that will complicate the application of factorials. For instance, if current and voltage are both to be set at "low" and "high" levels in a factorial experiment, it may possibly happen that operational conditions will be adequate for $(V_{\text{low}}, I_{\text{low}})$ and $(V_{\text{high}}, I_{\text{high}})$ trials but difficulties can be expected in running both $(V_{\text{low}}, I_{\text{high}})$ and $(V_{\text{high}}, I_{\text{low}})$ trials if the difference both in I and V between the "high" and "low" levels is sufficiently high. Reducing the difference between levels could increase the possibility of generating stable operational conditions for most of the trials. Unfortunately this would also increase the relative participation of the experimental error in the data. Another alternative would be to run the factorial with some of the input variables transformed into more suitable formats, for instance the use of the ratio (V/I) instead of I and V separated. This may, however, complicate interpretation of the final model.

In the present programme, a truly factorial scheme was substituted, in experimental steps S2 and S3, by an experimental design where not all of the input variables were perfectly orthogonal with some of the others in order to adjust the experiment to the natural requirements of the process. While this approach may complicate later data analysis by introducing some collinearity into the model, distortion of the initial factorial experiment was limited to those variables in which previous results had indicated the necessity of this adjustment.

6.1.2.Data analysis

The selection of the initial set of candidate input variables to be included in model building may have a profound influence in the final form of the model. For instance, in experimental step S1, a first modelling exercise was performed using pulse frequency (F), wire feed rate (w), welding speed (v) and gap width (g) as initial variable candidates. The resulting model for arc length in S1-B1 after variables selection was:

$$\ln(l_a) = 2.210 + 0.015F - 0.29w - 0.11g \quad [6.3a]$$

which detected a significant effect of gap width on arc length. Later work using slightly different initial variable candidates (mean current, wire feed rate, welding speed and gap width) did not detect any influence of gap width. At least two hypotheses may be presented in order to explain this apparent discrepancy. Firstly, the weld pool level can be considered to be raised by the constraining effect of the joint side walls resulting in an apparent decrease in standoff distance. This effect would be inversely proportional to the gap width and, in association with the constant voltage operation of the power supply during peak period, would cause an increase in current and arc length. Alternatively and more probably, the interaction between joint geometry and power supply characteristic (see §6.4) could explain an increase in both current level and arc length for the narrower gap operation. In both cases, the influence of gap in arc length would be associated with variations in welding current.

Therefore, when current was included as an initial variable candidate and selected as a significant factor to describe arc length variation, it incorporated in the model most of the information that was associated in the previous equation with gap width which was then not considered significant by the variable selection routine. Compared with the initial equation, the latter one,

$$\ln(l_a) = 1.065 + 0.0199I - 0.456w \quad [6.3b]$$

does not apparently reflect the interaction between power supply characteristic and joint geometry. The initial input variable set containing welding current and wire feed rate was adopted and used in the present work for all response variables, even though this selection is not the most commonly employed in welding research where current and voltage are more often preferred. Among the reasons for this choice, it can be mentioned the determination of simpler models for some responses and the fact that current and wire feed rate were the variables directly controlled in the two last experimental blocks.

The selection of an initial set of predictor variables depends on many factors, some of them of a subjective nature such as motivation and the experience of the researcher. Many different alternatives may be possible and equally suitable. One important consideration is to avoid whenever possible the situation in which collinearity problems are incorporated in the predictors set with the result that they would greatly affect data analysis and result in a model that, although fitting the experimental data well, may have very little connection with the real system. The close link between final model form, initial predictors set and experimental design is a basic characteristic of statistical modelling. The consequence is that results of empirical models tend to be very specific and extrapolation to other systems should be done very cautiously.

In the present programme, data analysis was made up of four inter-related steps: selection of dependent variable transformation, selection of the "best" subset of input variables, model fitting and model diagnosis (§5.3). Transformation was found to be an important measure to improve modelling results with few of the final equations (Model A) being developed on the original, untransformed responses (i. e., with a transformation factor of one). The resultant modelling equations with transformed response tended to be simpler and easier to interpret than alternative models with included interaction between input variables (model B). In general, the first three modelling steps can be fairly well automated by means of modern statistical software packages. However, the forth step is, in its simpler and more usual form as employed here, strongly dependent on the visual interpretation of plots and, therefore, a package that provides good interactive facilities at some stages of the process can result in a more efficient tool than a fully automated one.

6.2.Bead characteristics

A large number of parameters were defined and used to characterize weld bead geometry and defect formation in the present work. A direct analysis of all these parameters across five different experimental blocks would result in a very lengthy and confusing process. Therefore, in an attempt to simplify the analysis of results, a three-step approach was

followed. In a first step (present section), general weld bead characteristics were grouped into three classes before being analysed by studying the main features of their modelling equations. A graphical approach to represent process operation characteristics was developed and analysed in section §6.3. Finally, aspects relevant to horizontal-vertical welding will be discussed in section §6.4.

The weld bead is formed by material provided from two sources: (a) filler metal (wire) and (b) melted portions of the workpiece. Now, most of the parameters introduced in the present work can be related to one of these sources of material and, based on that, a classification can be worked out to systematize their analysis:

- . Bead parameters related with wire fusion: Deposited area (A_d), mean bead height (h_{mean}), and production time (t_p).
- . Bead parameters related with plate fusion: Lateral penetration area (A_p), axial penetration area (A_a), and lateral lack of fusion (l_f).
- . Bead parameters related with both sources: Bead area (A_t), H/W ratio (R) and undercutting factor (f_u).

6.2.1. Bead parameters related with wire fusion

All parameters included in this group can be alternatively represented by simple theoretical expressions based on mass balance between melting rate and deposited area (equation [5.12]). This predicted simple behaviour is reflected in the statistical models by a very good fit of the experimental data and by the absence of a current term in the equations (table 5.21 and 5.25) for a initial set of input variables that includes w , v and g . In particular, model C type equations for A_d and h_{mean} approximate well to their theoretical counterparts. For instance, the mean value of the coefficients for w and v empirically obtained for deposited area expressions in the five experimental steps are respectively 1.039 and 1.074, very close to the expected value of one. Therefore, the assumptions of the mass balance model and the experimental conditions appear to be both satisfactory as far as this class of bead parameter is concerned.

By comparing the constant term of the theoretical expression for A_d (equation [5.13]) with its empirical values, the expected wire diameter (d_{we}) for each experimental step can be calculated by:

$$d_{we} = [(4/k'\pi)\exp(a_0)]^{1/2} \quad [6.4]$$

where k' is a constant related with the measuring units and equal to $16.7(\text{m.s})(\text{mm.min})^{-1}$. Values for d_{we} calculated by this method are presented in table 6.1. The mean of the estimated values for all experimental steps agrees rather well with the measured wire diameter (1.18mm). However, individual results reveal a large scatter and, if they are used to calculate metal losses (δ_m) of the process by:

$$\delta_m = 100[1 - (d_{we}/d_w)^2], \quad [6.5]$$

metal additions (i. e., $\delta_m < 0$) of over 20% are predicted. Such discrepancies are, however, explained by an inadequate use of the empirical model. Equation [6.4] was obtaining by setting $\ln(w)$ and $\ln(v)$ to zero in the empirical model which corresponds to a very large extrapolation from the conditions used in the experimental blocks. A more adequate expression would be:

$$d_{we} = [(4/k'\pi)A_{dC} \cdot v_C/w_C]^{1/2} \quad [6.6]$$

where v_C and w_C are values of v and w corresponding to the central point of the experimental design, which is the point where a minimum in the variability of the predicted values of A_d is expected, and A_{dC} is the calculated deposited area at this location. Calculated values of d_{we} are shown in table 6.2. The individual results match rather well with the measured wire diameter and suggest metal losses under 10% for all experimental steps.

As expected from the mass balance equation, modelling expressions for production time depend significantly only on wire feed rate and gap width. Figure 6.1 presents surface plots of production time for experimental blocks S1-B1, S1-B2 and S2-B1. The results from the different blocks are rather similar, the small differences being probably associated with metal loss levels (table 6.2). The results also agree well with those estimated by Fennel (1986) who expected a time of 145s to weld a 325mm diameter pipe with a 20mm thick wall using a four head GMAW system and a 6-8mm gap.

The simple format, good precision and uniformity amongst experimental blocks of the modelling equations of this section are closely related to the set of initial input variables adopted and the simple underlying physical model that could be associated with A_d , h_{mean} and t_p . Should a different set of initial input variables be selected so that more complex processes would have to be reflected in any model linking input and response, the final models would probably be less uniform and precise.

6.2.2. Bead parameters related to plate fusion

6.2.2.1. Introduction

In opposition to the group of parameters discussed above, parameters that are related with plate fusion will more probably depend on how energy from the arc is transferred to the workpiece and cannot be represented by a simple mass balance model. As this can be expected to depend on complex interactions of different factors, many of them not well understood, the resulting statistical models are likely to be more complicated and less precise than the previous ones. Dissimilarities between statistical modelling equations for a given response may provide an indication of differences in process characteristics.

Different mechanisms, such as heat conduction in the workpiece (Christensen et al. 1965, and Quintino 1986), fluid flow in the weld pool (Szekely 1986), impingement of liquid drops of filler metal on the workpiece (Essers and Walter 1979) and arc pressure (Halmoy 1979) have been associated with and may play a role in plate fusion and penetration. In bead-on-plate GMA welding, plate fusion is characterized by two distinct overlapping regions: (a) a more or less central finger region, which is generally associated with one or both of the two latter mechanisms, and (b) a shallower and approximately elliptic bath formed possibly by heat conduction in a liquid layer. Finger penetration generally dominates in argon shielded GMAW, but the relative importance of the two regions varies with current, voltage, travel speed, gas composition, etc (Gurev and Stout 1963).

In NGW, fusion of the workpiece is more complex because, unlike bead-on-plate or even groove welding, it is necessary to provide penetration not in one only direction (under the weld pool), but in three different ones, including both sidewalls (Malin 1987). Sidewall fusion is more probably associated with radial heat diffusion from the arc column and may be affected by arc length and voltage as confirmed by some authors (Kurakawa et al. 1966, Belchuk and Titov 1970, and Matsunawa and Nishiguchi 1979).

In bead-on-plate welding, it is well established that, at low travel speeds, the liquid volume in the pool can be so high that it tends to flow under the arc cushioning the base metal and impairing its fusion. A critical travel speed has been found by Quintino for pulsed GMAW at around 1-3mm/s below which plate penetration is greatly reduced. A similar critical speed can be expected for NGW conditions which should be displaced to higher travel speeds due to the confining effect of the side wall on the weld pool (Matsunawa and Nishiguchi 1979).

6.2.2.2. Modelling results

Modelling equations for lateral penetration area (A_p) presented the same general form, including the same response transformation, in all experimental blocks that yielded a significant model. However, important differences in terms of the final set of significant input variables were found for experimental block S3-B1 which were performed in the horizontal-vertical position. In the downhand position, A_p increased with current while decreasing with wire feed rate, welding speed and gap width as shown by the coefficients of its modelling equations (table 5.21) and by its surface plots (figure 6.2). The direction of maximum increase for a response adequately represented by a model A type equation, in the plane defined by welding current and wire feed rate (I, w), is parallel to the vector $\mathbf{m}_{I,w}$:

$$\mathbf{m}_{I,w} = (1, \alpha_{I,w}) \quad [6.7]$$

where $\alpha_{I,w} = a_w/a_I$ (in Am^{-1}min) is the ratio between the regression coefficients for w and I in the modelling equations. Calculated values of $\alpha_{I,w}$ for A_p , voltage and arc length are shown in table 6.3. These values are relatively close indicating that a good correlation between A_p , V and l_a may be expected and this is further supported by the similarity of surface plots for A_p (figure 6.2), V and l_a (figure 6.3). Therefore, both V and l_a can be expected to significantly influence lateral penetration as would be expected if lateral fusion is determined mainly by radial heat transfer for the arc.

In a manner similar to results from other authors (for instance, Foote 1986 and Jackson and Sargent 1966), lateral penetration tended to be greater for those experimental blocks that used a helium based shielding gas. No significant improvement in lateral fusion could be associated with higher CO_2 contents for argon based shielding mixture by comparing experimental blocks S1-B1 and S1-B3. Results also suggest that, in argon based shielding, regression coefficients in the equation for A_p for both current and wire feed rate are significantly greater (in module) than those for helium based shielding. As a result, lateral fusion of the joint can be expected to be more sensitive to changes in current and wire feed rate in argon based shielding.

Although modelling results for lateral lack of fusion (l_f) were generally poorer in terms of standard of fit than those for A_p , both parameters tended to be influenced by current and wire

feed rate in a comparable way but in an opposite direction (figure 6.4). Therefore similar correlations between l_f and V or l_a may also be expected.

For downhand position operation, welding current and gap width are the main input variables controlling axial penetration area, A_a (figure 6.5). A_a increases with g possibly by a reduction in the confining effect of the side walls on the molten weld pool. In similar operational conditions, argon based shielding gases tended to present greater A_a , and this may be associated with a more intense finger action with this shielding gas composition.

An analysis of the general aspects of plate fusion indicates that, among the shielding gas compositions tested in the narrow gap experimental blocks, those employing high helium content show improved lateral fusion of the workpiece as indicated in terms of both A_p and l_f . Results also suggest that improved plate fusion characteristics can be associated with steady direct current operation. In pulsed current operation (particularly with high peak currents), wire melting rate tended to be higher than in steady current operation due to the higher joule heating of the wire (§2.2.4). This difference can be partially explained in terms of the effect of w on the volume of the molten pool. However, even if this effect is discounted by overlapping the areas of similar operational conditions in the surface plots of figures 6.2, 6.4 and 6.5, welds using steady current (block S2-B1) will still generate higher plate fusion in both lateral and axial directions than a similar block that operated with pulsed current (S1-B2). This is a different behaviour from that commonly reported in the literature for bead-on-plate welding (Foote 1986, Quintino 1986, and Maruo and Hirata 1982) which indicates only minor differences in plate fusion between pulsed and steady current. Besides current operational mode, another difference between blocks S1-B2 and S2-B1 is related to minor differences in shielding gas composition which may have an important influence in process stability (Chapter 7). However, the influence of this effect on plate fusion was not assessed in the present programme.

6.2.3. Bead parameters related to both wire and plate fusion.

Bead area (A_t) directly results from the sum of A_d , A_a and A_p . Therefore, it can be assumed that modelling equations for A_t should reflect the relative influence of the input variables in each of the parameters above. Based on this assumption, one can expect positive regression coefficients for welding current due to its influence on plate fusion (both lateral and axial), and negative ones for welding speed due to its strong influence on deposited area and in lateral penetration. Based on the same assumption, other input variables should be expected to present less clear influences on the weld bead area. Surface plots for A_t are shown in

figure 6.6. The differences in A_t between the experimental blocks reflected the differences in plate fusion already discussed. In this sense, the larger bead areas were associated with experimental block S2-B1.

W/H ratio (R) can be roughly expressed in terms of the weld bead dimensions as:

$$R = \frac{H}{W} = \frac{h_{mean} + p_a}{g + 2p_p} \approx \frac{k_1 w / vg + k_2 A_a}{g + k_3 A_p} \quad [6.8]$$

where p_a is the maximum axial penetration, p_p is the lateral penetration, and k_1 , k_2 and k_3 are constants. As both lateral and axial fusion increases with current, R would not be significantly affected by this parameter as confirmed by the modelling results. As far as the remaining variables are concerned, R seems to be strongly influenced by the variation of the mean bead height and modelling equations for R tended to have a similar format to that found for h_{mean} . Surface plots for R are shown in figure 6.7. Owing to its larger axial penetration and smaller lateral penetration, experimental block S1-B1 presented higher values of R when compared with blocks S1-B2 and S2-B1 (helium based shielding). This, however, does not necessarily imply a higher cracking susceptibility for block S1-B1 (see §6.3).

When model A type equations are considered, only welding current and wire feed rate (and, possibly, arc length) were considered to have a significant effect on the undercutting factor (f_u). However, interaction between input variables seems to be important to this response and the relatively complex model B type equations were found to significantly improve the representation of f_u (table 5.23). Surface plot for f_u are presented in figure 6.8.

6.3. Graphical representation of process behaviour

The equations obtained in this programme are mathematical representations of the information related to the different studied responses which was extracted (and "refined") from results of experimental trials. Expected values of the responses can be calculated from the model for conditions inside the operational space of the process covered by the experiment. However, one limitation with the modelling equations is that each model is related to a single response and yields only single results what makes it more difficult to analyse overall process tendencies, particularly if two or more responses are to be considered at the same time. The surface plots presented and discussed in previous sections can improve the representation of results by displaying the variation of a response over an region of the

predictors (input variable) space. However, they are still limited to a single response and can study, at most, only two predictor variables simultaneously.

A multi-response representation of the system can be obtained by stating constraining conditions for a set of responses and determining, from the modelling equations, the region of the operational space that satisfies all these conditions at the same time. This procedure is similar to that commonly employed in the tolerance box technique (Salter and Doherty 1981). But, although this approach allows the simultaneous study of several responses, it is still basically limited to only two independent variables.

In order to overcome this limitation, a multiplot representation was developed which allows up to four predictor variables to be simultaneously included in it. This representation uses an external (or "big") pair of axes in which two of the predictor variables (x_1 and x_2) are defined at three levels each, resulting in a grid of nine points (x_{1i} , x_{2j} , $i=1,3$ and $j=1,3$) over the plot area (figure 6.9a). At each grid location (x_{1i} , x_{2j}), a pair of internal (small) axes are defined for two other predictor variables (x_3 and x_4 , for instance) so that any point $P=(x_{3k}$, $x_{4l})$ defined by these axes actually corresponds to a point ($x_{1i}, x_{2j}, x_{3k}, x_{4l}$) of the four-dimensional (4D) space on the predictor variables. As a result, each pair of small axes represent a 2D section of the 4D space on the predictors for fixed values of x_1 and x_2 (figure 6.9b).

Once the multiplot representation is defined and predictor variables for both big and small pairs of axes selected, constraining conditions relevant to the process have to be established for each 2D section plot. At least two different constraint levels may be defined for the process, i. e.: (a)geometric features affecting the joint soundness and, (b)process stability and economic factors. Avoiding or minimizing problems at the former level was considered fundamental for the successful application of the process because cost and time delays associated with repairing defects would undermine any chance of applying the NG-II GMAW process in the J-laying method for pipeline fabrication. The latter level of requirements, although also fundamental, was analysed later under the restrictions defined by the first level of constraining conditions.

In order to specify constraining conditions based on formation of weld defects, the parameters defined to indirectly indicate defect susceptibility (f_u and R , §5.2.3) were plotted against one of the predictor variables with the presence, or not, of defects indicated for each experimental point (figures 6.10 and 6.11). Based on the analysis of these plots, critical values for each parameter could be obtained so that no experimental trial likely to generate the relevant defect would stand below the horizontal line defined by the critical value.

Critical values of 1.0 and 0.2 and valid for experimental blocks S1-B1, S1-B2 and S2-B1 were defined by this criterion for R and f_u respectively. This value for critical R is significantly higher than values suggested for Kurokawa et al. (1966) who, however, worked with much higher current levels and, consequently, a more massive weld pool. For lack of fusion formation, the direct measured value of lack of fusion length in a bead cross section was used to defined constraining levels. Negative values of l_f , as defined in §5.2.3, were used to indicate absence of fusion defects.

A nought value for l_f could be an obvious initial candidate to critical value for fusion defect sensitivity. However, from a statistical point of view, this choice would actually imply that, although the expected value of l_f was nought, there would be still a 50% chance that an experimental trial, performed at that conditions, would generate a positive value of l_f . An approach that is more conservative and also reproduces better the "pass-non-pass" criterion used for both cracking and undercutting determination would be:

$$y_c = y_{\text{trans}}(l_f = 0) - 2s \quad [6.9]$$

where y_c is the critical value for the transformed form of l_f , y_{trans} (equation [2.35]), at $l_f = 0$, and

s is the estimated standard error of the transformed response.

This choice for the critical value corresponds approximately to a 4% chance that a positive value of l_f would result from an experimental trial performed under conditions defined by y_c .

Once critical levels for the responses considered relevant to the process are selected, estimated boundaries for adequate process operation can be obtained by setting the modelling equation for the given responses equal to their critical values, y_c :

$$G(x_1, x_2, x_3, x_4) = y_c \quad [6.10]$$

Where $G(\dots)$ is the modelling equation on predictors x_1 to x_4 .

Using, for instance, x_1 and x_2 to define the two external axes, expression [6.10] can be easily solved, if G is presented in the form of a model A or B type equation, for x_3 and x_4 in order to define boundaries for expected defect formation at each location (x_{1i}, x_{2j}) of the external grid:

$$x_4 = g(x_{1i}, x_{2j}, x_3, y_c), \quad i=1,3 \text{ and } j=1,3 \quad [6.11]$$

Lines for critical values of f_u and l_f considering wire feed rate and welding current as x_3 and x_4 respectively are shown in figures 6.12 to 6.14 for experimental steps S1-B1, S1-B2 and S2-B1. Each of these lines define a pair of values for x_1 and x_2 , a boundary which divides the plotting area into two sub-regions of opposite characteristics regarding expectancy of defect presence. In one of the sub-regions, the restriction imposed by y_c is not violated and defect likelihood is small. On the other region, however, the restriction is not satisfied and its likelihood is high. In figures 6.12 to 6.14, the former region for l_f lies over its critical line (i. e., in the region of higher current and lower wire feed rate), while, for f_u , it lies below its critical line. In both cases, the critical lines tend to run diagonally with a positive slope close to 45° .

Regions for expected defect-free operation are obtained by considering the critical lines for R , f_u and l_f together and finding, when it exists, the interception of the regions of acceptable operation for each response. The resulting multiplots for experimental steps S1-B1 and S2-B1 are shown in figures 6.15 and 6.16. In these figures, the regions of expected defect absence are represented by hatched areas.

A nought value for l_f was used to define its critical boundary in figure 6.15 while a more conservative limit, based on equation [6.9], was adopted in figure 6.16. The most extensive region of low defect likelihood was associated to experimental block S2-B1 (figure 6.16) with a 7mm gap width. This information was used to define operational conditions for horizontal-vertical welding trials (block S3-B1). Results indicate that the process is highly sensitive to minor changes in input variables, including not only those used in the multiplot representation but also other variables, such as wire positioning in the gap. Therefore, development of effective control systems may be a necessary requirement to the application of the process in production.

Finally, in both process representations, regions for adequate operation in terms of fusion defects tend to extend diagonally in the (I, w) plane reflecting the role of arc length (or voltage) in controlling lateral fusion. Mean slopes for these regions are approximately 0.05 and $0.067 \text{ mA}^{-1}\text{min}^{-1}$ for S1-B1 and S2-B1 respectively. The reciprocals of the values are close to (in absolute value) the parameter $_{I,w}$ (table 6.3) for V and l_a indicating that, in these regions, V and l_a should remain relatively constant. For instance, when the multiplot representation for S1-B1 (figure 6.15) is compared with its surface plot for arc length (figure 6.3a), a 3-4mm arc length seems to be associated with the region of adequate operation for an 8mm gap and 8mm/s speed.

6.4. Horizontal-vertical welding

The weld beads of experimental block S3-B1 were basically free from undercutting and centre line cracking problems. However, the conditions imposed on the weld pool by horizontal-vertical (HV) position resulted in a non-uniform fusion of the workpiece, with its lower face presenting much less fusion than the upper face (figure 5.7).

Compared with previous results for the downhand position, the modelling equation for lateral penetration area (including fusion in both upper and lower walls) indicated only welding speed to be significant (figure 6.17). Neither current nor wire feed rate seem to have a significant effect for the experimental conditions employed. As a result, arc length also seems to have little effect. This result was rather unexpected when compared with previous experimental blocks and may be partially linked to the short arc conditions that were intentionally used in this experimental block once a high tendency to undercutting in the upper wall was initially expected. These conditions together with the gravity influence on the HV position may have forced the arc to burn almost completely under the joint bottom.

The non-uniform characteristic of the arc lateral fusion in the HV position is clearly shown when the individual values of upper and lower side wall fusion areas are compared (figure 6.18). The ratio between fused area in the upper and lower walls:

$$R_{UL} = A_{pu}/A_{pl} \quad [6.12]$$

can be taken as a measure of the arc relative efficiency to melt the upper and lower walls. Mean values, at constant welding speed, for R_{UL} are presented in table 6.4 together with other parameters related with bead asymmetry. Results indicate that, for welding speeds equal or below 8mm/s, a fivefold difference in fusion is commonly present. For higher welding speeds, the relative advantage of upper side wall in melting efficiency is reduced mainly by a faster decrease in lateral fusion in this wall.

Lack of fusion behaviour in the HV position also indicates unequal arc melting efficiency (table 6.4). Under the welding conditions used in the experimental block, large negative values of l_f were common for the upper side wall while, in the lower side, extensive lack of fusion could be found. However, values indicated for l_{fl} may be overestimated by some margin due to the different methodology used to define lack of fusion in the lower wall (figure 5.8).

One further feature related with lateral fusion in the HV position is a tendency for $h_{\max}$ (figure 5.4) to be longer in the upper wall. As a result, the weld face tended to be inclined in relation to the side walls and a sharp corner may be formed between the weld face and the lower side wall. If this sharp corner is formed, the likelihood of fusion defect formation in this area is greatly increased for the next run. The difference between $h_{\max}$ in upper and lower walls respectively is commonly over 25% for welding speeds up to 8mm/s (table 6.4).

Higher fusion in the upper part of the joint is also demonstrated by the axial penetration area which has an asymmetrical character as shown by the values of the ratio between the upper and lower halves of A_a (R_{ALU} , figure 6.19). A surface plot for A_a in block S3-B1 is presented in figure 6.17.

Hence, the most striking feature of the NGW process in the HV position is the asymmetrical character of workpiece fusion, particularly in the side walls. Similar results were observed by Foote (1986) who related them to sagging of the weld pool which shielded the bottom face of the joint from direct heating by the arc. In order to study this effect and to analyse other aspects of bead formation, Foote (1986) developed a simplified model for weld pool sagging in H-V position following closely the work of Berozovski et al. (1983) and Nishiguchi et al. (1978). In this model, the balance between gravity and surface tension forces was considered on a two dimensional static pool where arc force was considered negligible (see §2.4.2.1). Areas of undercutting and sagging were defined and regions of adequate bead formation found provided that the gap (bead) width was under about 12mm. However, this model does not consider the influence of the arc and can only be possibly applied to conditions found at the rear part of the weld pool. It is, therefore, doubtful that this model could analyse differential plate fusion in HV-NG welding which is probably more related to the interaction between gravity and arc force in the weld pool. In this situation, a layer of liquid metal would be forced by the combined action of the plasma jet and gravity to the bottom side of the joint, shielding this area from a more direct arc action (figure 6.20).

Therefore, asymmetrical plate fusion should be controlled, or at least reduced, by forcing an increased arc action on the lower side of the joint by, for instance, reducing gap width or welding with the wire positioned below the joint centreline. Complementary welding trials (table 5.8) demonstrated the effect of gap width in both axial and lateral fusion and lack of fusion tendency for H-V welding. Results indicate that a reduction of just 1mm in gap width can alter significantly fusion levels (figures 6.21 to 6.23). One further complementary trial was performed employing reduced gap width and off-centre wire positioning in a tapered joint preparation (figure 6.24). Figure 5.10b presents a macrograph of the multi-pass welded specimen. Improved bottom fusion can be observed with no indication of fusion defects.

Fusion characteristics may have been also improved by a lower wire feed rate which would tend to produce a longer arc.

Although experimental results have shown that plate fusion is significantly affected by welding position, the modelling equation for bead area in block S3-B1 is quite similar to those obtained for other experimental blocks.

6.5. Summary

Statistical modelling techniques such as those used in this programme provide powerful tools for designing and running an experimental programme of an industrial nature, analysing its results and building empirical models. These techniques do not, however, substitute a system for the expertise that may be available, and, if not employed effectively, misleading and confusing results may be obtained.

The results of the experimental blocks welded in the downhand position are in good general agreement with previous studies. In addition to traditional parameters, such as welding current, speed and, in special, gap width, the importance of other parameters, particularly the optimisation of shielding gas composition and power supply characteristics, was demonstrated. A multiplot representation of process operation was developed to study the simultaneous effect of up to four input variables. It demonstrated that acceptable welding conditions in terms of preventing fusion defects are linked to an approximately constant arc length.

Asymmetrical lateral fusion was the main characteristic of H-V welding operation. This characteristic was related to the combined action of gravity and arc force and, in order to minimize its effects, a narrower gap width and off-centre wire positioning were used.

In general, the results suggested conditions for obtaining welded joints free from fusion defects and with welding times compatible with the J-laying method. However, it also demonstrated that the process is rather sensitive to minor changes in welding parameters and the development of an adequate control system is expected to be a necessary step to its application in a real production situation.

Table 6.1 Calculated values of the wire diameter using the constant term from model C equations for A_d (equation 6.4)

Exp. Step	a_0	d_{we} (mm)	$-m$ (%)
S1-B1	2.838	1.14	7
S1-B2	2.710	1.07	18
S1-B3	3.064	1.29	-20
S2-B1	3.210	1.38	-37
S3-B1	2.710	1.07	18

Table 6.2 Calculated values of the wire diameter using point at the centre of the experimental design (equation 6.6).

Exp. Step	v_c (mm/s)	w_c (m/min)	A_{dc} (mm ²)	d_{we} (mm)	δ_m (%)
S1-B1	7	12	30.1	1.16	3
S1-B2	7	12	28.7	1.13	8
S1-B3	7	12	29.5	1.15	5
S2-B1	7	11	27.4	1.15	5
S3-B1	8	12	27.4	1.18	0

Table 6.3 Values of $\alpha_{I,w}$ (equation [6.7]) for lateral penetration area, voltage and arc length.

Exp. block	Values of $\alpha_{I,w}$ (Am^{-1}min)		
	A_d	V	l_a
S1-B1	-17	-18	-23
S1-B2	-15	-16	-
S1-B3	-	-15	-
S2-B1	-8	-	-

Table 6.4 Mean values for each welding speed of horizontal-vertical bead characteristics related with asymmetric plate fusion.

Welding speed	A_{pu} (mm^2)	A_{pl} (mm^2)	A_{pu}/A_{pl} -	h_{maxu}/h_{maxl} -	l_{fu} (mm)	l_{fl} (mm)
6	5.4	1.0	5.4	1.23	-1.22	0.77
8	2.4	0.3	7.1	1.37	-0.63	1.20
10	0.7	0.3	2.2	1.10	-0.17	0.57

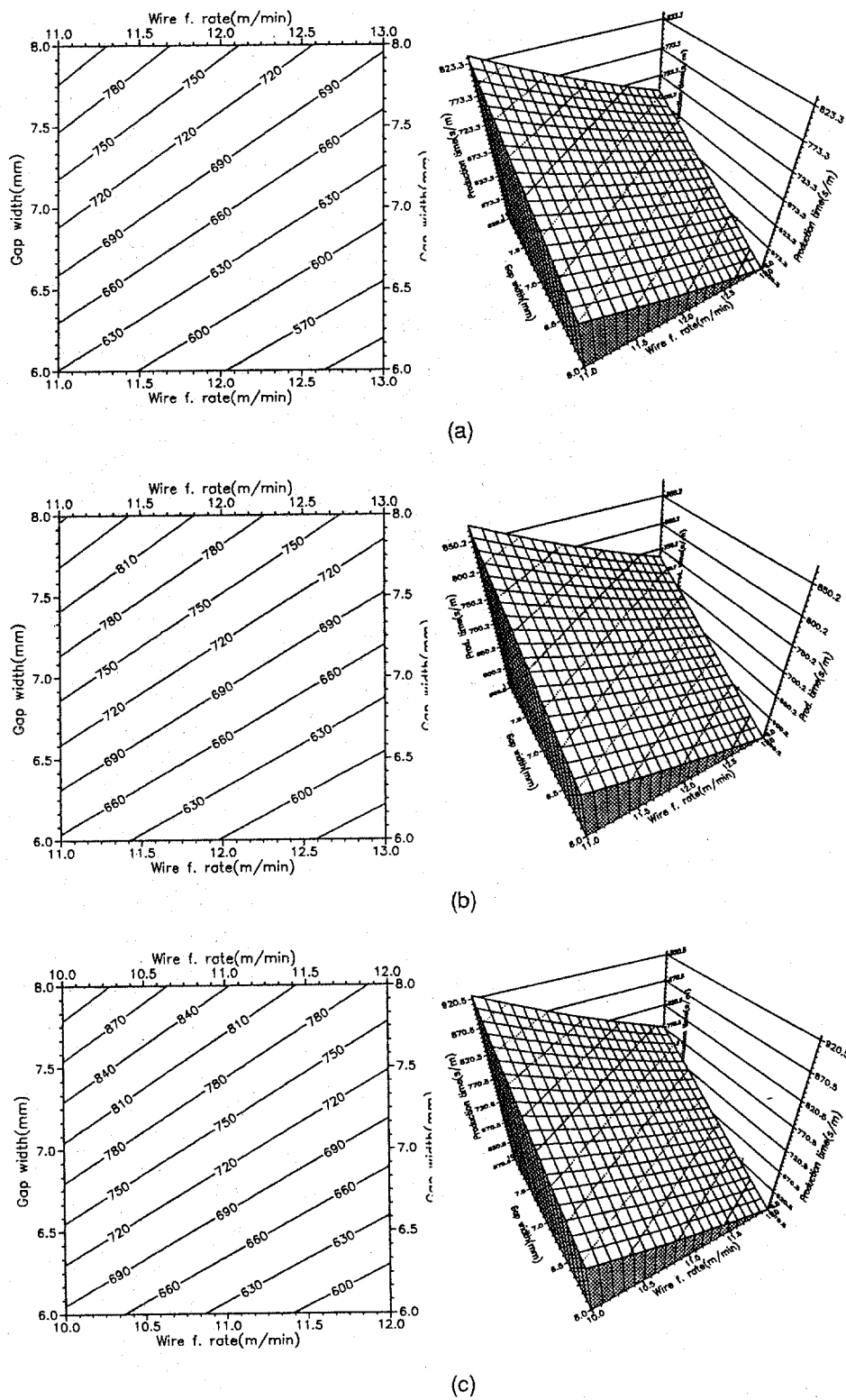


Figure 6.1 Surface plots for predicted production time in experimental blocks (a) S1-B1, (b) S1-B2 and (c) S2-B1.

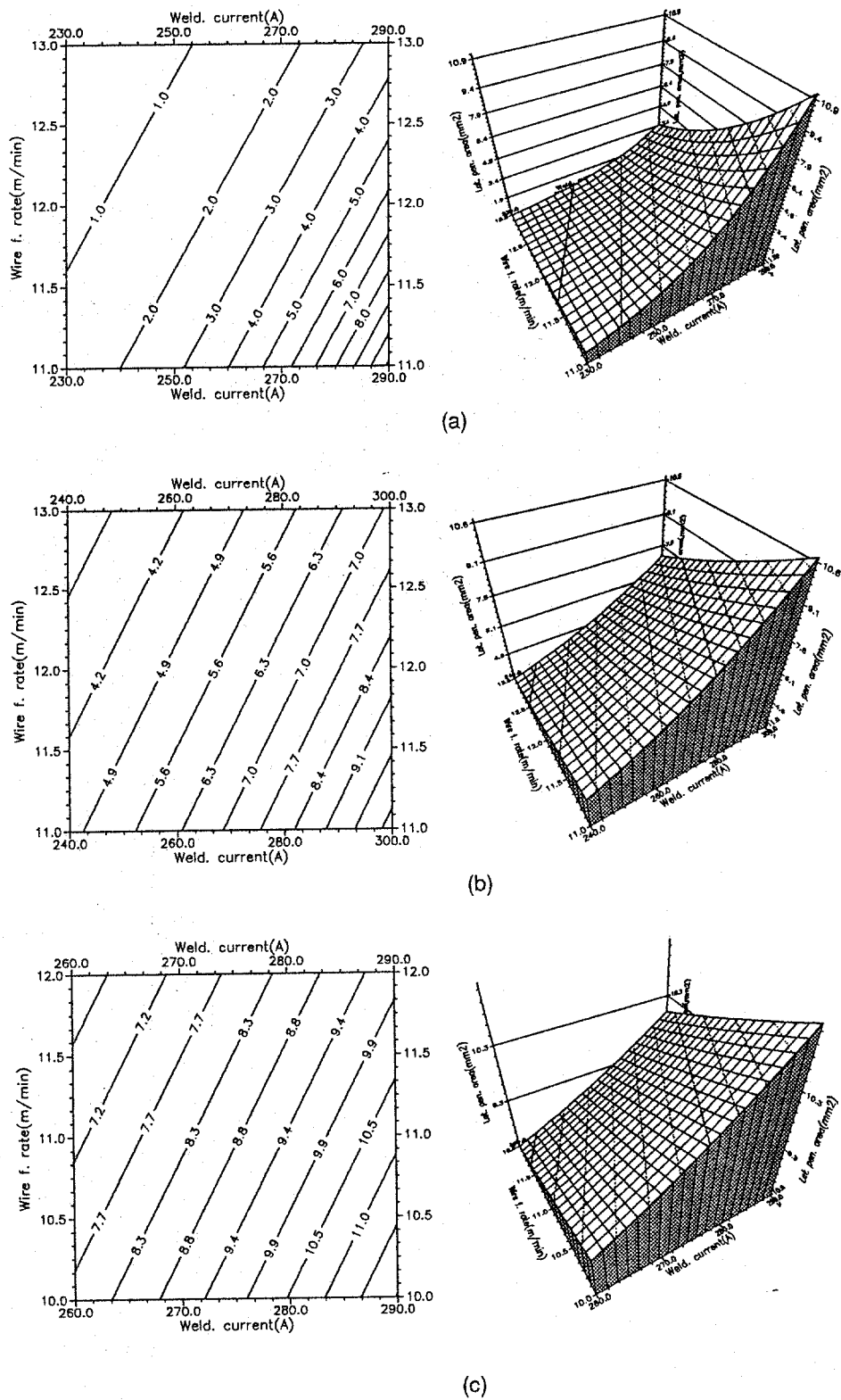


Figure 6.2 Surface plots for lateral penetration area in experimental blocks (a) S1-B1, (b) S1-B2 and (c) S2-B1. Gap: 7mm, welding speed: 7mm/s.

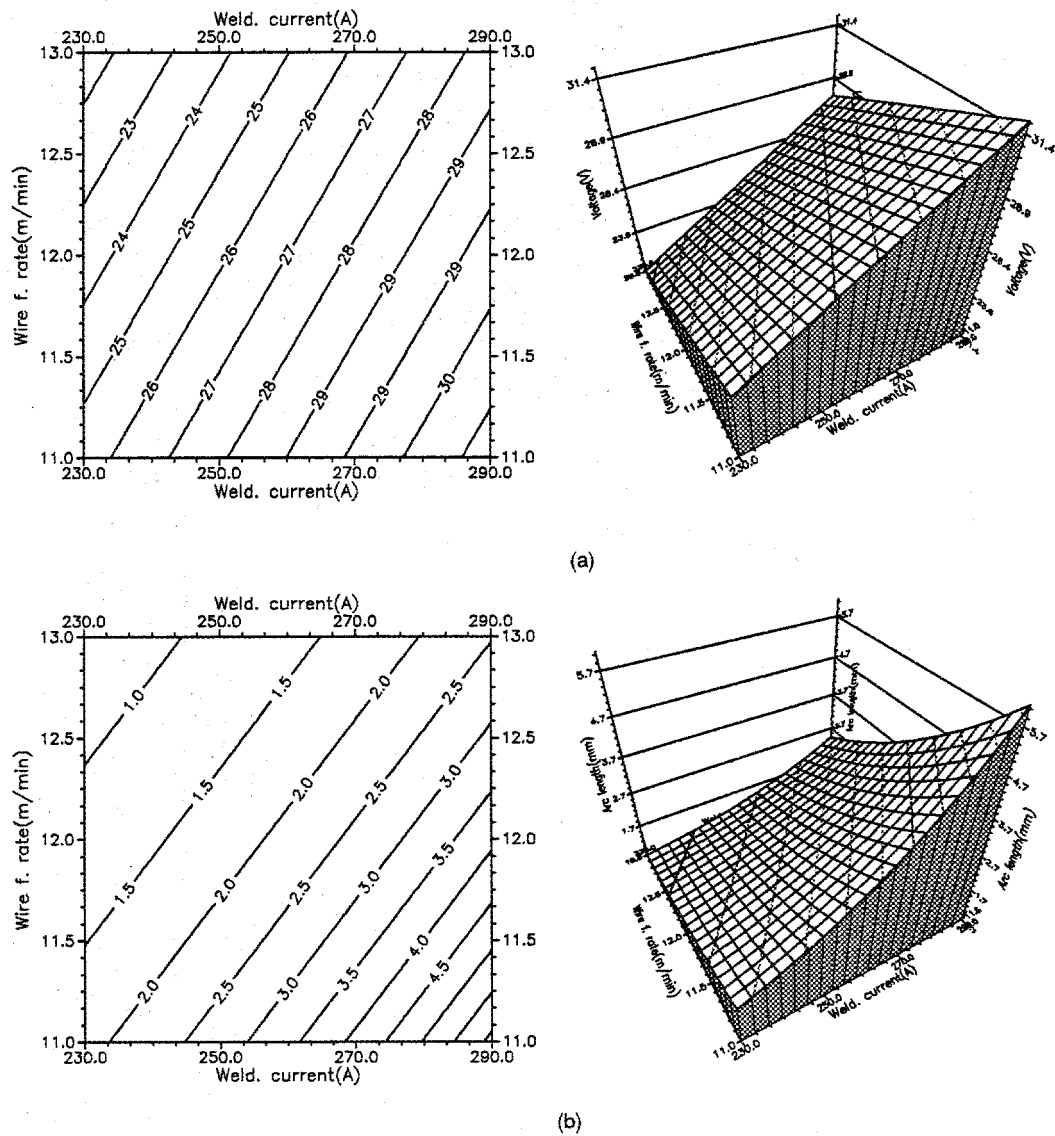


Figure 6.3 Surface plots for predicted (a) voltage and (b) arc length in experimental block S1-B1.

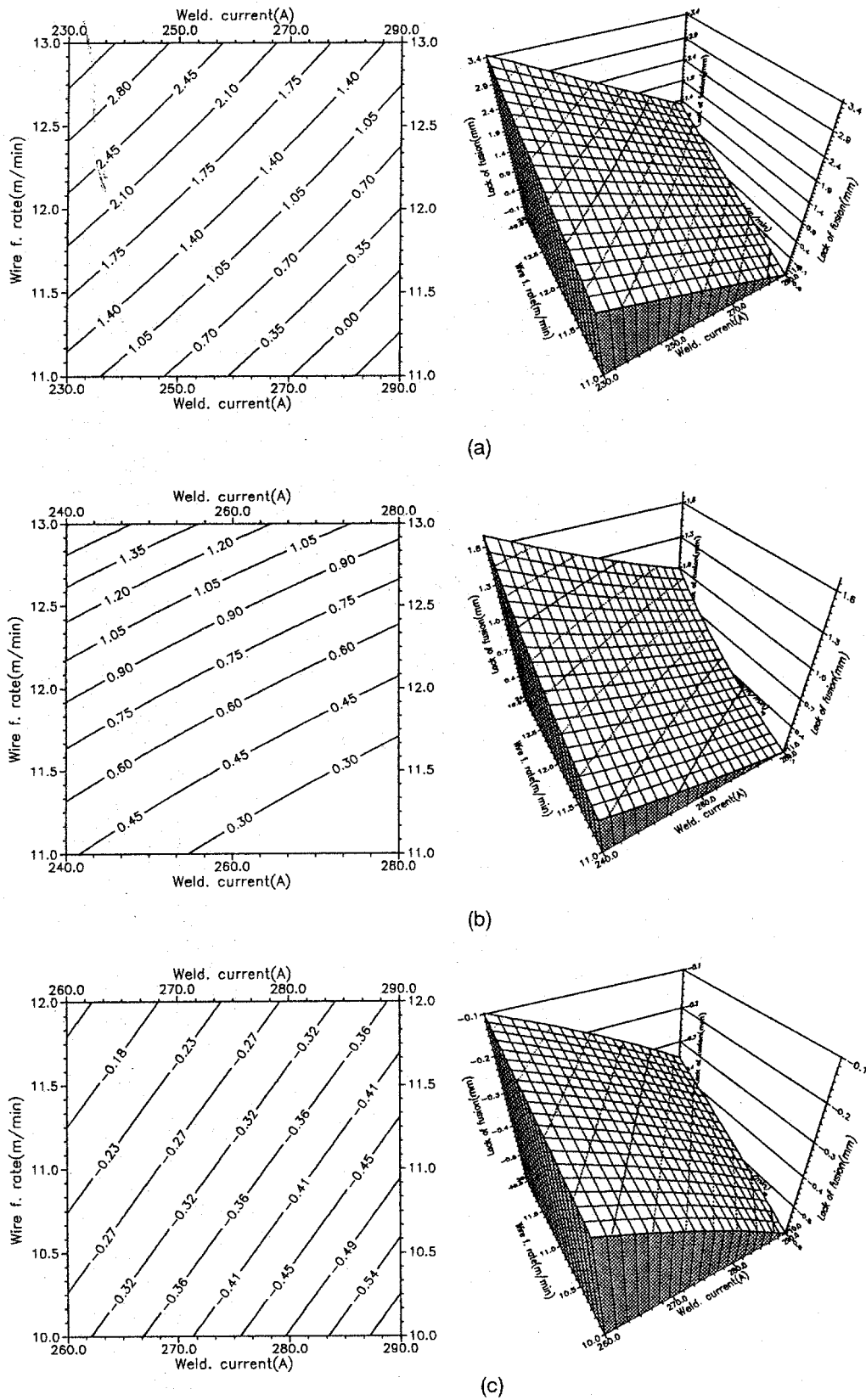


Figure 6.4 Surface plots for predicted lack of fusion in experimental blocks (a) S1-B1, (b) S1-B3 and (c) S2-B1. Gap: 7mm, welding speed: 7mm/s.

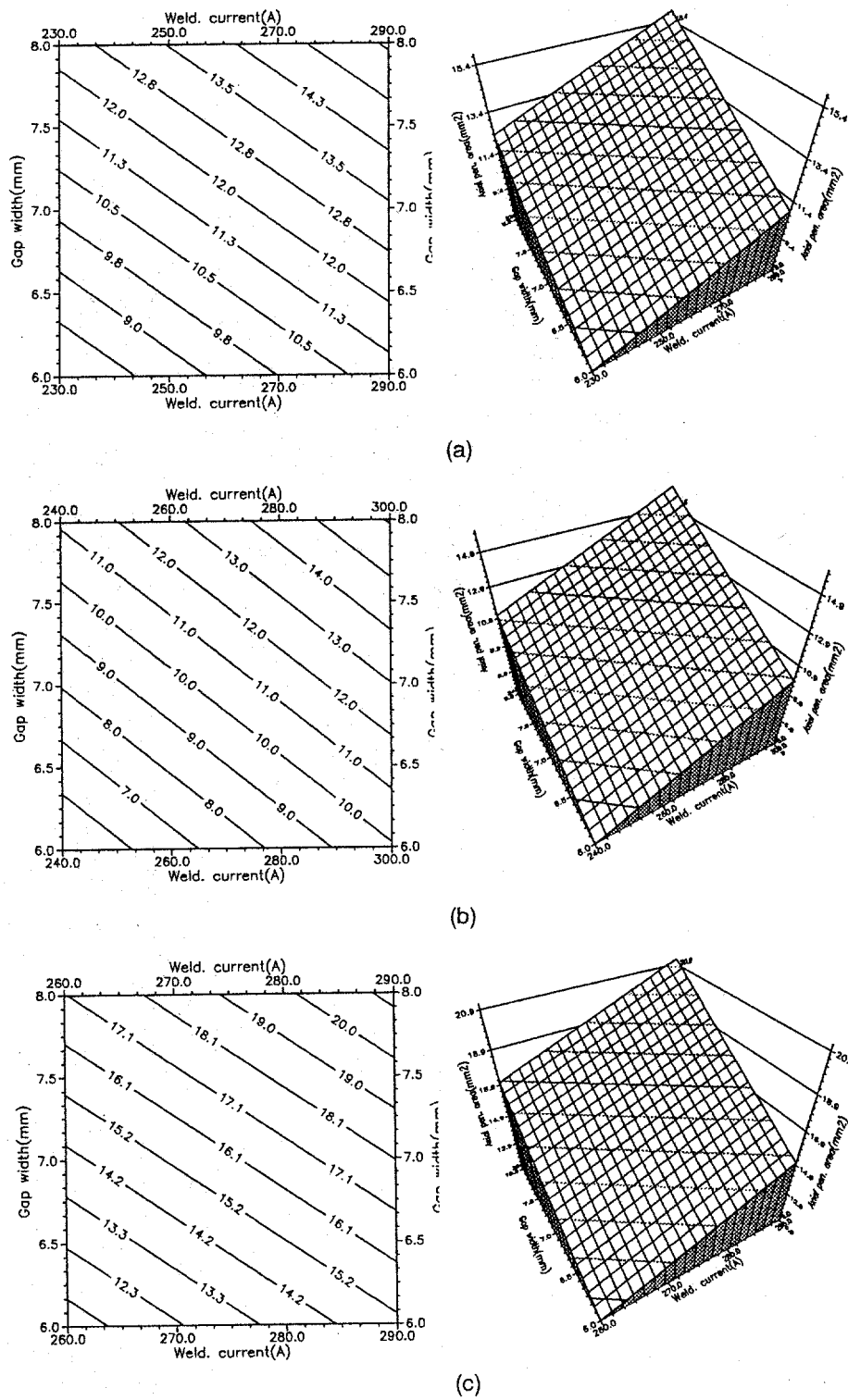


Figure 6.5 Surface plots for axial penetration area in experimental blocks (a) S1-B1, (b) S1-B2 and (c) S2-B1. Wire feed rate: 12m/min.

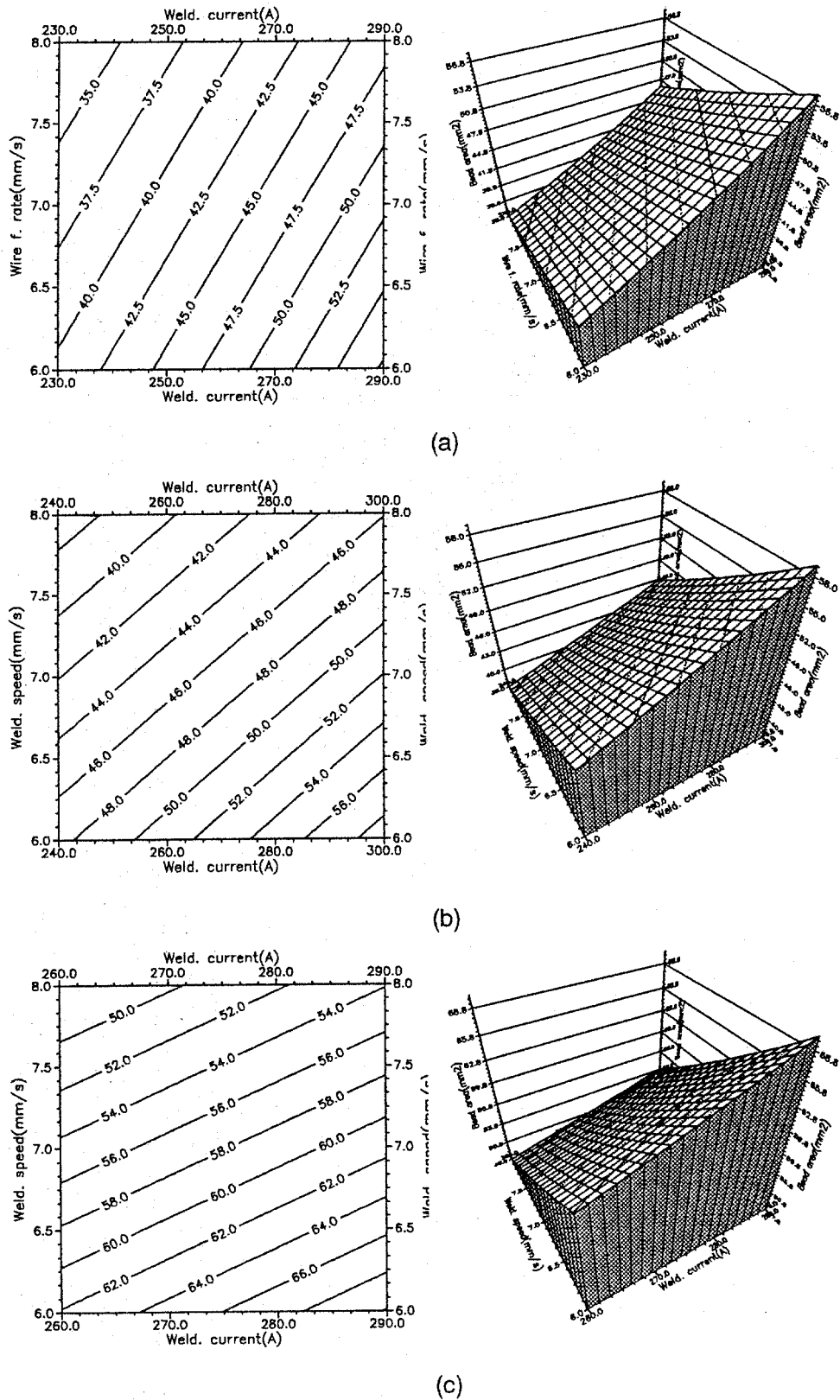


Figure 6.6 Surface plots for predicted bead area in experimental blocks (a) S1-B1, (b) S1-B2 and (c) S2-B1. Gap: 7mm, wire feed rate: 12m/min.

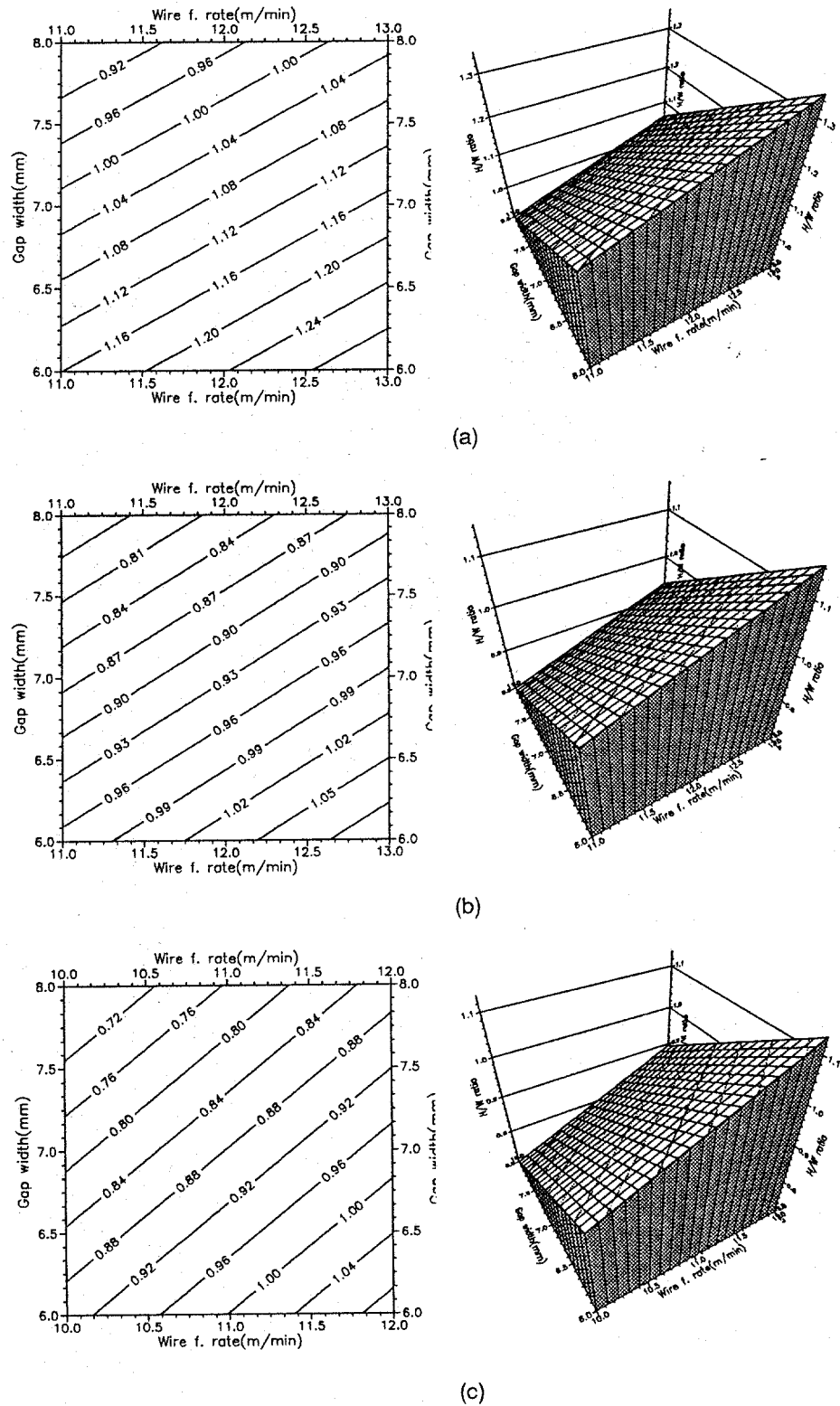


Figure 6.7 Surface plots for predicted H/W ratio in experimental blocks (a) S1-B1, (b) S1-B2 and (c) S2-B1. Welding speed: 7mm/s

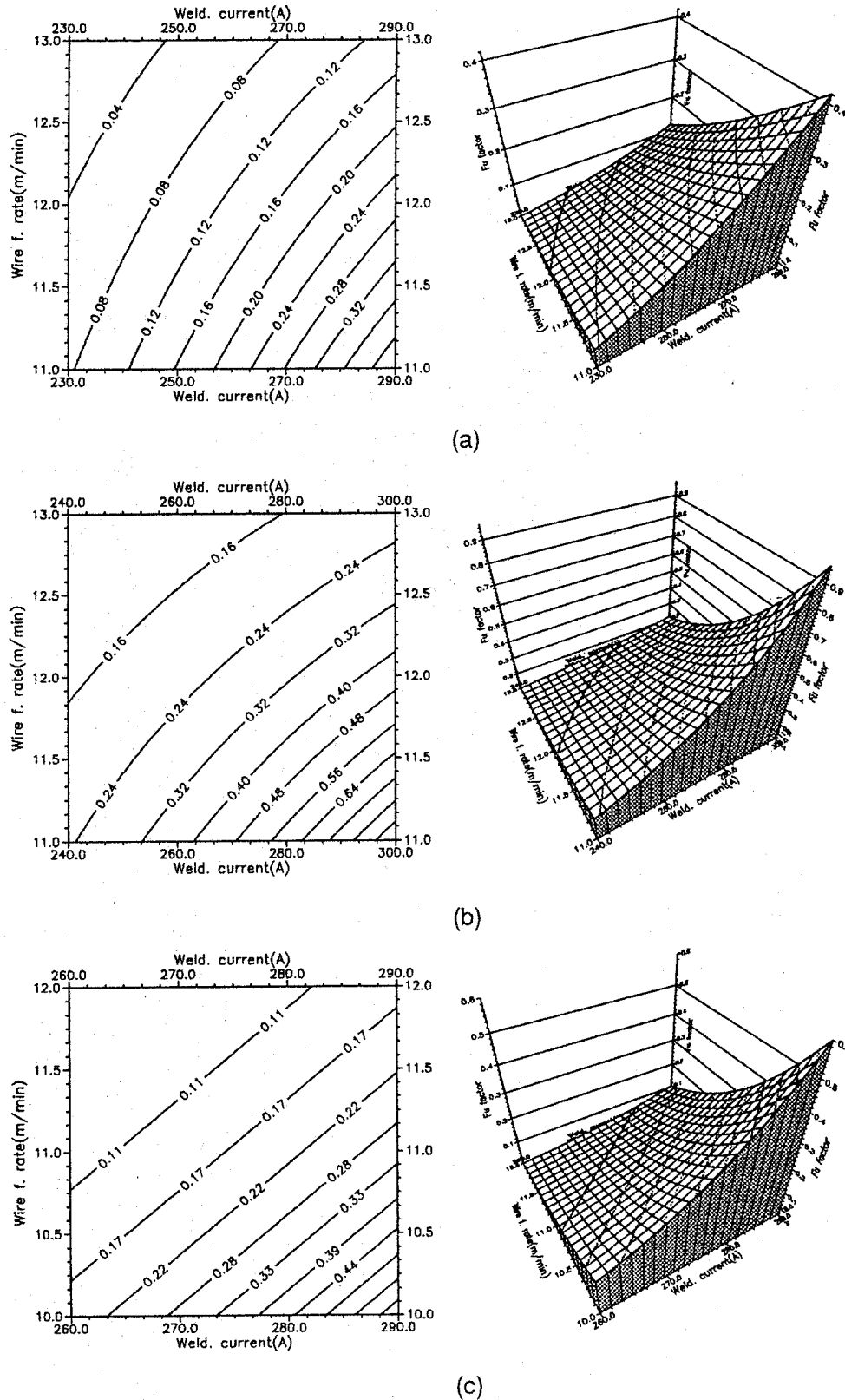


Figure 6.8 Surface plots for f_u factor in experimental blocks (a) S1-B1, (b) S1-B2 and (c) S2-B1. Gap width: 7mm, welding speed: 7mm/s

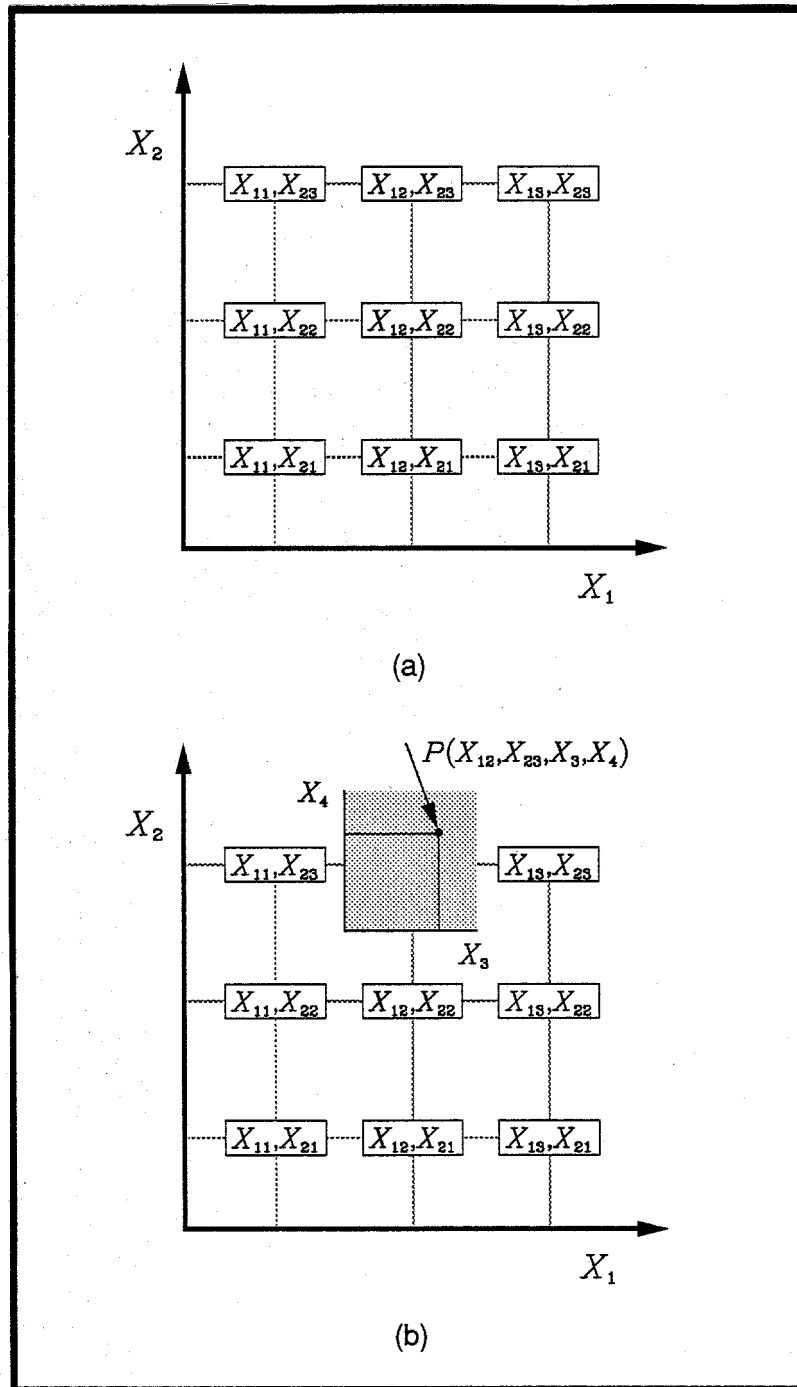


Figure 6.9

Principle of the multiplot representation of process behaviour. (a) Grid of points based on external axes x_1 and x_2 . (b) Definition of internal axes on x_3 and x_4 at a grid point.

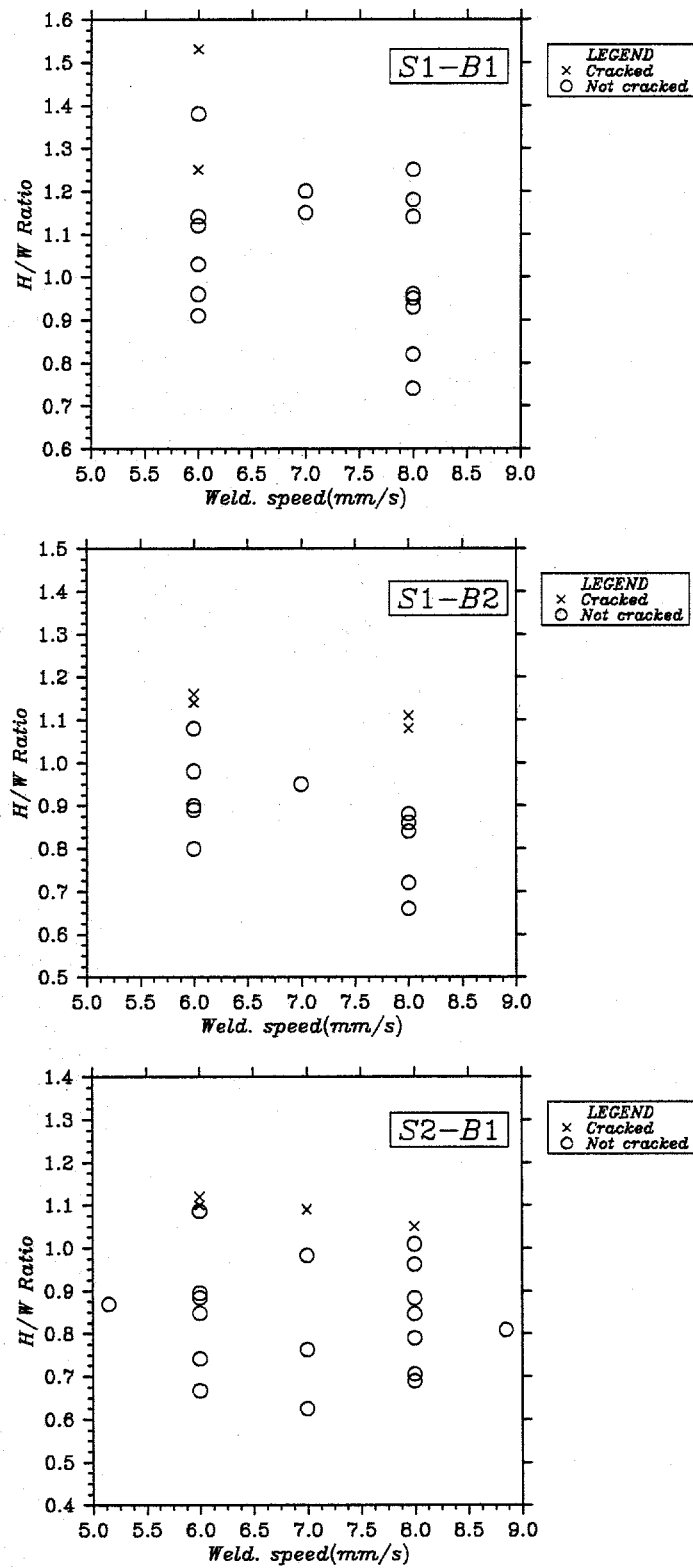


Figure 6.10 Relationship between cracking formation and H/W ratio.

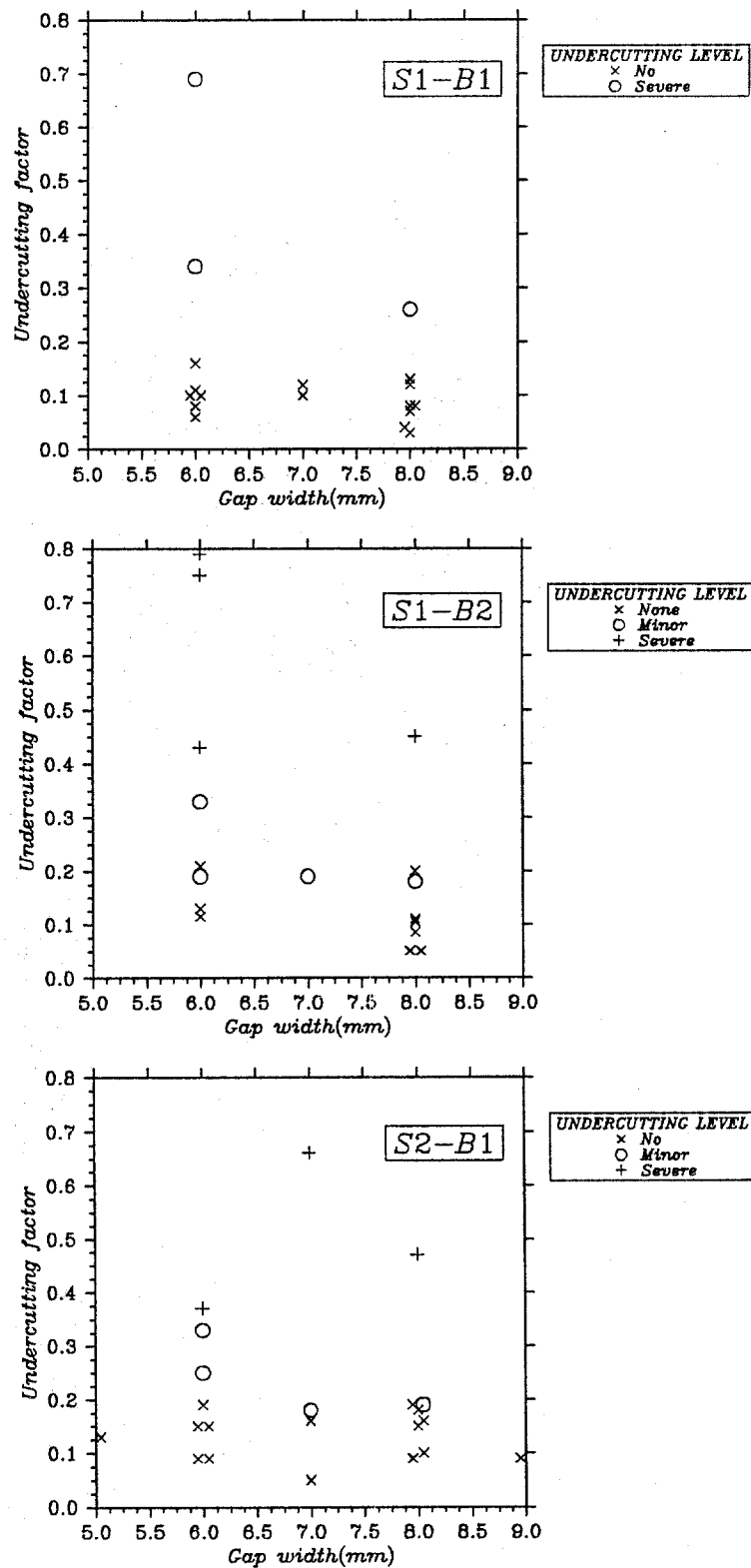


Figure 6.11 Relationship between undercutting presence and f_u factor. Undercutting level was arbitrarily considered severe for A_{und} over 0.5mm^2 .

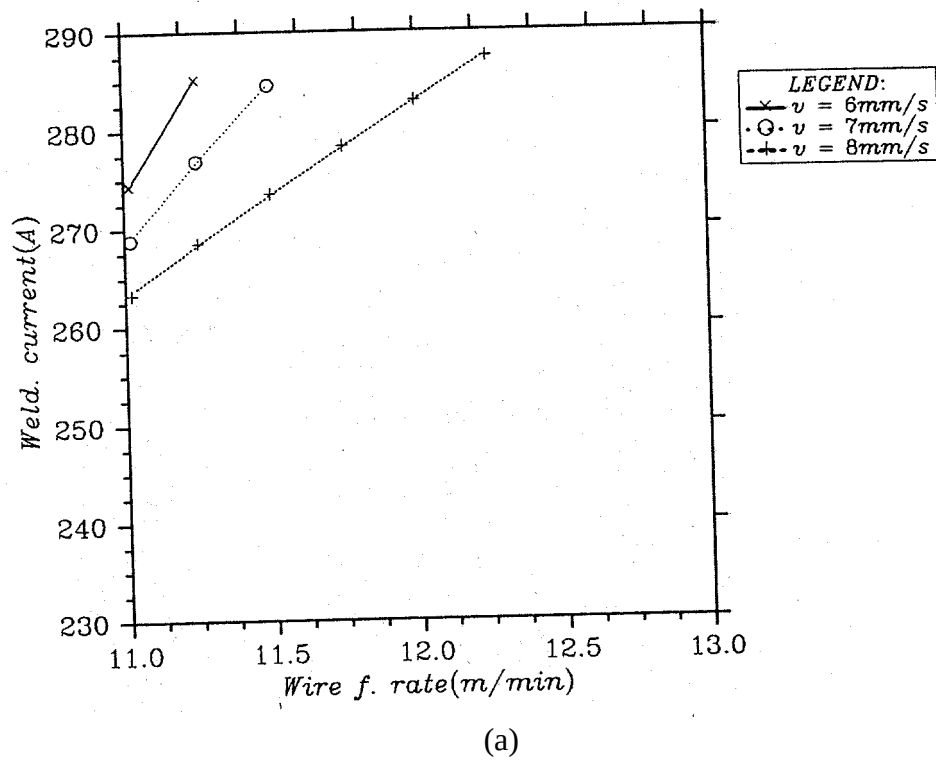
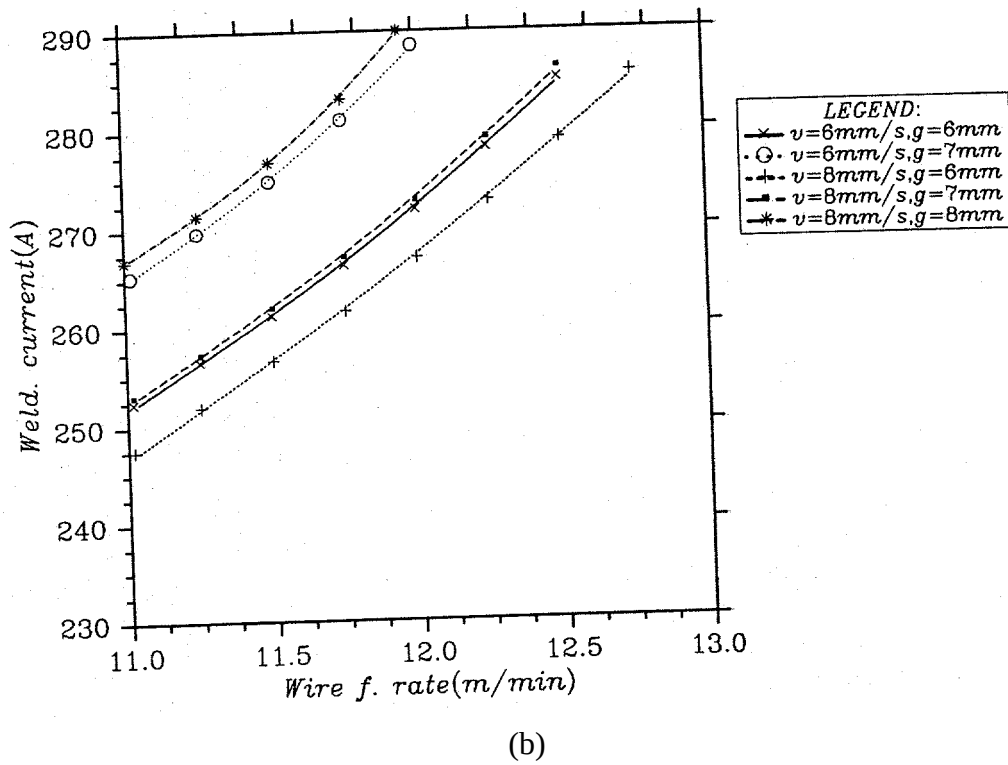


Figure 6.12 Lines for critical values of (a) l_f and (b) f_u . Experimental block S1-B1.

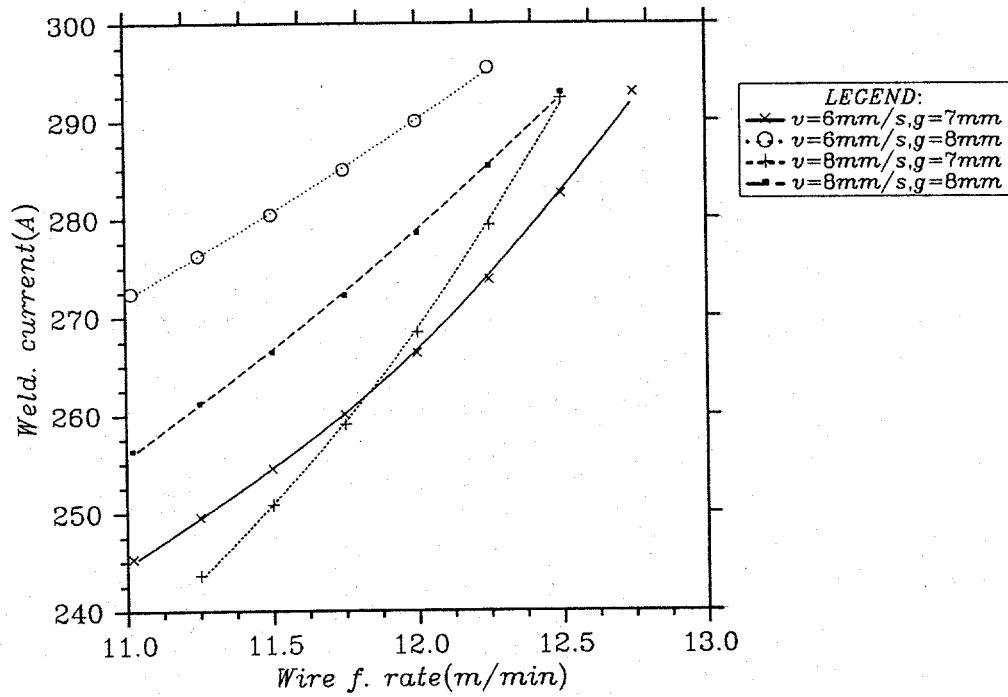


Figure 6.13 Lines for critical value of f_u . Block: S1-B2.

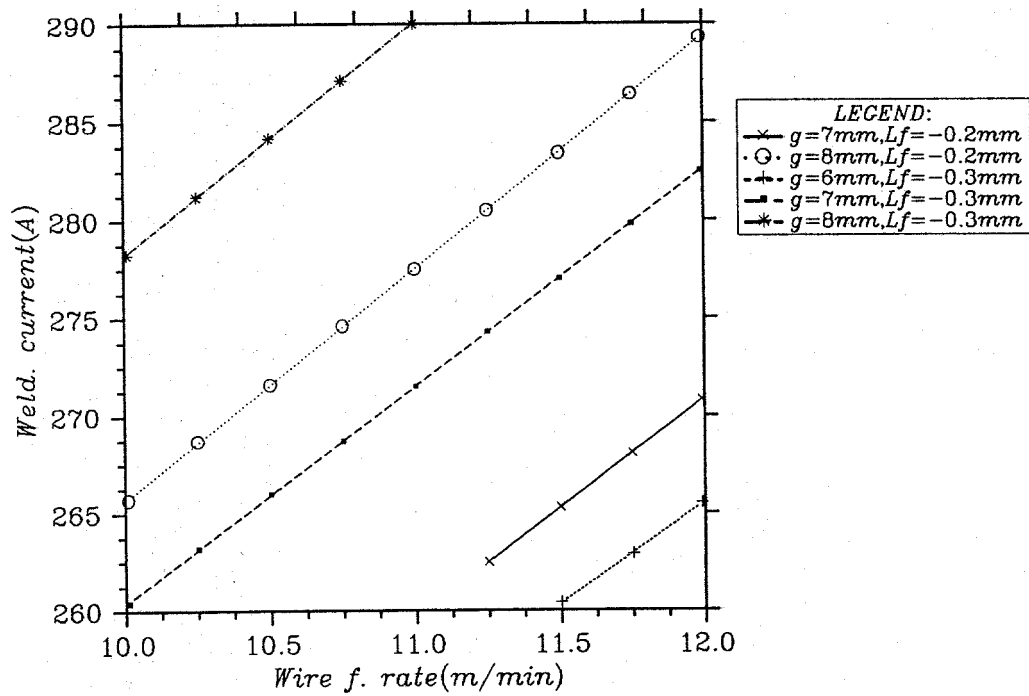


Figure 6.14 Lines for critical values of l_f . Block: S2-B1.

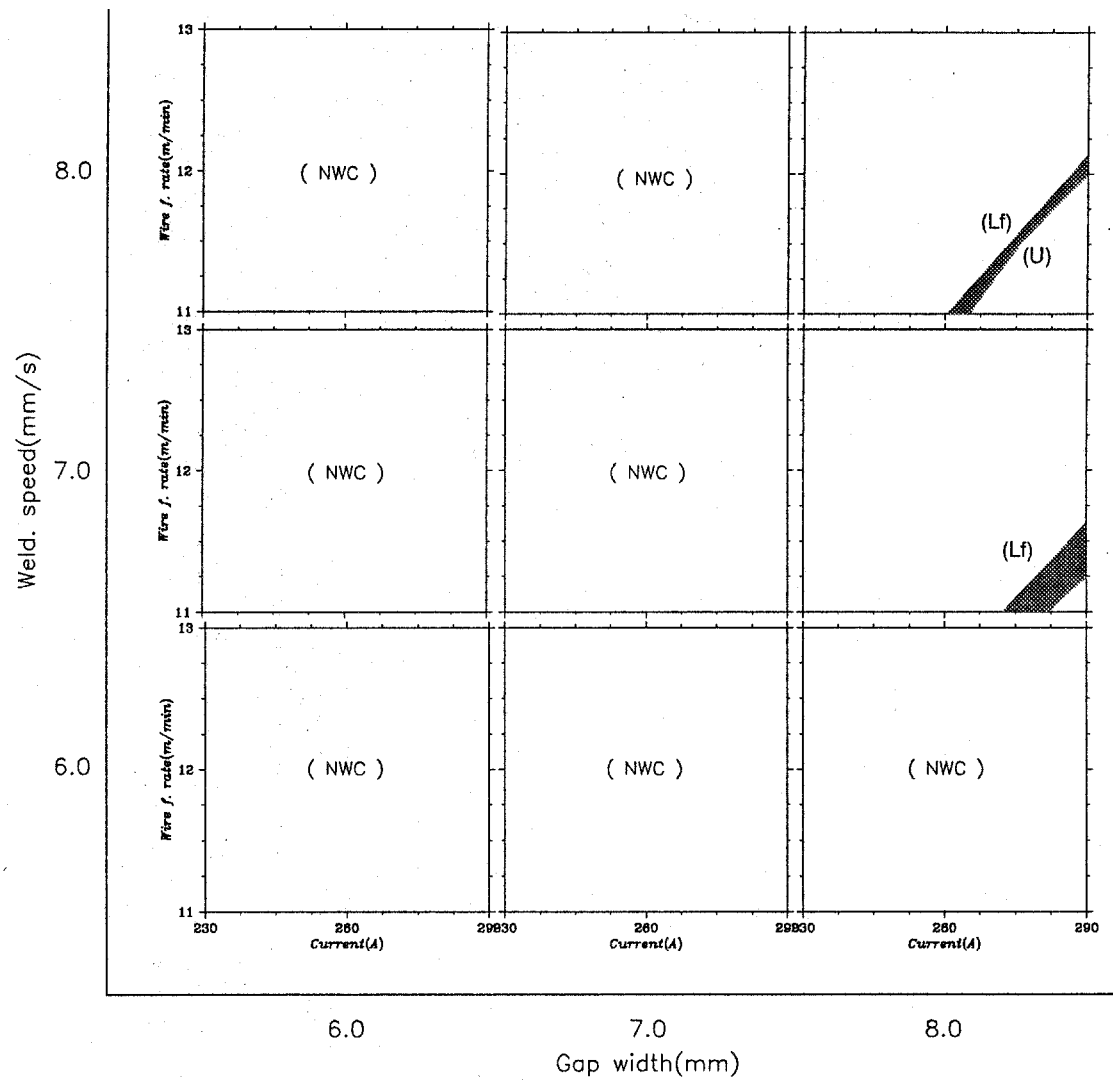


Figure 6.15 Multiplot representation of process operation for experimental block S1-B1.

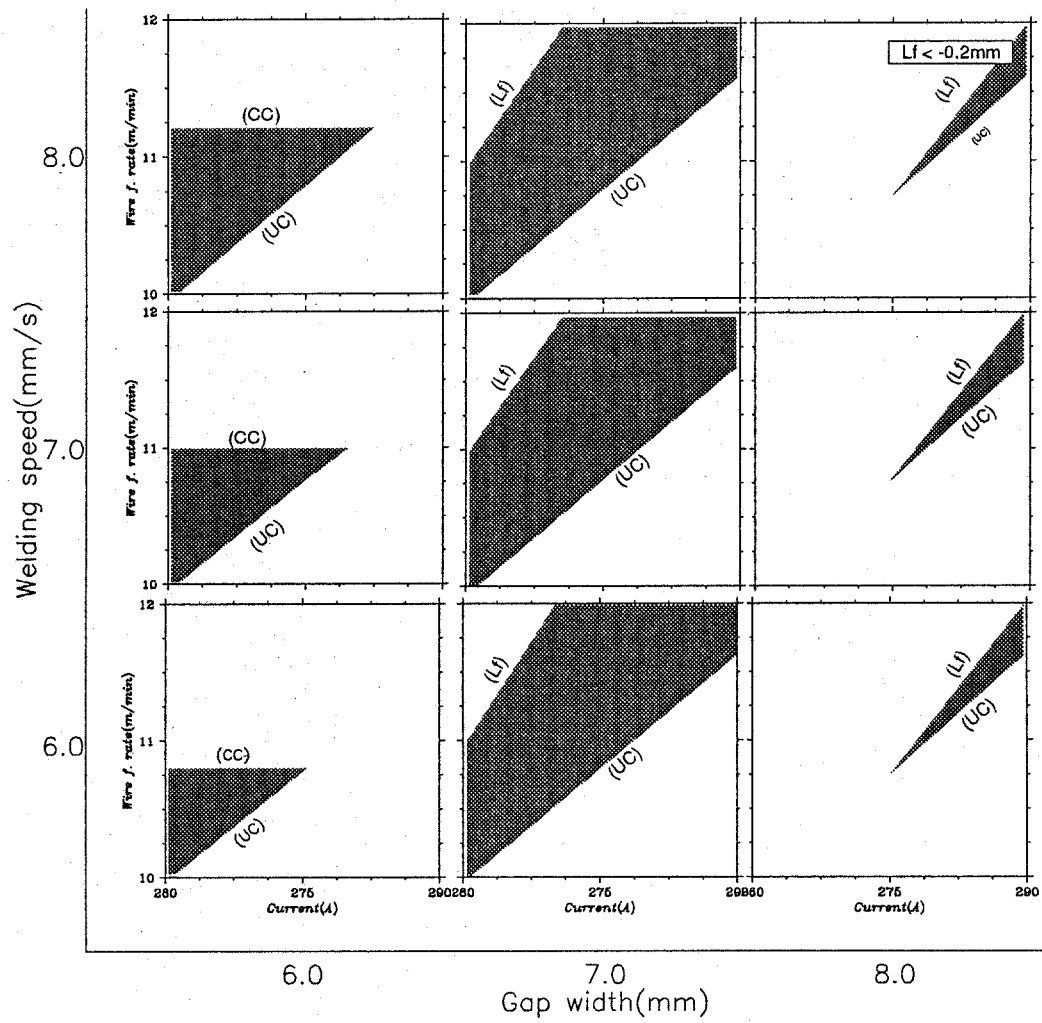


Figure 6.16 Multiplot representation of process operation for experimental block S2-B1.

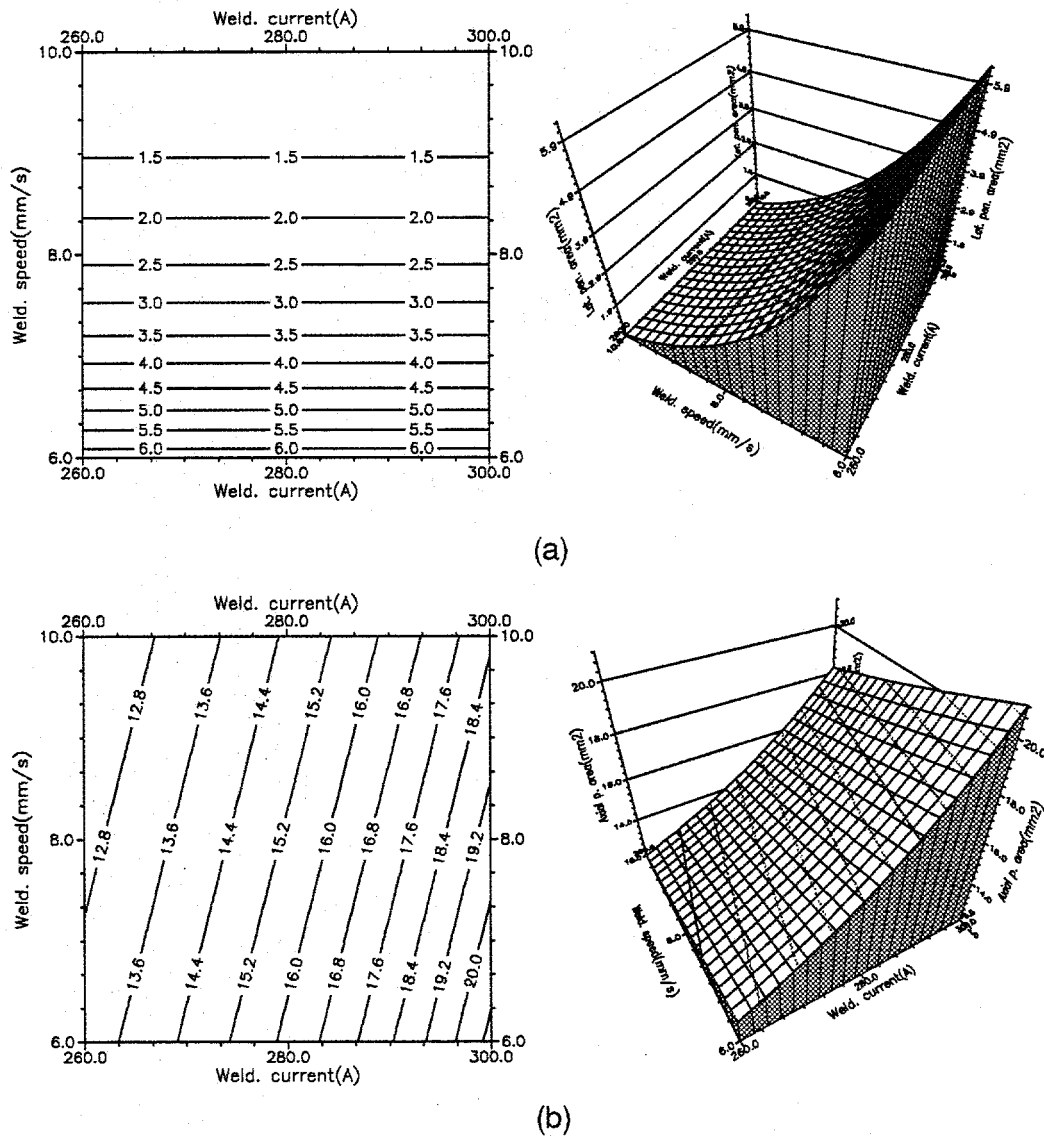


Figure 6.17 Surface plots for (a)lateral and (b)axial penetration areas in block S3-B1.

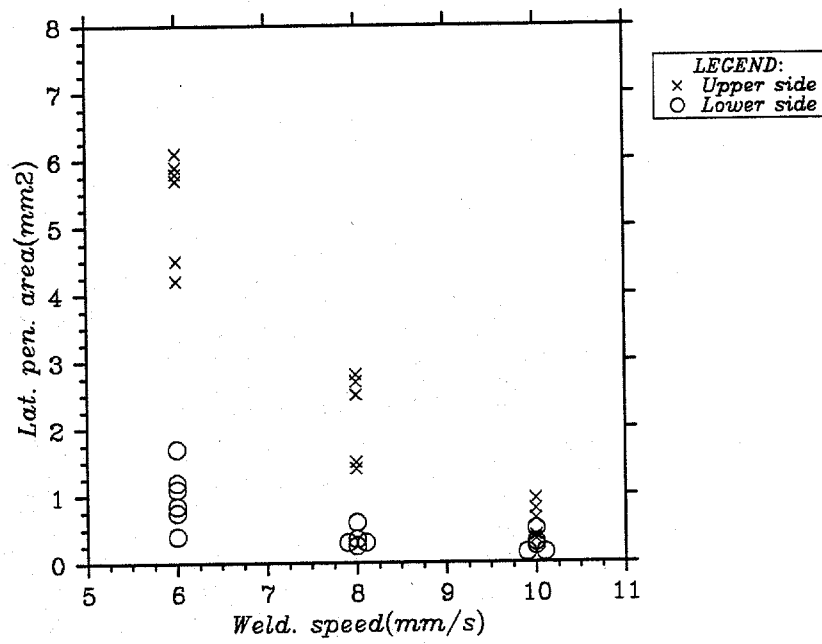


Figure 6.18 Variation of A_{pu} and A_{pl} with welding speed. Block: S3-B1.

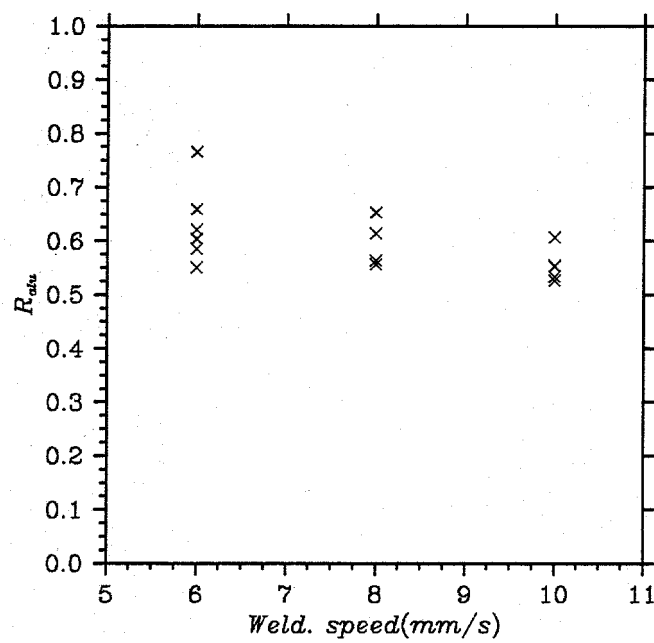


Figure 6.19 Variation of R_{alu} with welding speed. Block: S3-B1.

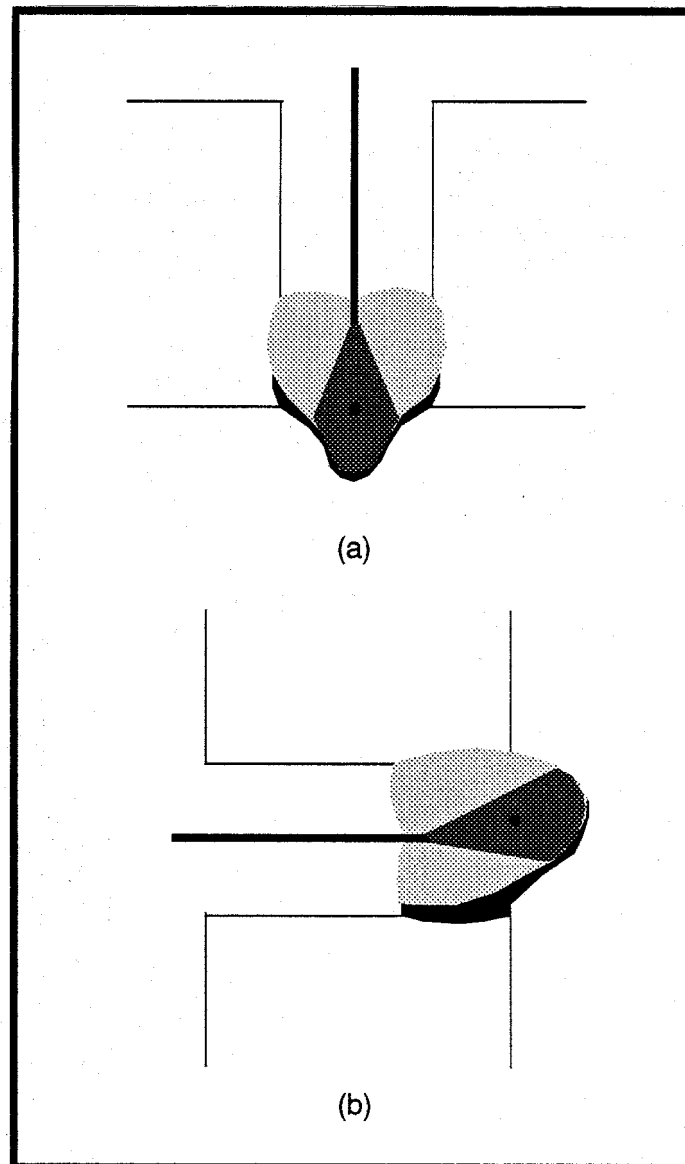


Figure 6.20 Schematic representation of gravity and arc force interactions in (a)downhand and (b)horizontal-vertical NGW.

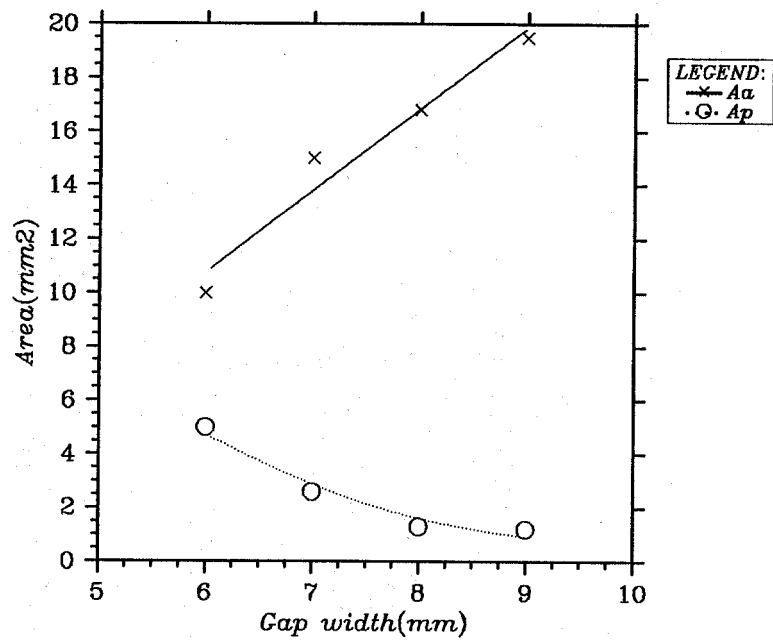


Figure 6.21 Variation of A_p and A_a with gap width in block S3-B1.

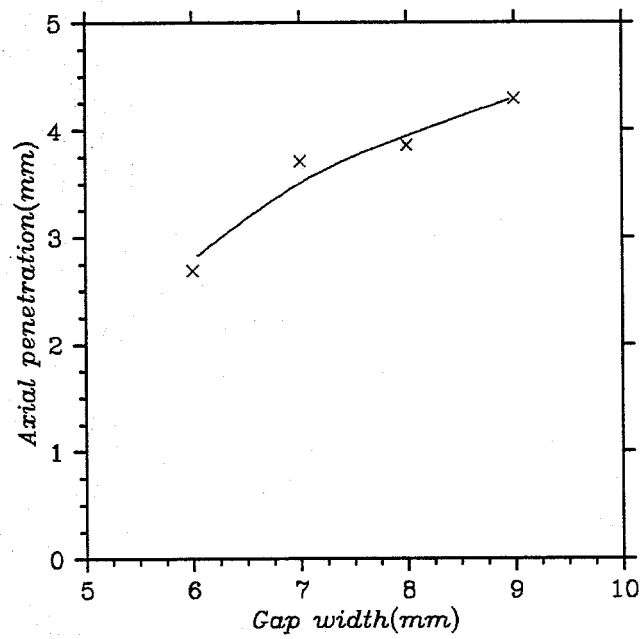


Figure 6.22 Variation of maximum axial penetration with gap width in block S3-B1.

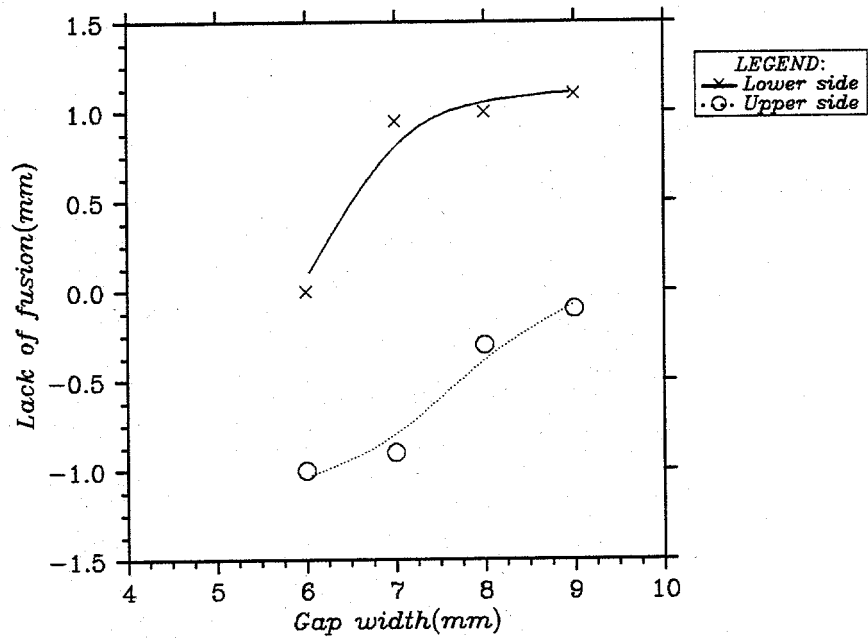


Figure 6.23 Variation of l_{fu} and l_{fl} with gap width in block S3-B1.

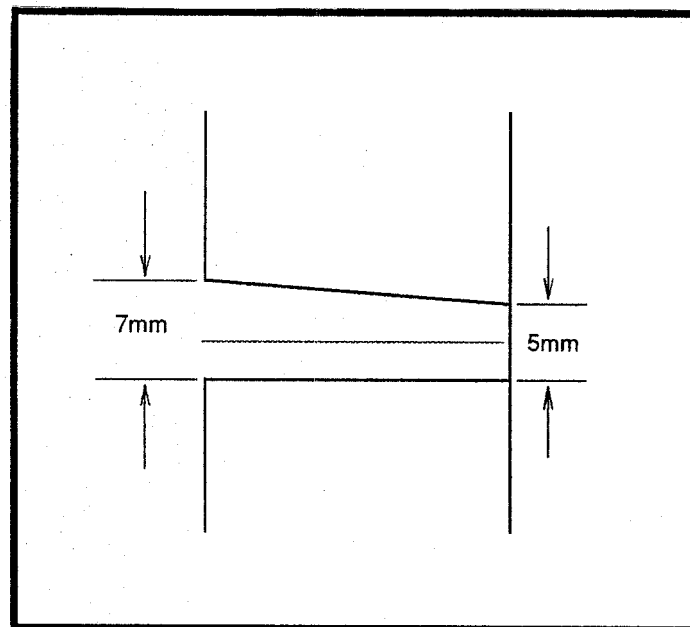


Figure 6.24 Schematic diagram of tapered joint preparation.

CHAPTER 7

7. SHIELDING GAS/PROCESS OPTIMIZATION

7.1. Introduction

When the first experimental step (chapter 5) was completed, it became apparent that, in spite of yielding better fusion characteristics, welding with the helium rich commercial mixture resulted in a less controllable behaviour in terms of arc stability.

Supplementary bead-on-plate trials using a commercial mixture of lower helium content (Helishield 101) also indicated very poor arc stability and metal transfer when a short arc was used. Furthermore, for a constant voltage power supply and non-pulsed current operation, abrupt changes in current level, process stability and arc length were observed when the arc length was intentionally and continuously changed, for instance, by increasing or decreasing wire feed rate (figure 7.1):

If the wire feed rate is not too high, the arc stabilizes a short time after starting welding. Then, a very stable process which operates at a relatively long arc ($> 5\text{mm}$) with almost no spatter can be observed (figure 7.2(a)). If the wire speed is steadily increased, the current will tend to increase and the arc to shorten as expected. However, at a certain critical point (figure 7.1, time t_1), the arc length is almost instantly reduced to a very small value, while the welding current drops by approximately 50 A and the process becomes very unstable with a repulsive drop metal transfer (figure 7.2(b)). Under these conditions, short circuit indications may or may not be observed on traces of welding current or voltage. The stable process can be reversed, again with a sharp transition in both arc length and current level, by reducing the wire feed rate (figure 7.1, time t_2).

Since the maintenance of a short and stable arc was considered fundamental to the process being investigated, an experimental investigation was undertaken to analyze the arc length dependent instability and to try to optimize shielding gas composition in terms of both stability and fusion behaviour. Additionally, since the operational characteristics of the process were established directly from the results of previous work (Fennel 1986), a critical review of these characteristics was felt necessary.

7.2. Arc length dependent process instability

Both constant voltage (CV), constant current (CC) and pulsed current operation modes were used to characterize and investigate the arc length dependent instability. A sharp transition between stable and unstable behaviour can be easily observed when constant voltage operation is used and, therefore, CV operation was used to study time dependent aspects of the phenomena. However, current changes measured in this condition do not help to explain fundamental aspects of the problem. The different voltage levels required at a constant current during the unstable and stable processes can be considered a more fundamental parameter and this was investigated using constant current operation mode. Finally, as pulsed

current was used in experimental step S1, some tests were performed to characterize the problem in this operational mode.

7.2.1. Initial experiments

A preliminary series of bead-on-plate tests was carried out in order to determine some initial characteristics of the instability phenomena. Variable wire feed rate trials (see previous section and figure 7.1) were performed with Helishield 101, argon and Argoshield 5. Results indicated that clear transition points could be observed when either He-101 or Ar were used but not with Ar-5.

In order to characterize the instability phenomena under constant current operation, a set of trials was carried out using sloped specimens (figure 7.3) which resulted in a continuous reduction in standoff distance during the welding trial. Argon and Ar-1%O₂ were used for shielding. Instead of presenting a sharp transition, as observed with constant voltage, the process stability tended to continuously deteriorate as the standoff was shortened. A large number of spikes appeared in the voltage trace at the same time as stability deteriorates. However, instead of presenting a definitive step from one state to the other, the voltage traces seemed to indicate a continuous transition.

7.2.2. Tests with constant voltage

Bead-on-plate welding trials were performed with the Fronius TPS-500 power supply in constant voltage operation. Each welding trial was started using a low voltage setting (=short arc) in order to force the process to operate initially in the unstable mode. After a short while, the voltage was rapidly increased to its test value and the welding operation continued until the process behaviour changed. This transition in behaviour was marked in the welding current trace by a sudden current increase (figure 7.4). A logging time interval of between 20 and 40 ms was used in the VELA to record the current trace. Logging times of this magnitude provided a total measuring time of 20-40s which was long enough in most cases to detect the transition in behaviour while keeping a satisfactory resolution (in time) to detect the instant of transition. The time necessary for the process to change its operational characteristics ($t_s = t_1 - t_0$, figure 7.4) was measured from current and voltage traces. Pure argon, Helishield 101 and mixtures of either gas with oxygen were used as shielding gases.

The results of the process stability tests with CV operation are presented in table 7.1 and figure 7.5. Despite a relatively large spread of the results, a clear tendency towards shorter transitions times for both higher oxygen content and arc voltage can be noticed.

The transition from unstable to stable operational mode (and vice versa) is quite remarkable for CV operation. Abrupt changes in current level and arc length take place during this transition. Current level differences of 40-90A were found while high-speed photographs by

the IMACON camera suggested a variation in arc length from 0-1mm during unstable operation to 7-8mm in stable operation (figure 7.6). At the same time, metal transfer also changes from a repulsive globular mode to spray. For all shielding gases but pure argon, the process did not tend to revert back into unstable operation once it has changed into the stable mode. For pure argon shielding, the process occasionally reverted back to unstable operation with the arc length shortening abruptly and apparently stubbing into the workpiece.

7.2.3. Tests with constant current

An extensive experimental programme was undertaken with constant current operation. Five shielding gas compositions were investigated: argon, Ar-25%He, Ar-75%He, helium and Ar-2%O₂. As the main objectives of these tests was to analyze the voltage levels associated with both the stable and unstable processes, most of the experimental trials were performed using pure inert gas shielding which was expected to promote the unstable process occurrence. The Ar-2%O₂ mixture was used to study the effect of oxygen on the process behaviour. Bead-on-plate welding trials with different standoff distances, wire feed rates and current levels were performed (table 7.2). No arc length measurements were performed in the experiment. However, considering the relative independence of wire melting rate from both shielding gas composition and arc length (Lesnewich 1958a and Nunes 1982), an approximately direct relationship between standoff distance and arc length can be assumed. In most of the trials, the ordinary experimental system with the GEC (AWP) M500 power supply was used. A few trials, however, were performed inside a hyperbaric chamber which was previously evacuated and then filled with shielding gas (argon) at atmospheric pressure. As the transitions in process behaviour tended to be much faster under CC operation than CV operation, a logging time of 1 ms was used to record the arc voltage traces.

In behaviour similar to the results reported in the previous section, process stability was worse for shorter arc (or shorter standoff distance) welding operation. Voltage traces for different gas compositions, current and standoff values are shown in figures 7.7 to 7.10. If the shielding gas contained argon and the arc length was sufficiently long, a stable spray arc could be formed (figure 7.11) and the voltage trace was relatively featureless. Shorter arc operation resulted in lower stability and a higher spatter level. Again, when the shielding gas contained argon, three characteristic voltage levels could be observed: (a) short circuit voltage, V_0 , (b) intermediate arc voltage level, V_{st} , and (c) high voltage level, V_{uns} (figure 7.12). Two very distinct metal transfer/arc modes seem to operate in this condition (figure 7.13). These appear to be similar to those observed in the previous section apart from the change in arc length that was associated with the CV characteristic and did not seem to take place in CC operation.

When pure helium was used for shielding, metal transfer tended always to be globular regardless of arc length. Although, no clearly distinct arc voltage levels could be observed, the voltage trace tended to be more irregular for short arc operation.

The voltage distribution from traces of different experimental conditions is shown by frequency polygon plots in figures 7.14 to 7.22. These plots were prepared by dividing the voltage range into an arbitrary number of intervals and counting the number of data points that were included in each interval. The presence of more than one peak of voltage in some of these plots is due to the different voltage levels of the process. Table 7.3 presents the measured values of V_{uns} and V_{st} .

V_{uns} and V_{st} tend to increase with standoff distance and helium content in the shielding gas (figures 7.23 and 7.24). The mean value of the difference between V_{uns} and V_{st} , however, decreased with helium content and also with welding current (figure 7.25). On the other hand, oxygen addition caused an increase in $(V_{\text{uns}} - V_{\text{st}})$, mainly by dropping V_{st} (compare plots for pure Ar and Ar-2%O₂, figure 7.23).

7.2.4. Tests with pulsed current

Bead-on-plate welds were deposited using He-1 or He-2 gas mixtures with different oxygen additions and wire feed rates. The Fronius TPS500 power supply was used in pulsed CVCC mode. The current trace was recorded with a logging time of 0.100 ms, a few seconds after the stabilization of welding conditions. The resulting data files were processed and the pulsed current parameters measured (table 7.4).

A trend similar to that of the previous sections was also detected with CVCC pulsed current operation. Particularly, a transition from a condition characterized by spray transfer and a stable and quiet arc to one dominated by unstable repulsive metal transfer was observed when the arc was shortened. The arc length seemed to change during the transition but not as clearly as with CV operation. One initial difficulty was to define a parameter to characterize the instability process in pulsed current. Both mean voltage and current tended to fluctuate more strongly during unstable behaviour but a clear tendency was not observed. However, test results indicated that a good correlation between process behaviour and the standard deviation of the peak current could be attained. Consequently, this parameter was selected to quantify the arc length dependent process instability under pulsed current (CVCC) operation.

The influence of wire feed rate and oxygen content in the gas on the process stability measured by the standard deviation of peak current (s_p) is shown in figure 7.26. This figure indicates that the unstable operation, which is associated with a value of s_p over 20A, tends to predominate for short arc operation (i. e., for high wire feed rate) and a low oxidizing potential of the shielding gas.

The current trace from bead-on-plate and narrow gap welding performed with different helium contents in the shielding gas (§7.3, table 7.5) was also studied to evaluate the effect of helium content in process stability (table 7.6 and figure 7.27).

7.3. Fusion characteristics

In order to study the effect of the helium content in Ar-He-2%O₂ mixtures on weld bead characteristics, bead-on-plate and narrow gap specimens were welded with different gas compositions (table 7.5). The trials were carried out using pulsed current (CVCC mode). The value of the welding current was recorded with a logging time magnitude of 0.100ms and used to calculate the pulse characteristics (table 7.6). Two transverse macrographs were prepared from each welded specimen and the bead geometric parameters measured from them (figure 7.28 and 7.29). The weld bead geometric parameters defined in §5.2.3 were measured in the narrow gap specimens. Similar parameters were used for bead-on-plate specimens (figure 7.30). Furthermore, dilution (δ) and penetration factor (f_p) were also measured to indicate plate fusion tendencies. Dilution was defined as usual:

$$\delta = A_a / (A_a + A_d) = A_a / A_t \quad [7.1]$$

while f_p was defined as:

$$f_p = 100 \cdot (p_1 + p_2) / p_{\max} \quad [7.2]$$

where p_1 , p_2 and $p_{\max}$ are shown in figure 7.30.

The measured bead parameters are presented in table 7.7. The influence of the helium content in the shielding on some bead characteristics for both narrow gap and bead-on-plate is shown in figures 7.31 and 7.32. It was found that axial penetration area in both NG and BOP welding trials and lateral penetration area in NGW trials increased with %He in the shielding. This increase was mainly associated with the secondary penetration while the finger penetration ($p_{\max}$) remained approximately constant at around 3.5mm for the bead-on-plate trials performed with the shielding gases that contained helium. The increase in fused area (A_a or A_p) results also in an improvement in dilution and penetration factor. There is a clear tendency for bead area to be greater in BOP than NG welding under similar conditions. A difference of around 10% between BOP and NG bead areas was found for the shielding gases containing He, independently of its actual content. Under Ar-O₂ shielding, a slightly higher difference (15%) was obtained. This difference resulted mainly from a reduction in A_a in NGW which was not entirely compensated by lateral fusion of the side walls. This may be explaining by the confining effect of the groove walls which would increase the weld pool height and make it more difficult for the arc to reach the base metal at the bottom of the joint. The results also indicated a tendency for deposited area be slightly smaller in welding trials with higher helium contents for both BOP and NG welding. Finally, bead width in BOP welding and mean bead height and H/W ratio in NGW were not significantly affected by gas composition.

7.4. Power supply characteristics

In spite of the enormous recent progress in process control and power supply electronics, constant voltage operation is still quite popular mainly due to its simple and effective self-adjusting arc capability (§2.2.6.2). However, this characteristic is strictly operative only for bead-on-plate welding or a similar geometric arrangement. Under these conditions and if the standoff distance is kept constant, any small variation in arc length is compensated by an opposite variation in stickout, i. e.:

$$h = s + l_a, \text{ and} \quad [5.1]$$

$$d(l_a) = -d(s) \quad [7.3]$$

Inside a narrow gap joint, two extreme conditions can be defined:

- . If the arc is short enough, it will root mainly on the bottom of the joint and the weld pool edges. The resulting system will respond to small perturbations similarly to bead-on-plate welding (figure 7.33a).
- . If the arc becomes too long, it will tend to deflect to the joint sidewalls and not reach the bottom of the joint. In this situation, the arc length will remain essentially constant and independent of the stickout (figure 7.33b):

$$d(l_a) = 0 \quad [7.4]$$

Intermediate conditions should prevail for operative conditions between these two extremes.

To investigate the response of the GMAW system to small perturbations, the summation of voltage drops around the current loop is considered (figure 7.34):

$$V = V_{\text{arc}} + V_s \quad [7.5]$$

Where V is the mean voltage provided by the power supply and measured between the workpiece and the torch contact tip,

V_{arc} is the arc voltage, and

V_s is the voltage drop along the electrode stickout.

For small variations the arc voltage can be considered independent of current and be represented approximately by equation [2.2]:

$$V_{\text{arc}} = V_a + V_c + El_a \quad [2.2]$$

The voltage drop in the electrode stickout is difficult to quantify because of the complex temperature profile in the stickout. However, the effective wire resistivity (ρ) can be

considered approximately independent of the welding current (Lund 1979 and Waszink and van den Heuvel 1979). This assumption can be considered valid particularly if the study is restricted to only small perturbations of the system about an established operating point. The resulting expression for the voltage drop in the stickout is therefore:

$$V_s = (\tau/A_w)sI \quad [7.6]$$

Substituting [2.2] and [7.6] in equation [7.5] and taking the derivative results:

$$d(V) = (\tau/A_w)s.d(I) + (\tau/A_w)I.d(s) + Ed(l_a) \quad [7.7]$$

In bead-on-plate welding, if the standoff distance is kept constant, relation [7.3] can be applied. For constant voltage operation, the power supply characteristic can be represented by:

$$V = V_0 - RI \quad [7.8]$$

where V_0 is the open circuit voltage, and

R is a resistive term linked to the power supply slope. Therefore:

$$-Rd(I) \approx (\tau/A_w)s.d(I) - (\tau/A_w)I.d(l_a) + Ed(l_a), \text{ or:}$$

$$\frac{dI}{dl_a} = \frac{(\tau/A_w)I - E}{R + (\tau/A_w)(h - l_a)} \quad [7.9a]$$

Where R [V/A] is the power supply slope.

Considering, for a 1.2mm mild steel wire and a welding current of 300A, $\tau/A_w \approx 1 \text{ } \Omega/\text{m}$, based on its electrical resistivity at approximately 800°C (ASM 1978), $R = 1\text{V}/100\text{A}$ and $E = 800 \text{ V/m}$ (Allum 1986), the derivative in [7.9a] will be equal to (in A/m):

$$\frac{dI}{dl_a} = \frac{500}{(1E - 2) + (h - l_a)} \quad [7.9b]$$

The negative value for the derivative in [7.9] just expresses the arc self-regulating capability in CV operation, i. e., the opposite direction of change for welding current and arc length. In CC operation, $d(I) = 0$ and:

$$\frac{dV}{dl_a} = -\frac{dV}{ds} \approx E - (\tau/A_w)I \approx 500\text{V/m} \quad [7.10]$$

Naturally, the arc self-regulation by variations in current does not operate in this case. Some arc length regulation can still be obtained, for wires of high electrical resistivity, through the effect of the stickout on the wire melting rate (equation [2.11]).

In narrow gap welding, for short arc operation (arc length less than some fraction of the gap width), expressions [7.9] and [7.10] can be considered still valid. However, if the arc is long enough to be deflected to the sidewalls, the different geometric configuration implies that [7.3] is not valid any longer and equation [7.4] should be used instead, then:

$$d(V) = (\tau/A_w)s.d(I) + (\tau/A_w)I.d(s) \quad [7.11]$$

and, for CV operation:

$$\frac{dI}{dl_a} = - \frac{(\tau / A_w)I}{R + (\tau / A_w)s} \quad [7.12]$$

Therefore, in a narrow gap joint, if the arc is long enough to deflect to the sidewall, the welding current will tend to increase in response to any reduction in stickout. This is an unstable condition because it will result in an increase in the wire melting rate and, therefore, in further reduction of the stickout. This result indicates that welding inside a very narrow gap with constant voltage can result in unstable behaviour if the arc deflects to the joint's sidewall as was previously observed by Matsunawa and Nishiguchi (1979). They, however, associated the problem with the distribution of cathode spots on the workpiece (§2.3.2). The present mechanism presents a simpler and more plausible explanation. The unstable behaviour will not be present in constant current operation which will still retain some self-regulation capability due to resistance heating of the wire.

7.5. Discussion

7.5.1. Arc length dependent stability

7.5.1.1. Introduction

The present study revealed process instability phenomena that depended on several factors, such as arc length, shielding gas composition, power supply characteristics and time. Disturbances in both arc shape and metal transfer were associated with the instability processes. When welding was performed with a constant voltage power supply, strong fluctuations in arc length and current level could be observed. Significant variations in arc length were not detected for constant current operation but a clear change in metal transfer and arc appearance could still be produced by shortening or elongating the arc.

Surprisingly, no direct study of these phenomena could be found in the literature, although, many references do exist to unexpected instabilities and process behaviour changes. Lucas

and Amin (1975) assigned alterations in metal transfer to the deoxidation level of GMAW steel wires of the same grade. Exploding drop transfer was associated with high oxygen levels in the wire whilst stream spray transfer predominated for low oxygen levels. No influence of shielding gas composition could, however, be found. In a paper studying arc stabilization by rare earth additions, Agusa et al. (1981) mention unstable operation with periodic spray transfer and wire stubbing in the welding of mild steel under pure argon shielding. Scale on the plate surface could prevent wire stubbing. Kiyohara et al. (1977 and 1979) linked changes in drop size and wire melting rate in the spray GMAW of aluminum with arc length. Rodwell (1985) studied arc disturbances and variable weld bead shape in the spray GMAW of stainless and mild steels. Sudden and violent changes in arc length and current level were associated with contamination on the wire surface and contact tip wear. Middleton (1988) observed an unexpected increase in voltage at short arc lengths during development of an arc-voltage-control system for the GMA welding of Inconel with constant current. Though this phenomenon resulted in the abandonment of the project, no further study of it was performed. Foote (1986) observed arc instability in bead-on-plate GMAW trials with Helishield 1 and certain wire compositions. A paper from Hazlett and Gordon (1957) shows welding current traces that present abrupt and unexpected changes in current level. However, no comment regarding this behaviour was made.

The present work has demonstrated the existence of an arc stability problem which was linked to shielding gases of low oxidising potential and short arc operation. Although oxygen level in the shielding is generally kept high enough to prevent this instability problem during the welding of mild or low alloy steels, completely inert shielding is necessary for most of the nonferrous alloys and a low oxidizing one can be advantageous for the welding of high alloy steels. The unstable behaviour was first observed in narrow gap welding trials with He-1 and, later, in bead-on-plate welding with He-101. Both of these commercial Ar-He shielding mixtures are formulated with only a low CO₂ content, sometimes with some residual oxygen (table 3.2). They were originally developed for the welding of stainless steels but have been also considered appropriate for mild and low alloy steel welding (Hilton and McKeown 1986). A stable spray operation could be obtained with these mixtures provided that an arc longer than about 5mm was used. Such a long arc was considered inadequate for the situation being analyzed in the present work even though it could be acceptable for other applications and is commonly used in experimental work with the GMAW process.

7.5.1.2. Phenomenological aspects

The following aspects have been disclosed by experimental results of §7.2:

- . Time dependency: Generally, the results of the experimental work indicated that the possibility of instability decreases with time. This was particularly evident for constant voltage operation where two very distinct stages could often be noticed, the unstable one tending to occur first. A time scale for transition from unstable to stable process of 10⁰-10¹s was observed with CV operation. When the shielding mixture presented

some oxidizing potential, the stable process did not tend to revert back spontaneously into the unstable one. For pure argon shielding, however, the process could return to unstable operation with the arc apparently collapsing towards the workpiece in a fashion similar to that described by Agusa et al (1981). The relationship between operating voltage and transition time (t_{us} , figure 7.5) can be approximately represented, for $t_{us} < 14s$, by a straight line. Extrapolating these lines to $t=0$, the expected value of the minimum operating voltage to prevent initial instability can be estimated (table 7.8). In constant current operation, a faster rate of change (time scale between 10^{-3} and $10^{-1}s$) was observed.

Effect of power supply characteristic: The results of the experimental work indicated that the power supply characteristic strongly affects the arc length dependent instability behaviour. Under constant voltage conditions, the transition from unstable to stable operation is marked by a clear change in current level and arc length (figure 7.35). Furthermore, each operating state, particularly the stable one, tends to last at least a few seconds.

In constant current operation, however, it is possible for stable and unstable processes to rapidly alternate with minor changes in arc length (§7.2.3). If the arc length is so short that the unstable process is present, the welding voltage is generally characterized by two distinct voltage levels and photographs indicate that both spray and repulsive transfer occur (figure 7.13).

The differences in process behaviour for CV and CC operation can be explained by analysing the inter-relationship between power supply and arc characteristics, and assuming that, in CC operation, the unstable process (dominated by repulsive drop transfer) is connected with the high voltage periods. This assumption seems to be reasonable as both unstable operation and high voltage periods tend to become less frequent for longer standoff distances. Figure 7.36 presents a diagram of an idealized sequence of events that can be used to represent the transition from unstable (point 1) to stable (point 4) operation when using a power supply of arbitrary slope $(dV/dI)_{ps}$. If the welding process is initially operating at point 1 (unstable operation) when arc behaviour changes into the stable mode, the voltage that it would require from the power supply would drop by $V_{uns}-V_{st}$, (i. e., operation would be moved at point 2 if the power supply presented CC characteristic). Responding to the new operating conditions, the process will tend to operate at point 3. However, once this results in current being increased from I_{uns} to I_{max} , the melting rate will exceed the wire feed rate and the arc length will tend to increase until equilibrium is restored again at some point 4. Both arc length and current variations will depend on the power supply slope. The flatter the power supply characteristic, the higher the variations will possibly be. If only the voltage drop associated with the arc is considered, the variation in current due to the change in process mode can be represented by:

$$I_{st} - I_{uns} = [V_{uns}(1) - V_{st}(4)] / (dV/dI)_{ps} \quad [7.13]$$

Where $V_{\text{uns}}(1)$ and $V_{\text{st}}(4)$ are the voltage levels for unstable and stable process operations at points 1 and 4 respectively. In constant current operation, the transition would be restricted to a change from point 1 to point 2. Therefore, only minor alterations in arc length may be expected if the wire melting rate is not significantly influenced by the transition.

In constant voltage operation, transition into the unstable process mode causes the arc to contract while the stable process makes it elongate. In both cases, the changes in arc length are favourable to the new process and, therefore, make it more difficult for a transition back to the former condition to occur. This agrees with the experimental results that showed longer transition times for constant voltage operation. It also may explain the apparent hysteresis in the transition that could be observed in some initial trials with CV operation as shown in figure 7.1. The higher voltage level associated with the unstable operation can even cause an increase in the mean arc voltage when the arc length is reduced. This result, which is completely unexpected when the unstable process is not considered, can explain the difficulties reported by Middleton (1988) in developing an arc-voltage-control system for the welding of Inconel (§7.5.1.1).

Pulsed current trials presented an intermediate behaviour between CV and CC operations. This could be expected considering the CVCC operation of the Fronius power supply which may be considered to correspond to a drooping characteristic between pure CV and CC operation. This, together with the more complicated current and voltage traces of pulsed operation, made it difficult to study the process stability by direct analysis of its traces. However, the alternative parameter that was employed (standard deviation of the peak current) could be considered satisfactory to represent the stability level associated with the arc length stability problem in CVCC operation. The results of the experimental trials indicate that a value of s_{peak} below 10A corresponds to stable operation while a value above 20A can be associated with unstable operation with repulsive metal transfer.

Arc length (and standoff) dependency: The experimental programme indicated that the likelihood of unstable (high voltage) operation was directly linked with arc length in such a way that it increased when the arc length was shortened. In general, factors that cause a reduction in arc length, such as a reduction in current, standoff distance or arc voltage, or an increase in wire feed rate, will increase the probability of unstable operation.

Short circuit transfer indications were commonly observed in voltage traces of CC welding trials which also indicated unstable operation. However, a closer examination of these traces (§7.2.3) indicate that the short circuits tend to be more frequent during the stable, or intermediate voltage, period. Often, after the occurrence of a short circuit, the process tends to change into unstable operation. However, a short circuit does not

seems to be essential for transition from V_{st} to V_{uns} which frequently takes place spontaneously.

In CC operation, both V_{st} and V_{uns} increase with the standoff distance and, in most cases, the relationship between these parameters and the standoff distance is reasonably represented by straight lines (figures 7.23 and 7.24 and table 7.9). On the other hand, the difference between V_{uns} and V_{st} seems to be less sensitive to the standoff distance.

Influence of shielding gas composition: Only two gas additions (helium and oxygen) to a base gas (argon) were studied in the present programme. Oxygen was considered the key factor in controlling the arc length dependent instability problem while helium was investigated because of its potential in terms of improving fusion in GMAW.

In all the shielding mixtures that contained argon which were evaluated, oxygen additions tended to reduce the likelihood of the unstable process. No significant effect could be detected in a few constant current trials made with He and He-O₂ mixtures. In CV trials, additions of oxygen resulted in shorter t_{us} and lower minimum voltage values to prevent initial instability (table 7.8). Although no arc length measurements were performed, visual observation of the arc indicated that, when oxygen was present, stable operation could be achieved at shorter arc lengths.

In CC trials, the relative frequency of V_{uns} periods at any standoff distance was much lower for Ar-2%O₂ than pure Ar. For all standoff distances over 14mm, the V_{uns} periods were reduced to sharp spikes when using Ar-2%O₂. Oxygen additions caused an overall reduction in the voltage level for stable operation (V_{st}), although the V_{uns} curve seemed to be essentially unaffected. The mean voltage tended also to be lower in Ar-2%O₂ due to the reductions in both V_{us} and unstable operation frequency. The slope of the V_{st} to standoff relationship for Ar-2%O₂ welding is also significantly lower than the slope for welding in pure Ar (table 7.9 and figure 7.37). Assuming that the electrode stickout is approximately independent of the standoff distance for constant current operation, the slope of the V_{st} to standoff curve can be used to obtain a rough estimate of the arc electric field strength, E . The value obtained in the present programme for pure argon shielding (640 ± 120 V/m), although close to, can be considered smaller, with a 95% significance level, than the value commonly presented in the literature (800 V/m). For Ar-2%O₂ shielding, an even smaller value (310 ± 40 V/m) was found.

Both CC and pulsed current experimental trials indicate that a helium content up to approximately 75% does not significantly affect arc behaviour with regard to the arc length process instability problem. Oxygen additions to mixtures containing up to this level of helium are effective in terms of reducing arc instability/metal transfer problems. In pure helium shielding, metal transfer tended to be globular, independent of the arc length, for the current levels used. As the spray-globular transition current

for helium shielding is considered higher than for argon (Rimskii et al. 1979), it is possible that, at current levels greater than those used here, spray transfer may be observed with helium shielding. In the CC tests, pure He shielded welding was apparently less unstable at longer standoff distances. This can be observed in the frequency plots of figures 7.17 and 7.22, by the narrower voltage distribution for longer standoff. As the standoff distance decreases, the stability of the helium shielded trials worsens considerably, abundant short circuiting happens and the mean process voltage drops sharply to levels that are even below the mean voltage for Ar-75%He welding. The difference between V_{uns} and V_{st} was shown to decrease at a rate of approximately $5E-2$ V/%He with the helium content in the shielding gas (figure 7.25). This reduction is associated with the tendency of V_{st} to increase faster than V_{uns} with the content of He in the shielding (figures 7.23 and 7.24). The slope of both V_{st} and V_{uns} against the standoff distance also increase with the helium content (figure 7.37 and table 7.9).

- . Effect of welding current: The results of CC trials indicated that an increase in the welding current from 260A to 300A causes the difference between V_{uns} and V_{st} to drop by approximately 1.5V independent of the helium content in the mixture (figure 7.25).
- . Effect of joint type: Although no systematic study was performed to evaluate the influence of the joint type on the process stability, some results of pulsed current trials seem to suggest that narrow gap welding presents a lower sensitivity to instability when compared with bead-on-plate welding (figure 7.27).

7.5.1.3. Tentative mechanism

The present experimental work revealed a clear association between arc length dependent instability problems and oxygen levels in the shielding gas. The favourable influence of oxygen in both arc stability, metal transfer and bead shape in GMAW welding of steel is well established. In terms of arc stability, oxide films are considered essential to the formation and stabilization of cathode spots which are generally located on the workpiece and close to the molten pool (Essers and van Gessel 1984, §2.2.2). When welding with pure argon shielding is performed on a relatively clean steel plate, the arc will quickly consume the oxide layer beside the weld pool and move outwards erratically on the surface of the plate resulting in a process that is more difficult to control (Boughton and Amin 1972). In the presence of an oxidising medium, the oxide layer located close to weld pool can be continuously regenerated resulting in the arc root being fixed at this position.

Experimental results elsewhere indicate that the addition of up to 5% oxygen to argon can reduce the spray-globular transition current of steel consumables. This reduction has been related to different factors such as increase in arc temperature (Brosilow 1978), magnetic effects associated with the paramagnetic nature of oxygen (Rimskii et al. 1979) and a

reduction in the surface tension of the molten electrode tip (Kennedy 1970, Norrish and Hilton 1988).

Finally, the presence of an oxidising component in the shielding can smooth the weld bead profile, reducing its wetting angle and reinforcement height, improve bead penetration and reduce undercutting tendency by decreasing the surface tension of the molten pool (Salter and Dye 1971, Norrish and Hilton 1988) or stabilizing the position of the arc root (Cresswell 1972).

It is the view of the author of the present work that it has demonstrated the existence of a further aspect of arc rooting problems that is closely related to arc length and the oxidising potential of the shielding gas. This particular phenomenon, although closely related to relatively well established aspects of the gas shielded welding of steel and resulting in strong changes in process behaviour, does not seem to have been reported in the literature to date. Instabilities at the start of GMA welds on steel are commonly observed and often explained by experienced welders by the low initial temperature of the workpiece. When working with a CV power supply, the arc tends to revert into stable operation a few seconds after its initiation, hence the problem has not been perceived as significant. In constant current operation, however, the transition in operating mode do not necessarily result in a longer arc and, if the shielding gas has a low oxidising potential (2% or less of oxygen or carbon dioxide), the unstable period can last longer, particularly, if a short arc is being used.

Although the experimental work in the present programme has not been planned to explore the fine details of arc physics that would be necessary for a more complete understanding of this arc length dependent instability, a tentative descriptive model can be developed to explain some aspects of the phenomenon.

Figure 7.38 presents a schematic representation of the GMAW arc region. Point C indicates the location of the cathode spots and the displacement r corresponds to their position in relation to the electrode-arc axis (OA). Under a shielding gas relatively rich in oxygen, the cathode spots will be located just at the edge of the weld pool and r will be at its minimum value. However, if the oxidising potential of the shielding gas is not sufficiently high, the cathodic region may have to expand in order to reach fresh oxide areas and r will be greater than this minimum value. An estimate of r can be obtained by considering that the oxide area that should be consumed by the arc per unit time in order to sustain the welding current (A_I) results both from fresh oxide areas that are brought to the arc region by welding torch translation (A_V) and surface oxide created in the arc region by any oxygen presented in the shielding (A_O):

$$A_I = A_V + A_O \quad [7.14]$$

In a first approximation, A_O can be considered proportional to the partial pressure of oxygen (p_{O_2}) in the shielding:

$$A_O = k_0 \cdot p_{O_2} \quad [7.15]$$

and:

$$A_V = (2r) \cdot v \quad [7.16]$$

where v is the welding speed. Therefore, by rearranging equations [7.14], [7.15] and [7.16]:

$$r = \frac{A_I - k_0 p_{O_2}}{2v} \quad [7.17]$$

Boughton and Amin Mian (1972) estimate that a 0.2 to 0.5 μm thick oxide layer would be consumed by the arc at a rate of $0.6 \text{ mm}^2/\text{As}$. So, for a 250A arc, $A_I \approx 150 \text{ mm}^2/\text{s}$. If the shielding gas is pure argon ($p_{O_2}=0$) and the welding speed is 7mm/s, the calculated displacement r of the cathodic region would be equal to approximately 10mm. In the presence of a small amount of oxygen in the shielding gas, r would be quickly reduced to its minimum value.

The cathodic displacement will result in an increase in the real arc length of the process. An estimate of this length can be given by (figure 7.38):

$$l_a(r) = (r^2 + l_a^2)^{1/2} \quad [7.18]$$

Which forms an angle θ with the electrode-arc axis:

$$\theta = \tan^{-1}(r/l_a) \quad [7.19]$$

Both $l_a(r)$ and θ will increase if r increases, for instance, by decreasing the oxygen potential in the shielding. θ can also be increased by decreasing the arc length l_a . For very short arc operation, θ can become so large that it would be very difficult for the arc to preserve its contact with the cathodic region and the resulting system would be very unstable. In this condition the arc may either extinguish or change to a different operating condition. It is proposed here that the latter can take place by the development of a new cathode spot operating under a different mechanism and located on the weld pool surface. Different mechanisms have been proposed in the literature for cold cathode operation, although mainly, in relation to vacuum arc processes. Vapour dominated cathodes are reported to develop in vacuum arcs on oxide free surfaces (Guile 1982) and their presence has also been suggested in welding arcs (Boughton and Amin Mian 1972). Changes in cathode operation mechanisms in vacuum arcs have been associated with abrupt variation in voltage (Fu 1989).

Based on the aspects discussed above, a descriptive model can be proposed for the arc length instability process (figure 7.39). For a given welding condition, r is approximately constant if the process is operating only in "stable" mode and is given by equation [7.17]. In this case, if the arc is shortened for any reason, θ will tend to increase and the existence of a critical value

of θ (θ_c), can then be postulated above which maintenance of contact with the cathodic region (point c, figure 7.39(a)) is so difficult that a new cathode spot (point c', figure 7.39(b)) is formed at the centre of the weld pool. This new cathode spot would operate by a mechanism possibly independent from surface contamination which, by being less energetically favourable than the previous condition, would result in a higher arc voltage (figure 7.39(c)). As the cathodic region would now be concentrated only one spot, a plasma jet directed from the weld pool to the electrode would be formed and would tend to blow the molten tip of the wire away from the pool, i. e., metal transfer would change into a repulsive mode. During single spot operation, oxide layers on the surface of the workpiece would not be consumed and would be brought closer to the arc region by both translation of the torch and surface reoxidation. Consequently, for a fixed arc length θ would decrease and make it easier for the process to operate again from the oxide sites, cathode spots would be formed back on the plate surface, the arc shape would change and spray operation would be restored for a period of time during which the oxide layer would be consumed. θ would increase again creating conditions for the formation of a new single spot in the pool.

Therefore, the welding system would tend to alternate periods of multi- and single-spot operation with different voltage levels as observed in the CC operation trials (figure 7.39(c)). In a shielding gas containing oxygen, r would tend to be smaller than in pure inert gas welding (equation [7.17]). Consequently, a smaller value of $I_a(r)$ could be expected which would partially explain the lower V_{st} values of welding trials with Ar-2%O₂ compared with pure argon. Lower values of r and θ would also reduce the tendency to unstable periods. In CV welding, the transition from stable to unstable mode will shorten the arc as discussed in §7.5.1.2 causing a further increase in θ that would make it even more difficult for the process to return to stable operation. Similar but opposite changes in I_a and θ would apply to the transition from unstable to stable operation.

The descriptive model presented above is obviously an oversimplification of the complex processes taking place in the arc during the changes in operation stability. Even so, it provides reasonable explanations for many aspects of the phenomenon such as arc length and oxygen dependencies and the influence of the power supply. The model does not consider the influence of time and, therefore, cannot deal with the apparent greater likelihood of unstable operation in the first moments of welding. Time dependency may be linked somehow with workpiece temperature distribution but no explanation was found for it.

7.5.2. Shielding gas/process optimization

7.5.2.1. Shielding gas

According to different authors additions of helium to an argon based shielding gas result in several changes in arc shape and behaviour, metal transfer and weld bead characteristics (§2.2.5). Generally, the results obtained in the present programme seem to agree well with

previous works regarding the influence of the helium content in shielding on the welding characteristics.

It has been found that fusion characteristics in both bead-on-plate and narrow gap welding was improved by increasing %He in the shielding. This improvement in fusion was mainly associated with an increase in secondary fusion in the workpiece whereas fusion related to finger penetration was little affected. Gurev and Stout (1963) related plate fusion in GMAW with two distinct mechanisms: (a) the finger-shaped region would be formed by the action of arc pressure and superheated metal drops on the workpiece and (b) the approximately elliptical region out of the finger (secondary fusion region) that would be formed with time by heat transport in the weld pool from the arc and the finger region. Regarding the finger penetration, the present results seem to indicate that the net arc action on the plate was little affected by gas composition under the pulsed welding conditions employed. The secondary fusion was, however, positively influenced by the higher energy of the arc associated with the presence of helium which resulted in a higher arc voltage (figure 7.40).

An unfavourable influence of helium content was found above 75% He when metal transfer and arc stability deteriorate, probably due to a sharp increase in the spray-globular transition current. Furthermore, oxygen additions appear to reduce problems of arc length dependent instability for all the gas compositions studied except pure helium.

Based on these results it was decided to implement in experimental steps S2-B1 and S3-B1 (chapter 5) a gas mixture containing approximately 75%He, 2%O₂ and argon. This gas composition was considered to achieve a balance between good arc stability and improved fusion in the ternary system Ar-He-O₂.

7.5.2.2. Power supply characteristics

The analysis of the interactions between power supply characteristics and joint geometry performed in section §7.4 indicated that, in a narrow gap joint two extremes situations can take place:

- (a) For a short arc operation (here "short" means an arc shorter than approximately half of the gap width) the process resembles bead-on-plate operation as far as its interactions with the power supply are concerned. Therefore, in short arc operation some arc self-adjustment capability based on a constant voltage component in the power supply characteristic will be desirable to control and prevent wire stubbing on the plate.
- (b) For long arc operation, however, such a constant voltage component would result in the process presenting unstable behaviour in terms of arc length control.

In an attempt to optimize the power supply response to the gap geometry and based on equipment available a mixed characteristic operation was implemented in experimental steps

S2-B1 and S3-B1 (chapter 5). This proposed operational mode involved constant voltage characteristic below a certain limit and constant current above this limit (figure 7.41). This operation with mixed characteristics allows control of arc length for short arc operation and does not generate a tendency for unstable arc wander along the joint side walls.

7.5.2.3. Steady and pulsed current

Based on the results of previous work (Fennel 1986), experimental blocks S0 and S1 (chapter 5) were performed with pulsed CVCC operation. However, once the mean welding current was generally kept above the spray-globular transition for a 1.2mm wire, the use of simpler continuous current operation could be considered. Even though it was considered that process stability might be impaired by the move into steady current, it was expected that the use of a current close to the transition level together with the optimized gas mixture would prevent a major worsening in process stability. Furthermore, steady current operation could result in a substantial reduction in wire melting rate by reducing the Joule heating of the wire. This reduction can be estimated through equation [2.13b]:

$$w - w_{np} = \beta s (I_p - I_b)^2 t_p t_b / (t_p + t_b) \quad [2.13b]$$

Taking $\beta = 5 \times 10^{-5} \text{ A}^{-2} \text{ s}^{-1}$ (Allum 1983), and supposing, for instance, $s = 18 \text{ mm}$, $I_p = 500 \text{ A}$, $I_b = 100 \text{ A}$, $t_p = 2 \text{ ms}$ and $t_b = 3 \text{ ms}$ as typical values for pulsed operation, the calculated increase in melting rate in pulsed current operation due to Joule effect would over 2 m/min . As low dilution and, consequently, fusion defects were major problems associated with the process, the reduction in fusion was considered to have a potential beneficial effect in terms of reducing fusion problems and was, therefore, adopted in experimental steps S2 and S3.

Table 7.1 Experimental conditions and results for the process stability tests with CV operation.

Shielding gas	Voltage (V)	I _{un} * (A)	I _{st} * (A)	t _{us} * (s)
Ar	33.0	255	-	>15.0
Ar	34.7	310	360	3.1
Ar	35.2	330	385	3.6
Ar+1%O ₂	31.8	270	345	7.1
Ar+1%O ₂	33.0	270	365	4.4
Ar+1%O ₂	33.0	260	345	4.2
Ar+1%O ₂	33.5	270	330	3.7
Ar+1%O ₂	34.1	-	370	0.3
Ar+2%O ₂	30.7	275	355	4.0
Ar+2%O ₂	31.8	285	360	2.7
Ar+2%O ₂	33.0	-	360	0.6
H101	33.5	265	-	>25.0
H101	34.7	275	335	12.4
H101	34.7	230	295	11.9
H101	35.8	240	310	12.9
H101	35.8	230	305	8.5
H101	36.0	235	315	10.4
H101	36.4	240	310	8.7
H101	37.5	260	330	4.4
H101	37.5	250	325	1.0
H101	38.1	260	325	3.8
H101	38.1	255	320	1.7
H101+1%O ₂	32.4	260	-	>25.0
H101+1%O ₂	34.1	270	315	14.2
H101+1%O ₂	34.7	265	320	11.7
H101+1%O ₂	36.4	270	330	6.5
H101+1%O ₂	37.5	285	335	4.7
H101+3%O ₂	33.5	265	305	7.6
H101+3%O ₂	34.1	260	305	8.2
H101+3%O ₂	34.6	265	310	2.9
H101+3%O ₂	34.7	-	330	0.0
H101+3%O ₂	35.8	-	325	0.0
H101+4%O ₂	30.7	255	295	14.0
H101+4%O ₂	31.8	-	305	0.4
H101+4%O ₂	31.8	255	300	9.3
H101+4%O ₂	33.0	255	305	2.8
H101+4%O ₂	33.0	-	305	1.1
H101+4%O ₂	34.5	-	310	0.0

Power supply:
Wire feed rate:
(*) See figure 7.4

Fronius
9 m/min

Standoff distance:
Initial voltage: 27 V

22 mm

Table 7.2 Experimental conditions used with the constant current process stability trials.

Trial #	Shielding gas	Welding current (A)	Wire feed rate (m/min)	Standoff distance (mm)	OBS
A1	Ar	260	8	14	
A2	Ar	260	8	17	
A3	Ar	260	8	17	
A4	Ar	260	8	20	
A5	Ar	260	8	20	
A6	Ar	260	8	20	
A7	Ar	260	8	23	
A8	Ar	260	8	23	
A9	Ar	260	8	26	
A10	Ar	260	8	26	Chamber
A11	Ar	260	8	29	Chamber
A12	Ar	260	8	32	Chamber
A13	Ar	300	10	14	
A14	Ar	300	10	17	
A15	Ar	300	10	17	
A16	Ar	300	10	20	
A17	Ar	300	10	20	
A18	Ar	300	10	23	
B1	Ar-25%He	260	8	14	
B2	Ar-25%He	260	8	17	
B3	Ar-25%He	260	8	20	
B4	Ar-25%He	260	8	23	
B5	Ar-25%He	260	10	14	
B6	Ar-25%He	260	10	20	
B7	Ar-25%He	260	10	23	
B8	Ar-25%He	260	10	26	
B9	Ar-25%He	300	10	14	
B10	Ar-25%He	300	10	17	
B11	Ar-25%He	300	10	20	
B12	Ar-25%He	300	10	23	

cont.

Table 7.2(cont) Experimental conditions used with the constant current process stability trials.

Trial #	Shielding gas	Welding current (A)	Wire feed rate (m/min)	Standoff distance (mm)	OBS
C1	Ar-75%He	260	8	14	
C2	Ar-75%He	260	8	17	
C3	Ar-75%He	260	8	20	
C4	Ar-75%He	260	8	23	
C5	Ar-75%He	260	8	26	
C6	Ar-75%He	300	10	14	
C7	Ar-75%He	300	10	17	
C8	Ar-75%He	300	10	17	
C9	Ar-75%He	300	10	20	
C10	Ar-75%He	300	10	23	
C11	Ar-75%He	300	10	26	
D1	He	260	8	14	
D2	He	260	8	17	
D3	He	260	8	20	
D4	He	260	8	23	
D5	He	260	8	26	
D6	He	260	8	26	
D7	He	300	10	14	
D8	He	300	10	17	
D9	He	300	10	20	
D10	He	300	10	23	
E1	Ar-2%O ₂	260	8	14	
E2	Ar-2%O ₂	260	8	14	
E3	Ar-2%O ₂	260	8	17	
E4	Ar-2%O ₂	260	8	20	
E5	Ar-2%O ₂	260	8	23	

CONSTANT FACTORS

Power supply: GEC (AWP) M500

Operation mode: Constant current

Short cir. det.: 15 V

Wire diameter: 1.2 mm

Weld. position: Downhand

Weld. speed: 6 mm/s

Gas flow rate*:

20 l/min (Ar)

23 l/min (Ar-25%He)

35 l/min (Ar-75%He)

60 l/min (He)

* Gas flow rates calculated by equation [3.2] (except for Ar and Ar-2%O₂).

Table 7.3 Results of the constant current process stability trials.

Trial #	Standoff distance (mm)	V_{mean} (V)	V_{st} (V)	V_{uns} (V)
A1	14	28.6	25.5	34.0
A2	17	30.6	27.0	36.5
A3	17	29.8	26.5	36.0
A4	20	30.9	28.3	37.5
A5	20	31.0	28.5	37.0
A6	20	29.2	28.5	38.0
A7	23	31.9	31.9	-
A8	23	31.4	31.4	-
A9	26	32.0	32.0	-
A10	26	34.8	31.4	40.0
A11	29	35.4	34.2	41.9
A12	32	37.4	37.4	-
A13	14	28.6	25.8	33.3
A14	17	31.9	28.3	34.3
A15	17	31.9	27.3	34.0
A16	20	32.0	32.0	-
A17	20	32.2	30.0	36.5
A18	23	34.5	34.5	-
B1	14	31.0	27.5	35.3
B2	17	32.9	28.8	36.8
B3	20	34.0	32.0	38.0
B4	23	35.7	36.0	-
B5	14	25.3	25.0	31.5
B6	20	30.9	28.0	35.0
B7	23	33.5	29.8	36.0
B8	26	36.7	30.8	38.0
B9	14	30.9	28.8	34.5
B10	17	32.5	30.5	35.0
B11	20	36.0	36.0	-
B12	23	37.0	37.0	-

cont.

Table 7.3(cont) Results of the constant current process stability trials.

Trial #	Standoff distance (mm)	V_{mean} (V)	V_{st} (V)	V_{uns} (V)
C1	14	32.2	30.0	36.0
C2	17	36.6	33.0	39.0
C3	20	38.6	36.0	41.0
C4	23	40.3	39.5	42.8
C5	26	42.0	42.0	-
C6	14	32.5	31.5	35.3
C7	17	37.4	36.0	38.5
C8	17	37.2	35.5	38.5
C9	20	40.2	38.0	41.5
C10	23	42.2	41.0	44.3
C11	26	43.7	43.7	-
D1	14	30.8	-	-
D2	17	33.6	-	-
D3	20	41.4	-	-
D4	23	43.9	-	-
D5	26	45.0	-	-
D6	26	44.6	-	-
D7	14	32.4	-	-
D8	17	34.9	-	-
D9	20	41.9	-	-
D10	23	43.3	-	-
E1	14	26.7	23.5	36.0
E2	14	25.7	23.5	36.0
E3	17	24.5	24.5	37.5
E4	20	25.5	25.5	39.0
E5	23	26.2	26.2	-

Table 7.4 Experimental conditions and measured current structure parameters in the pulsed current trials with He-1 and He-2 gases.

Gas	Wire feed rate(m/min)	I _{mean} (A)	I _{peak} (A)	s _{peak} (A)	t _{peak} (ms)	Frequency (Hz)
He1	10	274	454	57	2.11	199
He1	12	307	513	35	2.31	200
He1+3%O ₂	10	267	449	7	2.07	200
He1+3%O ₂	10	270	453	8	2.09	200
He1+3%O ₂	11	270	452	48	2.06	203
He1+3%O ₂	11	270	460	53	2.10	200
He1+3%O ₂	12	287	482	43	2.23	200
He1+5%O ₂	10	269	447	7	2.10	200
He1+5%O ₂	11	274	463	6	2.14	200
He1+5%O ₂	11	279	468	7	2.16	200
He1+5%O ₂	12	286	483	14	2.23	200
He1+5%O ₂	12	287	485	18	2.24	199
He2	10	252	480	45	2.14	198
He2	11	269	499	34	2.26	197
He2	12	277	504	32	2.35	197
He2	12	310	512	37	2.31	196
He2+3%O ₂	10	248	480	9	2.14	190
He2+3%O ₂	11	249	481	55	2.12	190
He2+5%O ₂	10	246	473	5	2.17	191
He2+5%O ₂	11	257	497	9	2.19	191
He2+5%O ₂	12	265	502	15	2.26	192

Table 7.5 Experimental conditions for bead-on-plate and narrow gap welding trials with different Ar-He-2%O₂ shielding mixtures.

Trial #	Ar/He ratio	Specimen type*	I _b (A)
1	1/0	BP	50
2	1/0	BP	50
3	1/0	NG	50
4	1/0	NG	50
5	7/3	BP	50
6	7/3	BP	50
7	7/3	NG	50
8	7/3	NG	50
9	3/7	BP	100
10	3/7	BP	100
11	3/7	BP	100
12	3/7	NG	100
13	3/7	NG	100
14	0/1	BP	100
15	0/1	BP	100
16	0/1	NG	100
17	0/1	NG	100

CONSTANT FACTORS

Power supply: Fronius TPS500

Peak voltage: 40 V

Operation mode: CVCC pulsed

Peak time: 2 ms

Gas flow rate: see table 4.9

Frequency: 200 Hz

Wire diameter: 1.2 mm

Weld. position: Downhand

Gap width: 7 mm

Weld. speed: 7 mm/s

Wire feed rate: 12 m/min

* BP - Bead-on-plate welding

NG - Narrow gap welding

Table 7.6 Measured current structure parameters in the pulsed current trials with different Ar-He-2%O₂ mixtures.

Trial #	V_{mean} (V)	I_{mean} (A)	I_{peak} (A)	s_{peak} (A)	t_{peak} (ms)	Frequency (Hz)
1	23.5	250	506	5.5	2.12	199
2	23.5	255	502	3.8	2.06	198
3	21.5	255	507	4.0	2.11	195
4	22.5	250	507	4.3	2.09	198
5	25.0	245	504	6.0	2.10	198
6	24.5	253	504	5.0	2.11	195
7	24.5	245	503	6.3	2.11	197
8	23.5	255	507	3.7	2.15	196
9	29.2	250	497	30.6	2.08	198
10	29.0	250	492	34.6	2.04	198
11	30.0	255	489	38.0	2.07	198
12	29.0	250	510	4.6	2.14	198
13	29.5	260	512	4.5	2.21	198
14	30.0	240	495	38.8	2.02	198
15	31.5	250	489	36.2	2.05	199
16	30.0	240	495	18.2	1.98	198
17	31.5	250	480	42.0	2.03	198

Table 7.7 Weld bead characteristics for different He/Ar ratios. (a)Bead-on-plate welding, (b)narrow gap welding.

(a)

He/Ar -	Bead Nb	A _t (mm ²)	A _d (mm ²)	A _f (mm ²)	Dil. (%)	P _{max} (mm)	f _{pen} (%)	Width (mm)
0/1	1	47.9	33.2	14.7	31	3.1	25	11.4
0/1	2	46.1	33.8	12.3	27	3.1	27	11.9
Mean	-	47.0	33.5	13.5	29	3.1	26	11.7
3/7	1	44.1	29.7	14.4	33	3.3	35	12.1
3/7	2	46.0	30.3	15.7	34	3.4	38	12.1
Mean	-	45.1	30.0	15.1	34	3.4	37	12.1
7/3	1	51.1	31.4	19.7	39	3.6	49	13.3
7/3	2	49.1	30.3	18.8	38	3.3	74	12.4
7/3	3	51.1	28.7	22.4	44	3.3	78	13.0
Mean	-	50.4	30.1	20.3	40	3.4	67	12.9
1/0	1	47.8	28.6	19.2	40	3.4	82	11.1
1/0	2	51.9	30.5	21.4	41	3.3	87	12.4
1/0	3	53.4	29.0	24.4	46	3.8	87	11.7
Mean	-	51.0	29.4	21.7	42	3.5	85	11.7

(b)

He/Ar -	Bead Nb	A _t (mm ²)	A _d (mm ²)	A _p (mm ²)	h _{mean} (mm)	R _{h/w} -
0/1	1	38.4	30.4	1.5	4.7	0.98
0/1	2	39.1	30.1	1.2	4.5	0.93
Mean	-	38.8	30.3	1.4	4.6	0.955
3/7	1	40.4	29.3	2.4	4.5	0.98
3/7	2	39.3	30.6	1.2	4.8	1.00
Mean	-	39.9	30.0	1.8	4.7	0.99
7/3	1	45.3	30.1	5.6	4.8	0.98
7/3	2	47.3	29.5	5.5	4.7	1.03
Mean	-	46.3	29.8	5.6	4.8	1.005
1/0	1	45.7	28.7	6.1	4.5	0.96
1/0	2	48.1	29.2	5.8	4.4	0.93
Mean	-	46.9	29.0	6.0	4.5	0.945

Table 7.8 Estimated values of the operating minimum voltage to prevent unstable operation at weld start (based on data from table 7.1).

Shielding gas	Oxygen content (%)	Minimum voltage (V)	Slope (V/s)
Ar	0	36	
	1	34.5	
	2	33	
He-101	0-1	38.5	0.3
	3	35.2	0.2
	4	33.3	0.2

Table 7.9 Simple linear regression models for the variation of V_{uns} and V_{us} with standoff ($I=260A$).

Gas	Reponse (V)	Slope (V/mm)	Intercept (V)	R ²	SigF
Ar	V_{st}	16.0	0.64	0.978	0.0000
	V_{uns}	27.7	0.49	0.971	0.0000
Ar-25%He	V_{st}	13.4	0.96	0.956	0.0221
	V_{uns}	29.0	0.45	0.996	0.0408
Ar-75%He	V_{st}	15.8	1.02	0.998	0.0000
	V_{uns}	25.9	0.75	0.985	0.0077
Ar-2%O ₂	V_{st}	19.2	0.31	0.995	0.0002
	V_{uns}	29.0	0.50	0.999	-

Obs: SigF - Significance of F ratio.

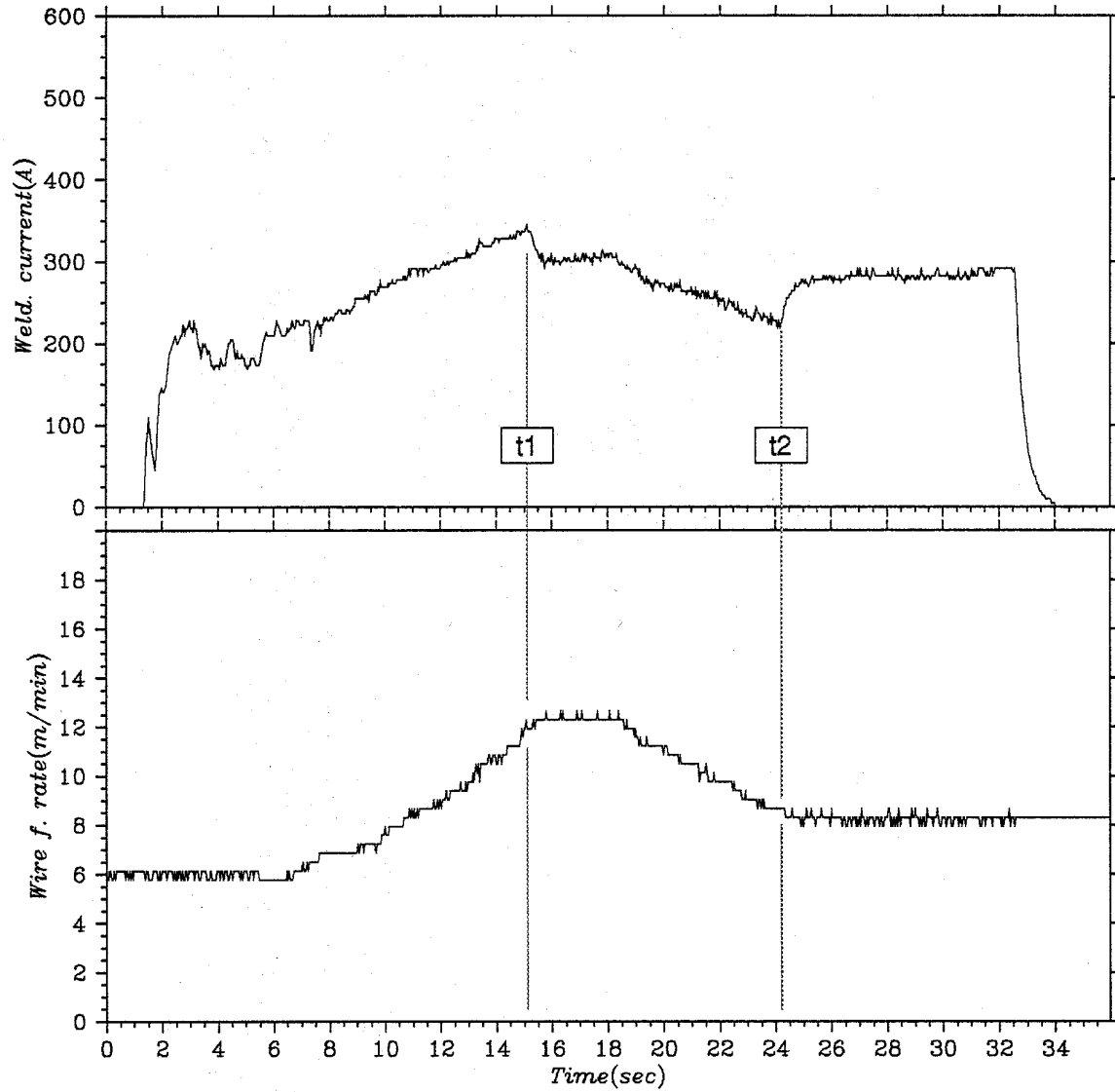


Figure 7.1

Welding current variation associated with a continuous variation in wire feed rate. Trial performed with constant voltage. Shielding gas: Helishield 101. Open circuit voltage: 35V. Abrupt alterations in process stability occurred at points t1 and t2.

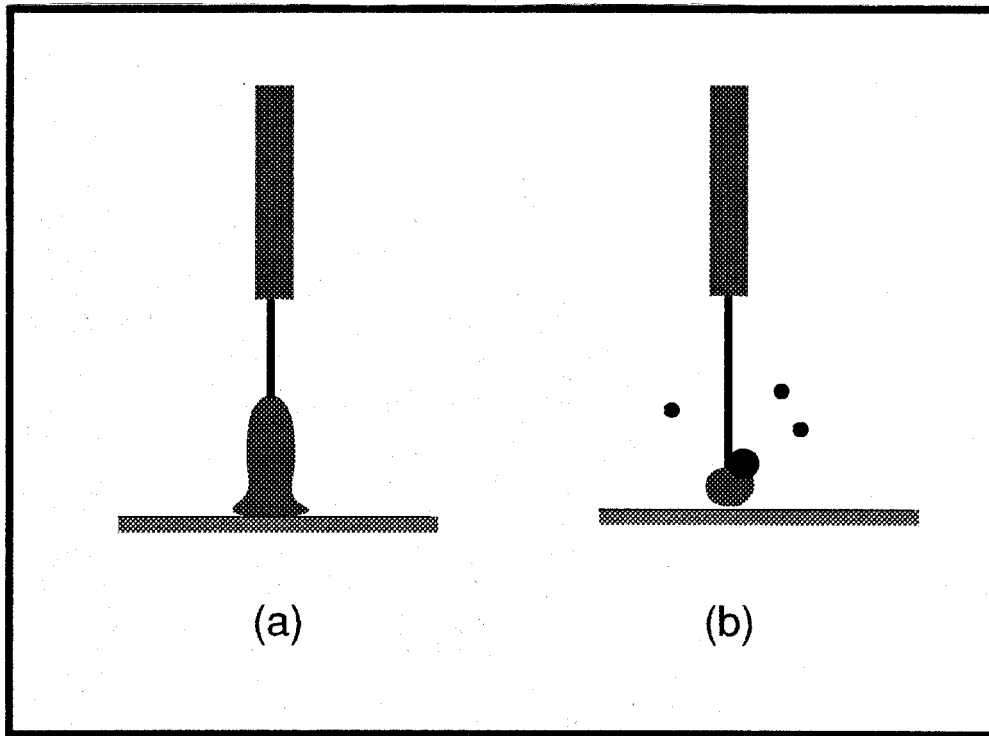


Figure 7.2 Schematic representation of the stable (a) and unstable (b) operational modes.

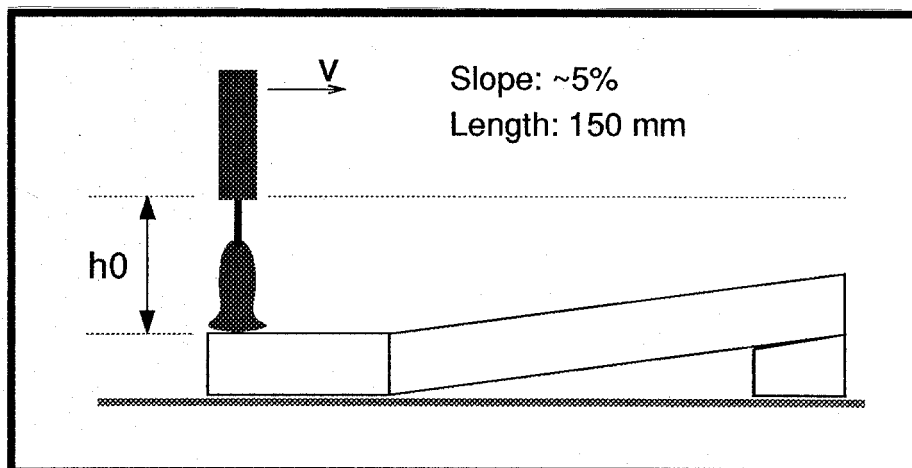


Figure 7.3 Sloped welding specimen.

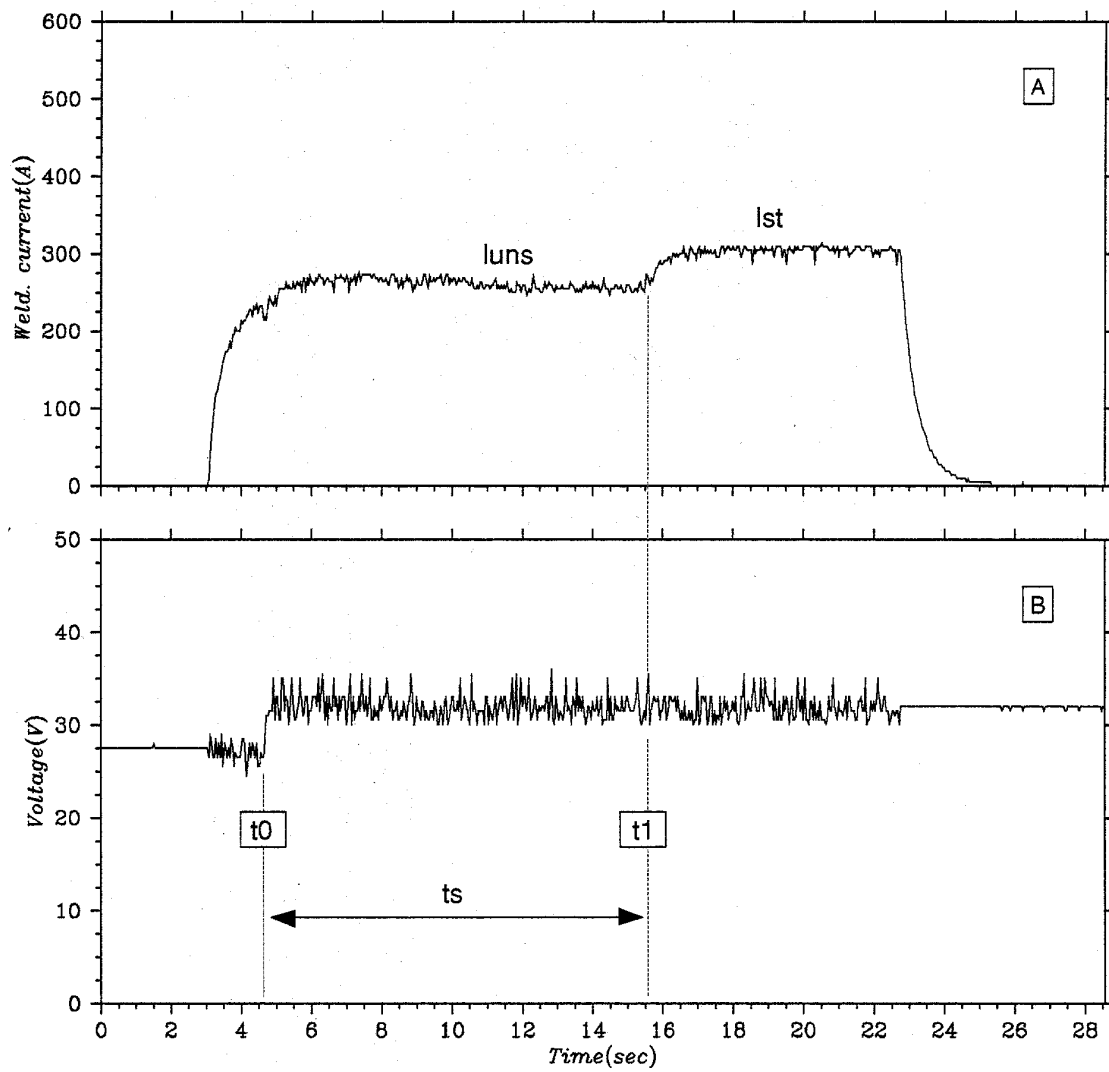


Figure 7.4 Constant voltage stability test result. I_{un} - current level at unstable mode, I_{st} - current level at stable mode, and t_{us} time necessary for the change to take place from unstable to stable mode.

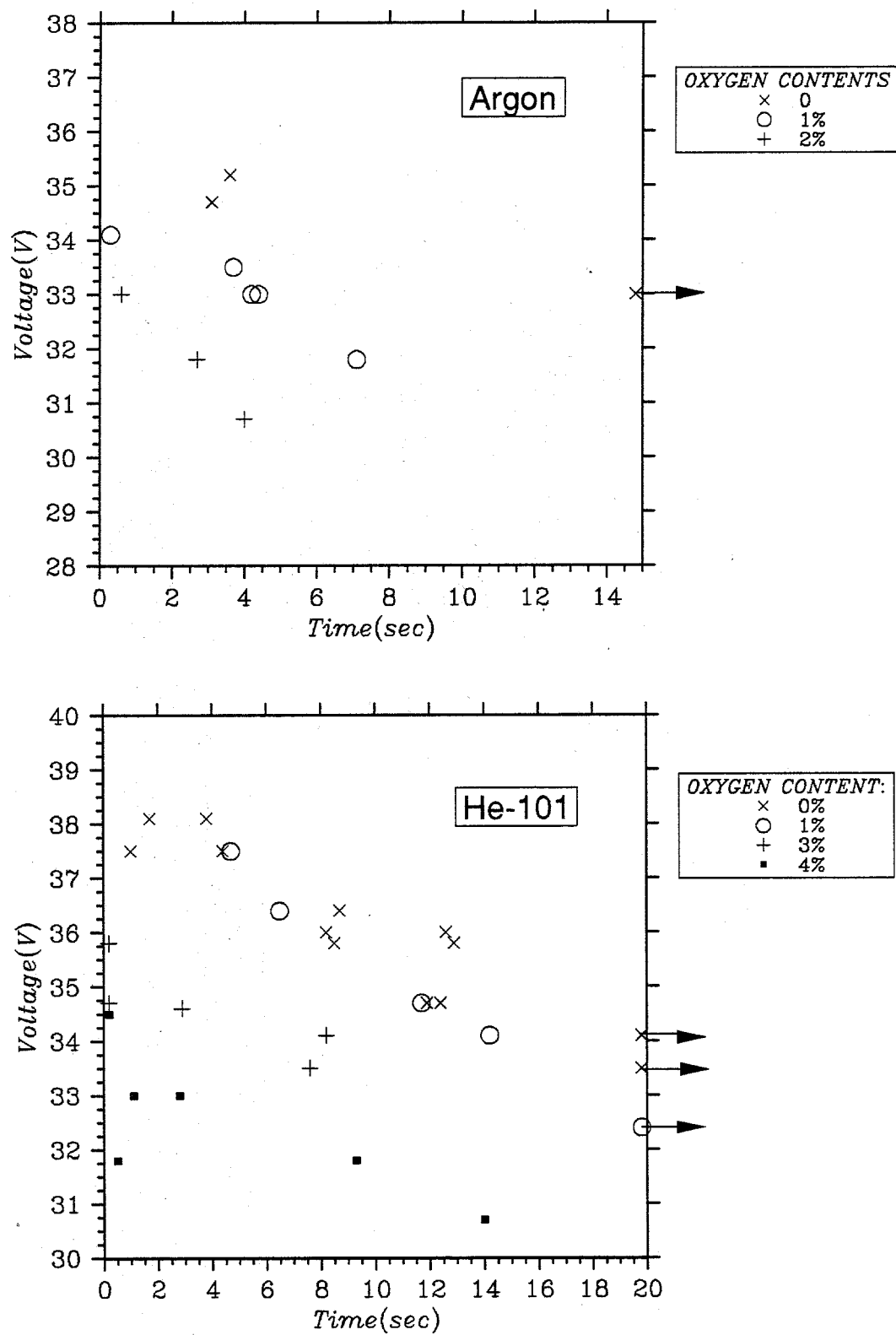
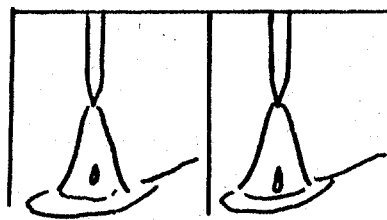
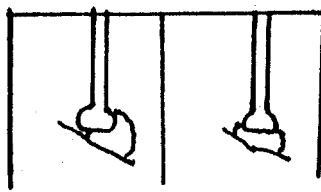


Figure 7.5 Effect of oxygen content and voltage on the time necessary for process stabilization.



(a)



(b)

Figure 7.6 Schematic drawing from the IMACON photographs of the arc for the CV stability trials. (a) Spray transfer, (b) repulsive drop transfer.

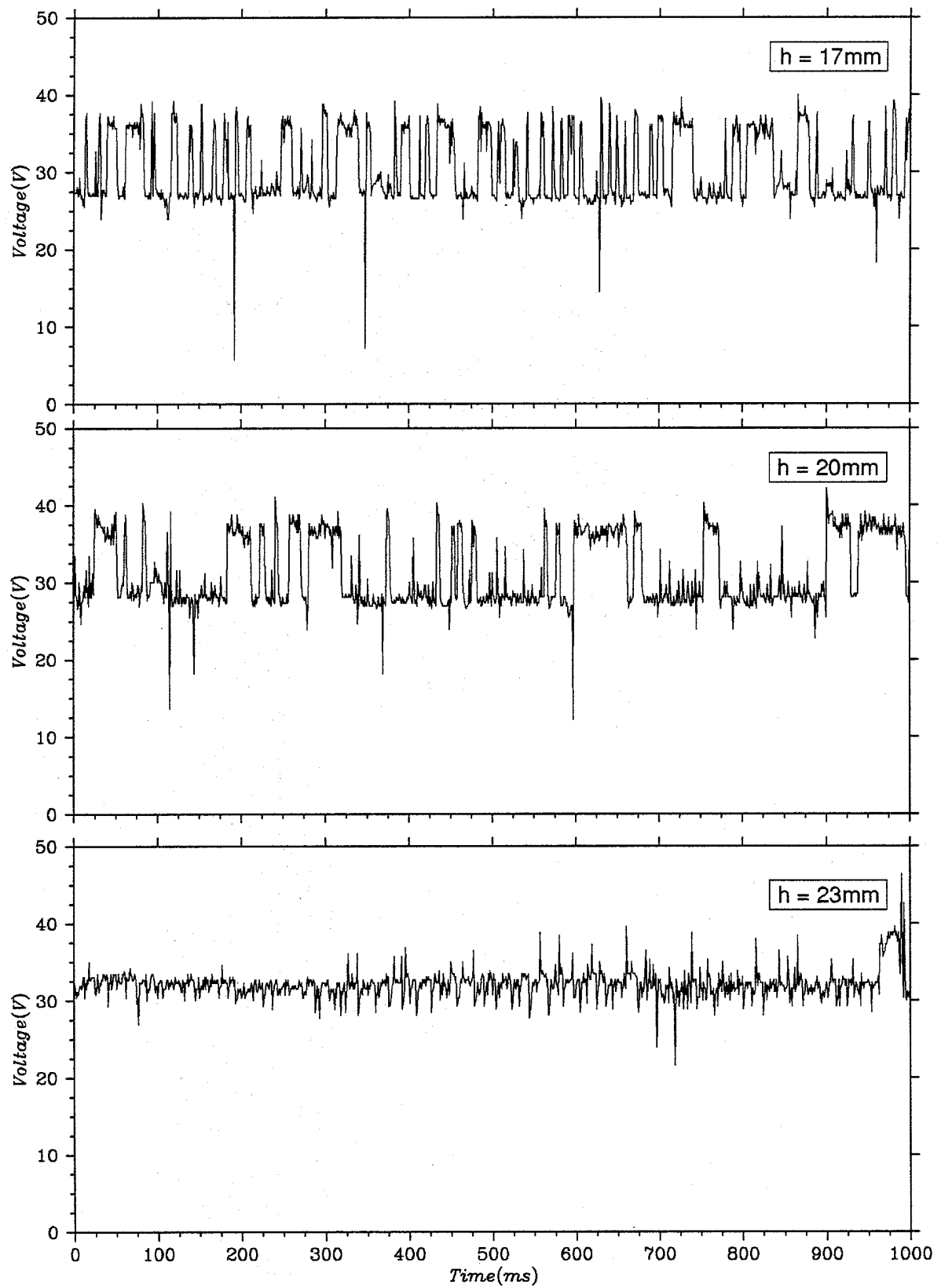


Figure 7.7 Voltage traces for different standoff distances (h) in CC stability trials. Shielding gas: argon. Current: 260A.

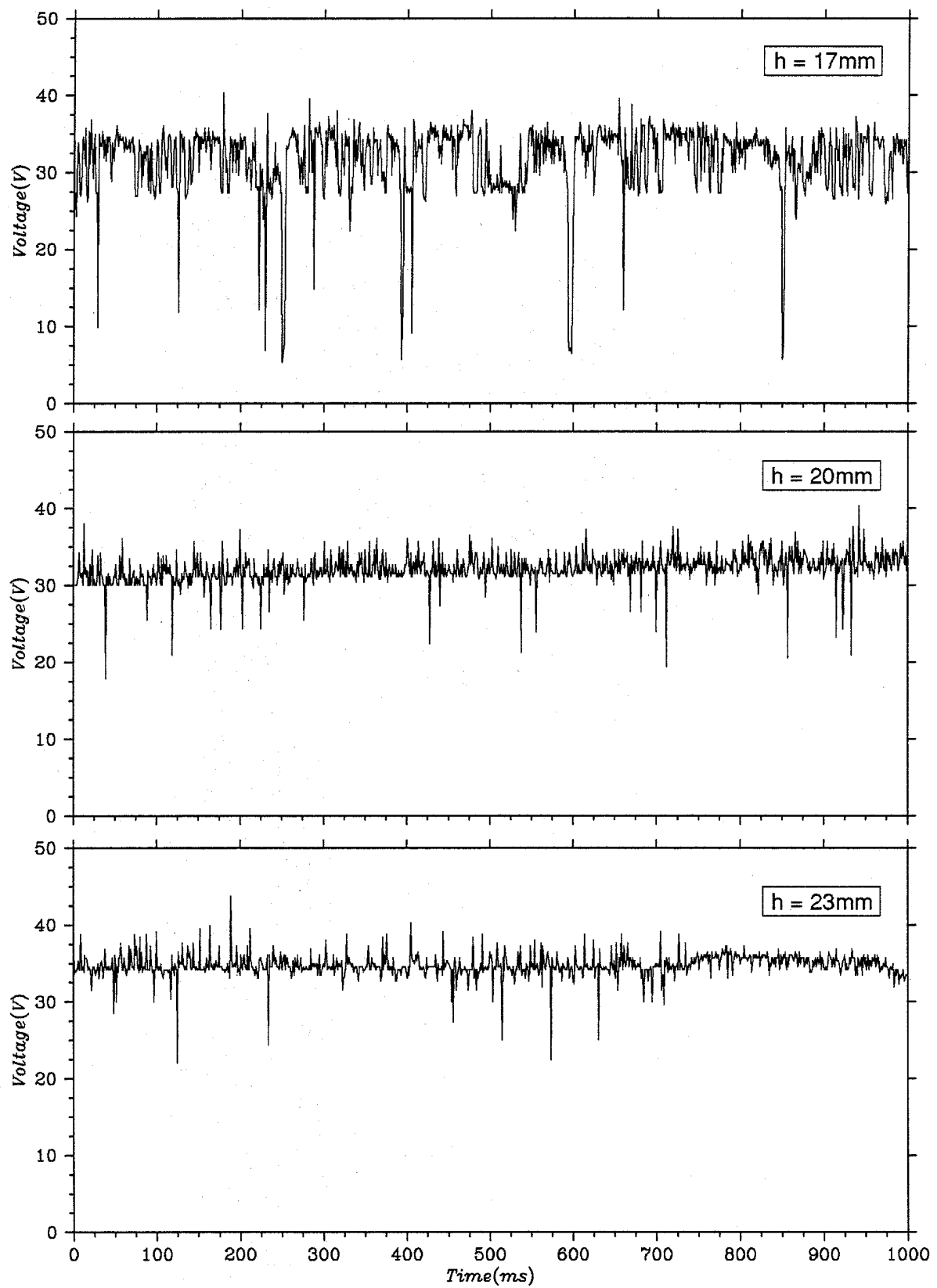


Figure 7.8 Voltage traces for different standoff distances (h) in CC stability trials. Shielding gas: argon. Current: 300A.

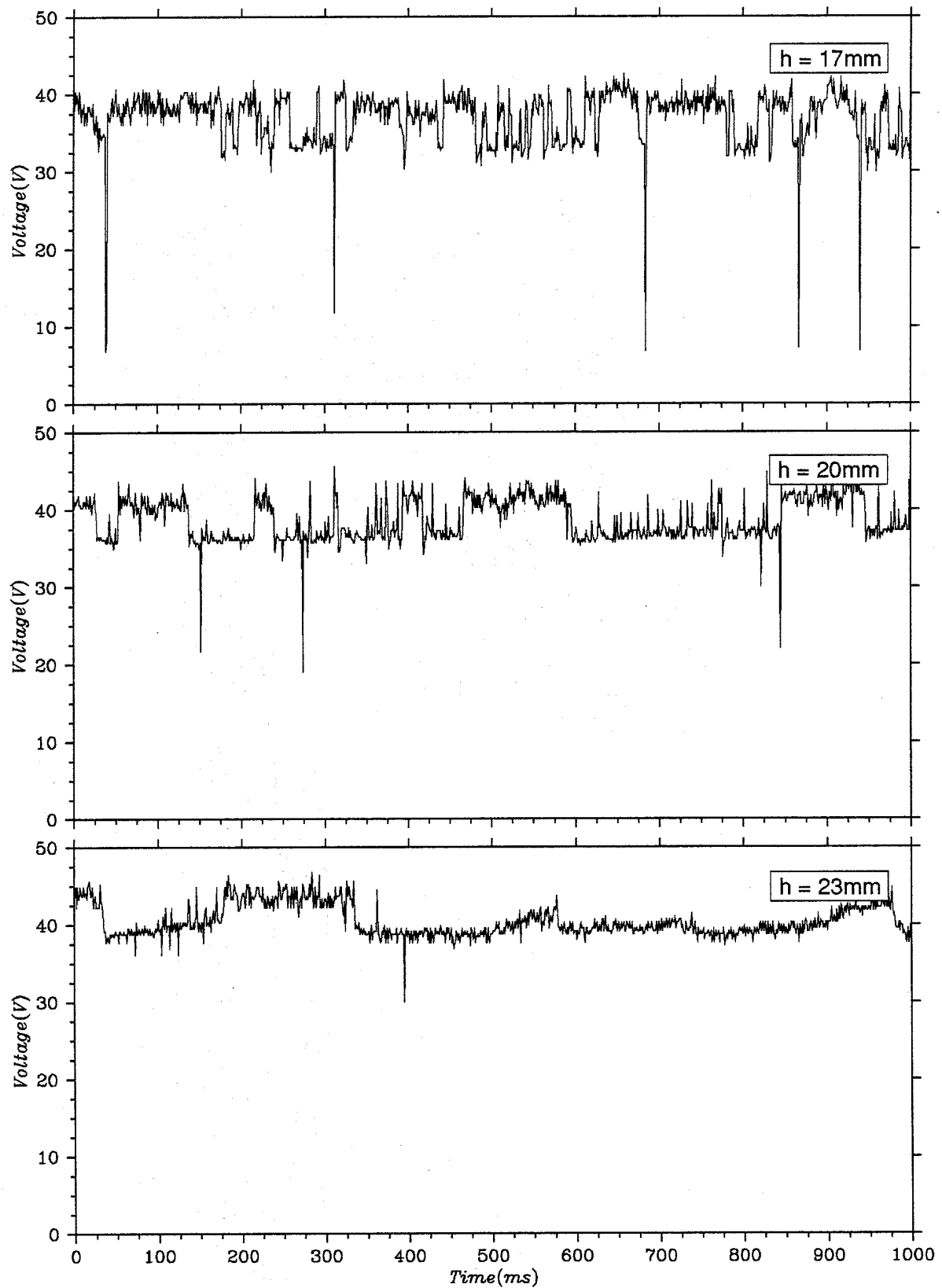


Figure 7.9 Voltage traces for different standoff distances (h) in CC stability trials. Shielding gas: Ar-75%He. Current: 260A.

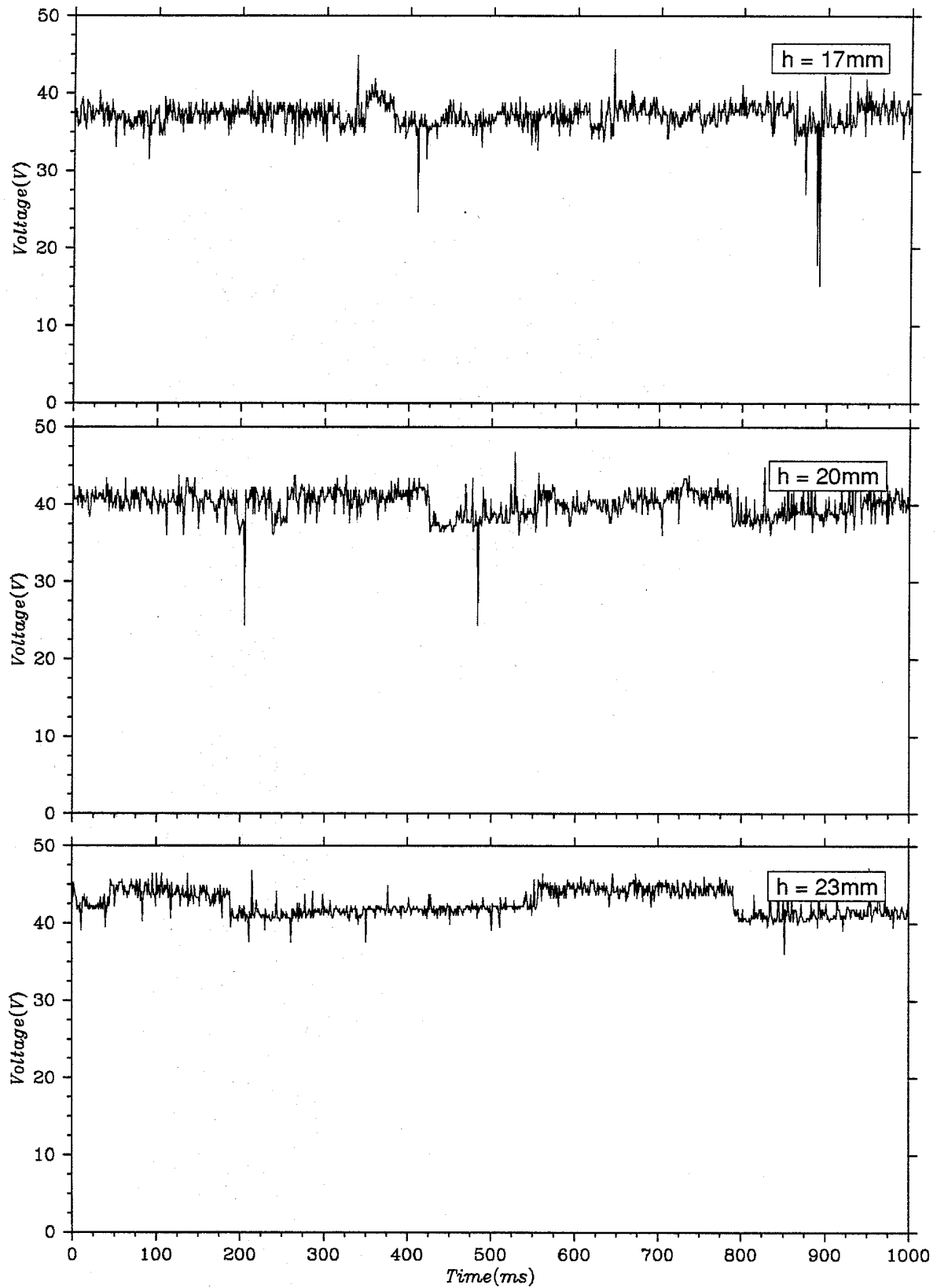


Figure 7.10 Voltage traces for different standoff distances (h) in CC stability trials. Shielding gas: Ar-75%He. Current: 300A.

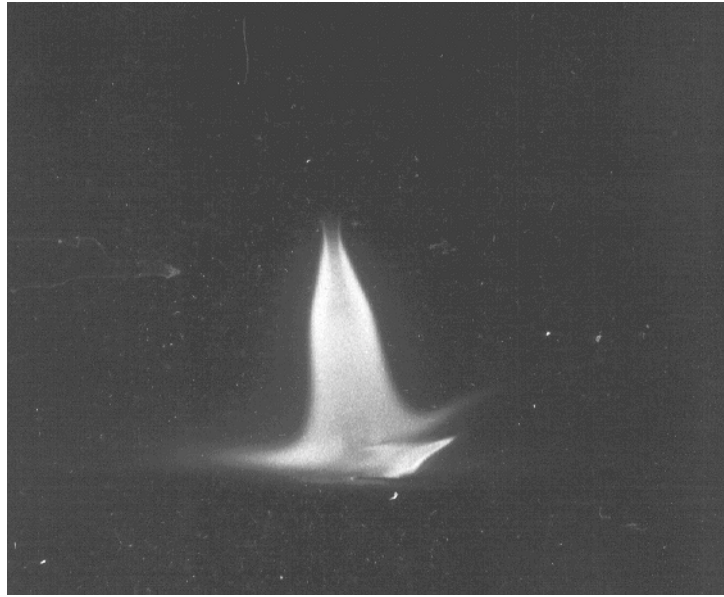


Figure 7.11 Stable spray arc operation with a 26 mm standoff distance. Shielding gas: argon. Current: 260A.

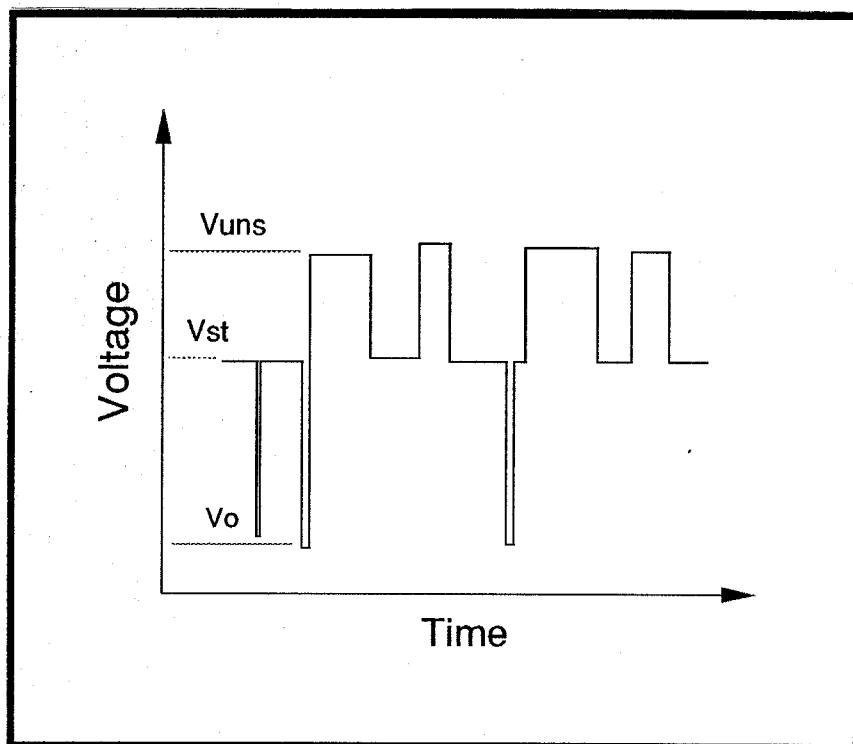


Figure 7.12 Schematic representation of the voltage trace in CC stability trials. V_0 : Short circuit voltage. V_{st} : Intermediate arc voltage level. V_{uns} : High voltage arc level.



(a)



(b)

Figure 7.13 Stable(a) and unstable(b) operations observed during the same welding trial with a standoff of 20mm. Shielding gas: argon. Current: 260A.

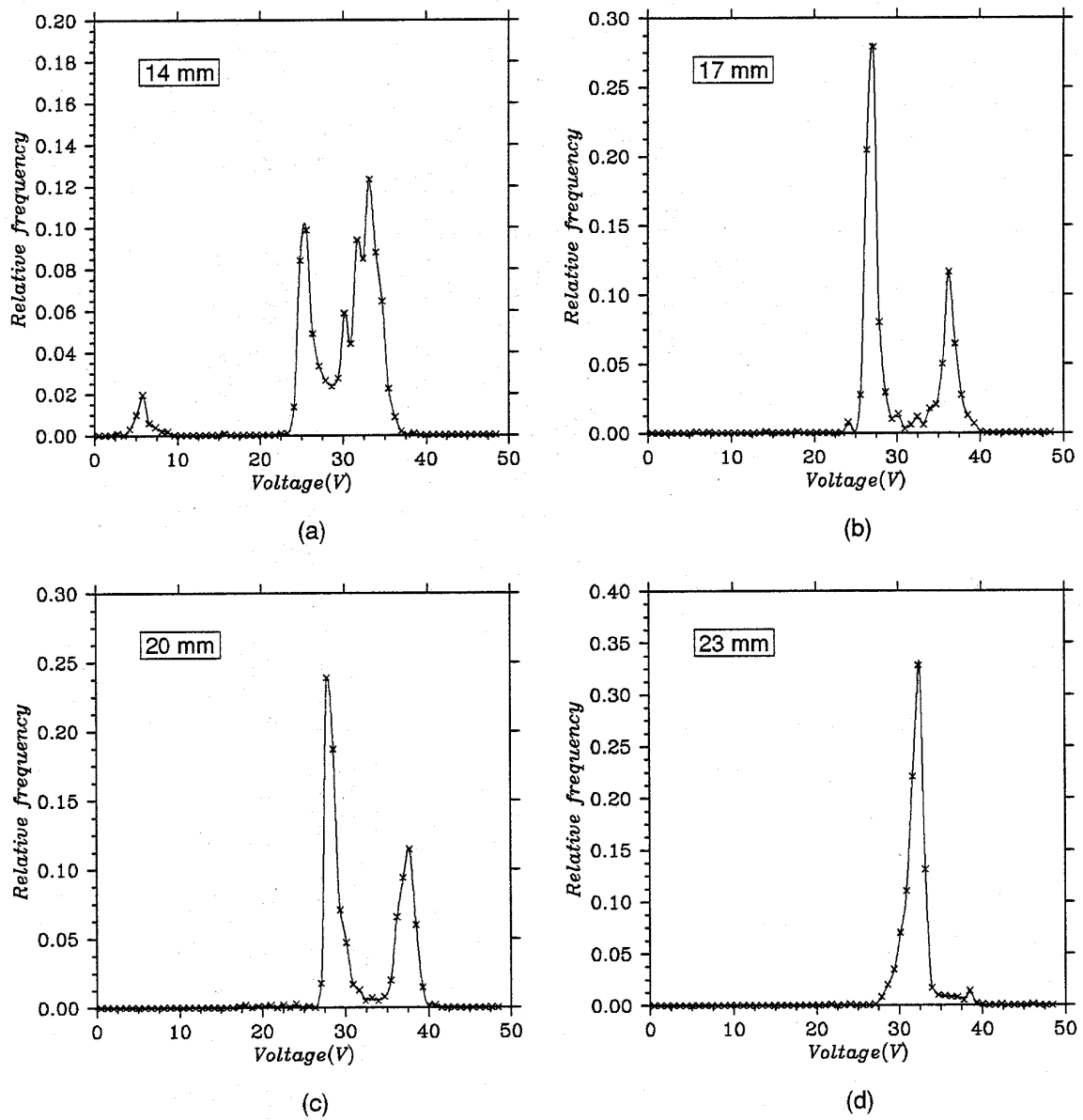


Figure 7.14 Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: argon. Current: 260A.

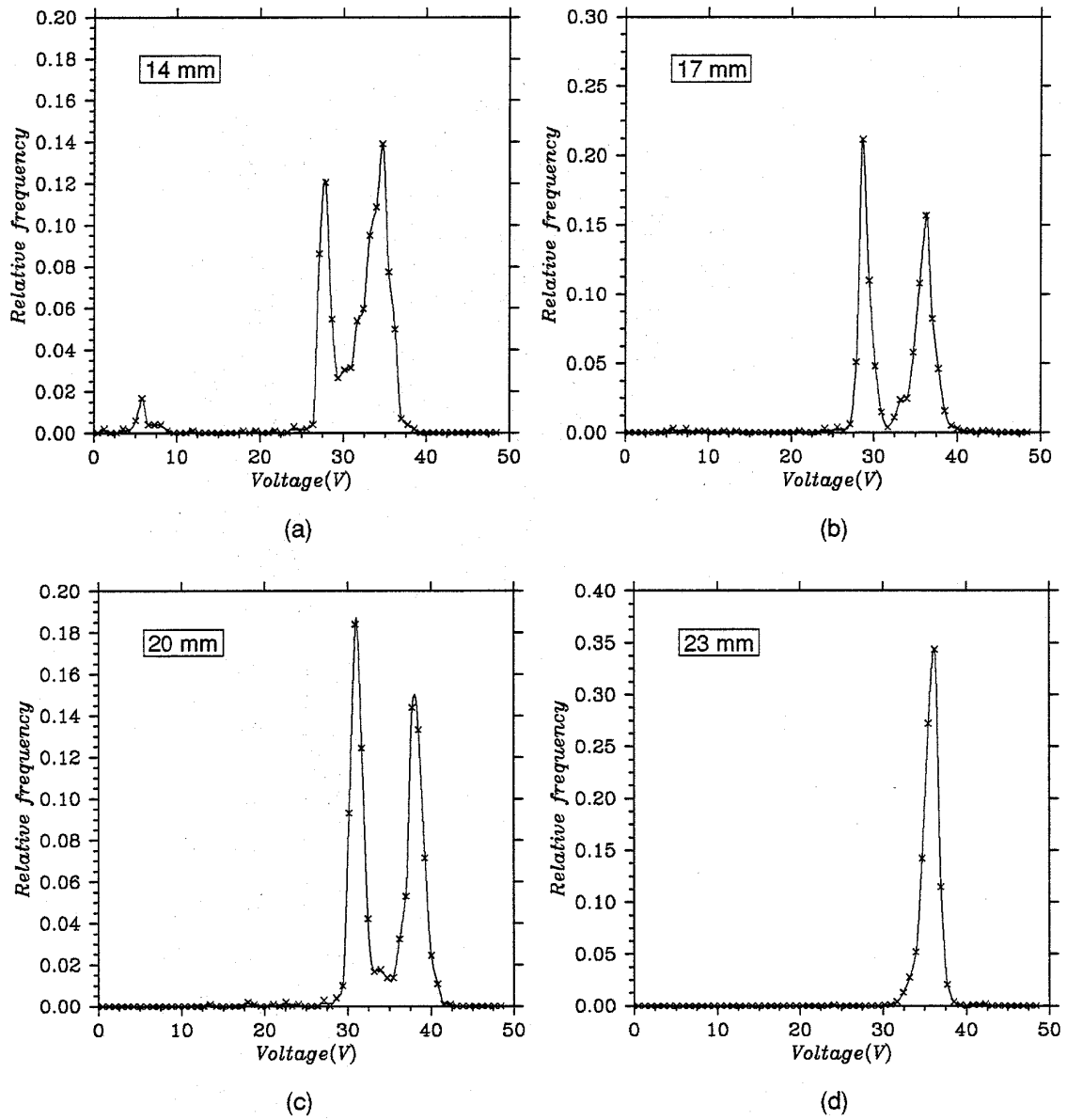


Figure 7.15 Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: Ar-25%He. Current: 260A.

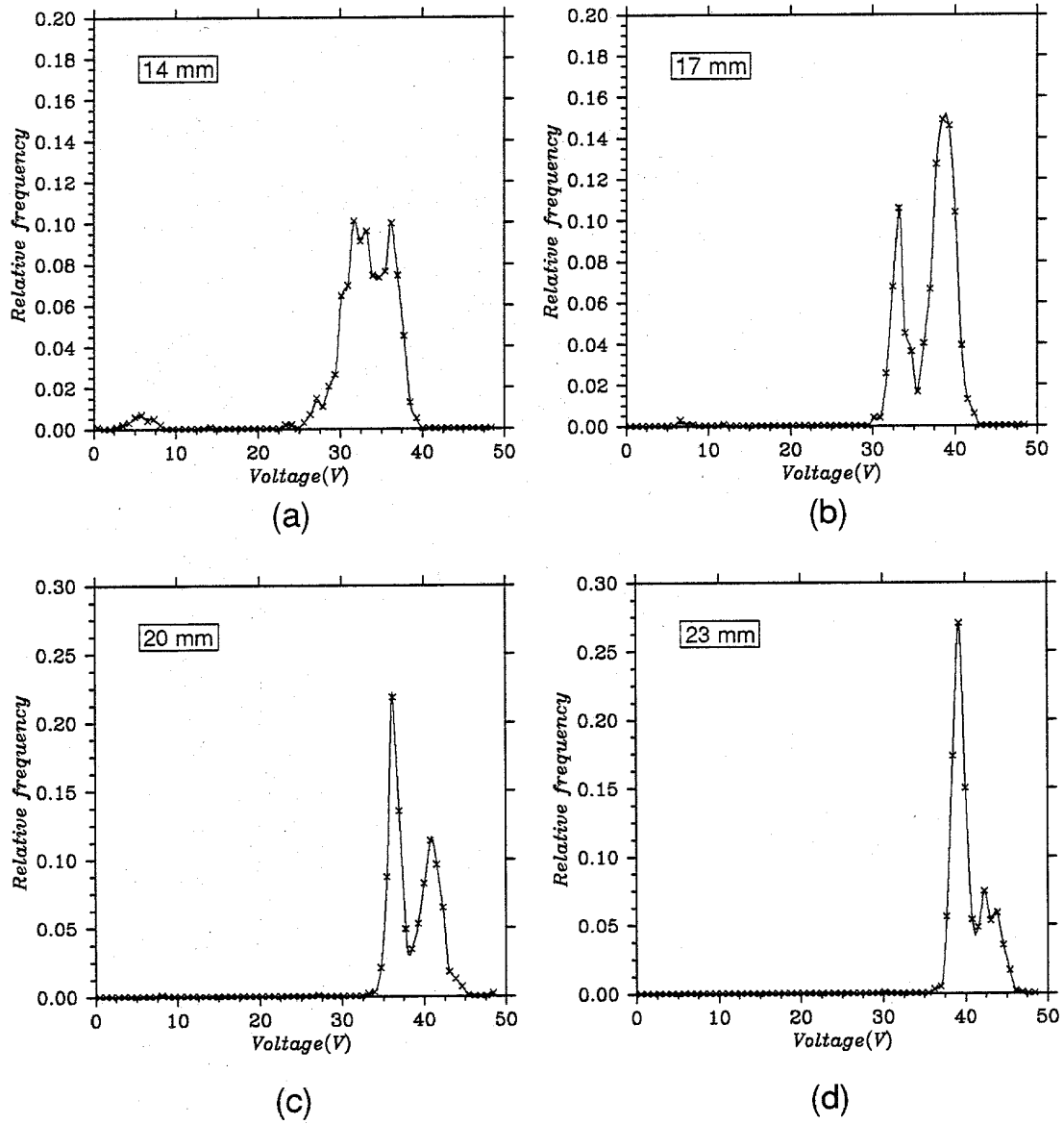


Figure 7.16 Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: Ar-75%He. Current: 260A.

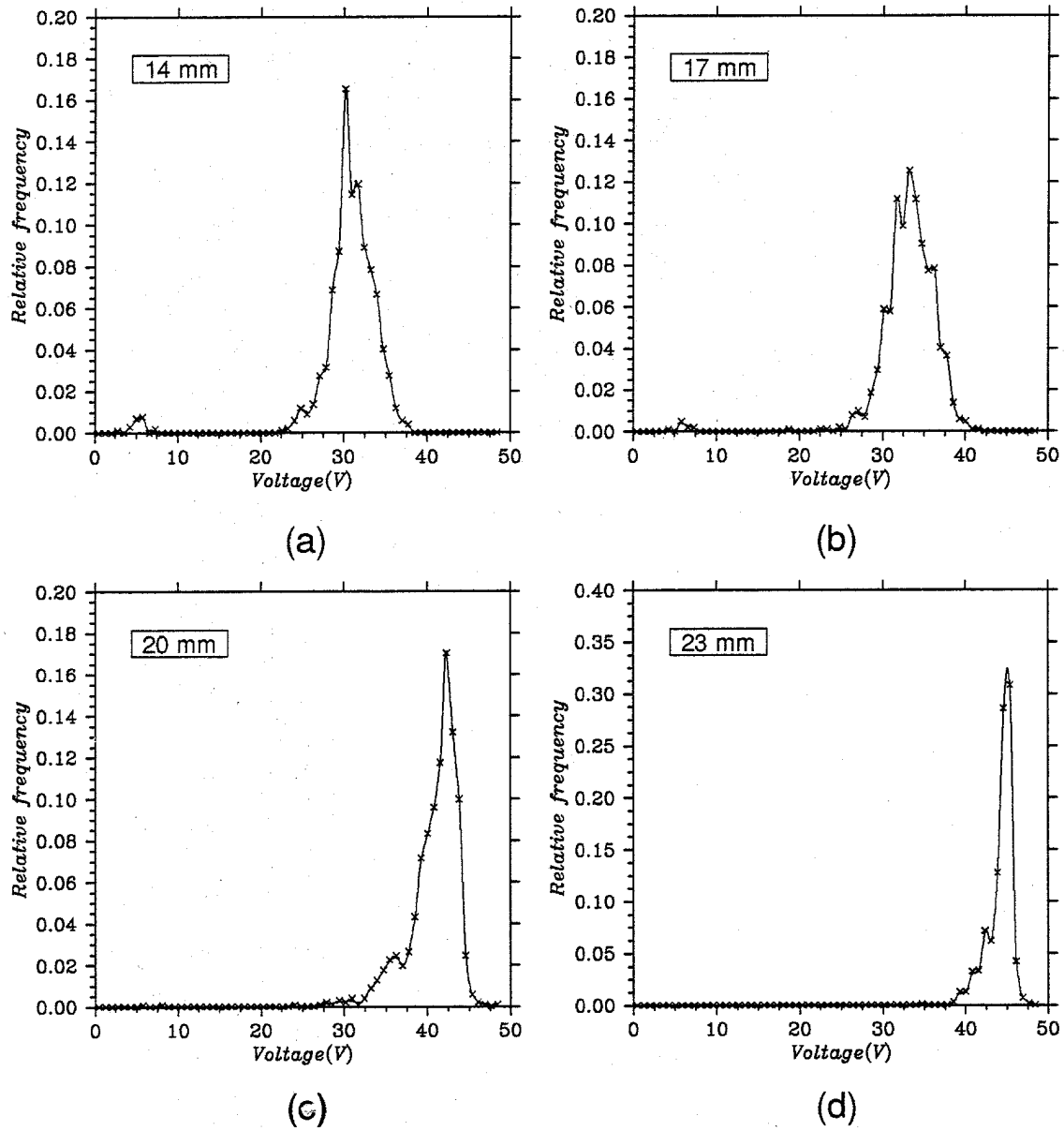


Figure 7.17

Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: He. Current: 260A.

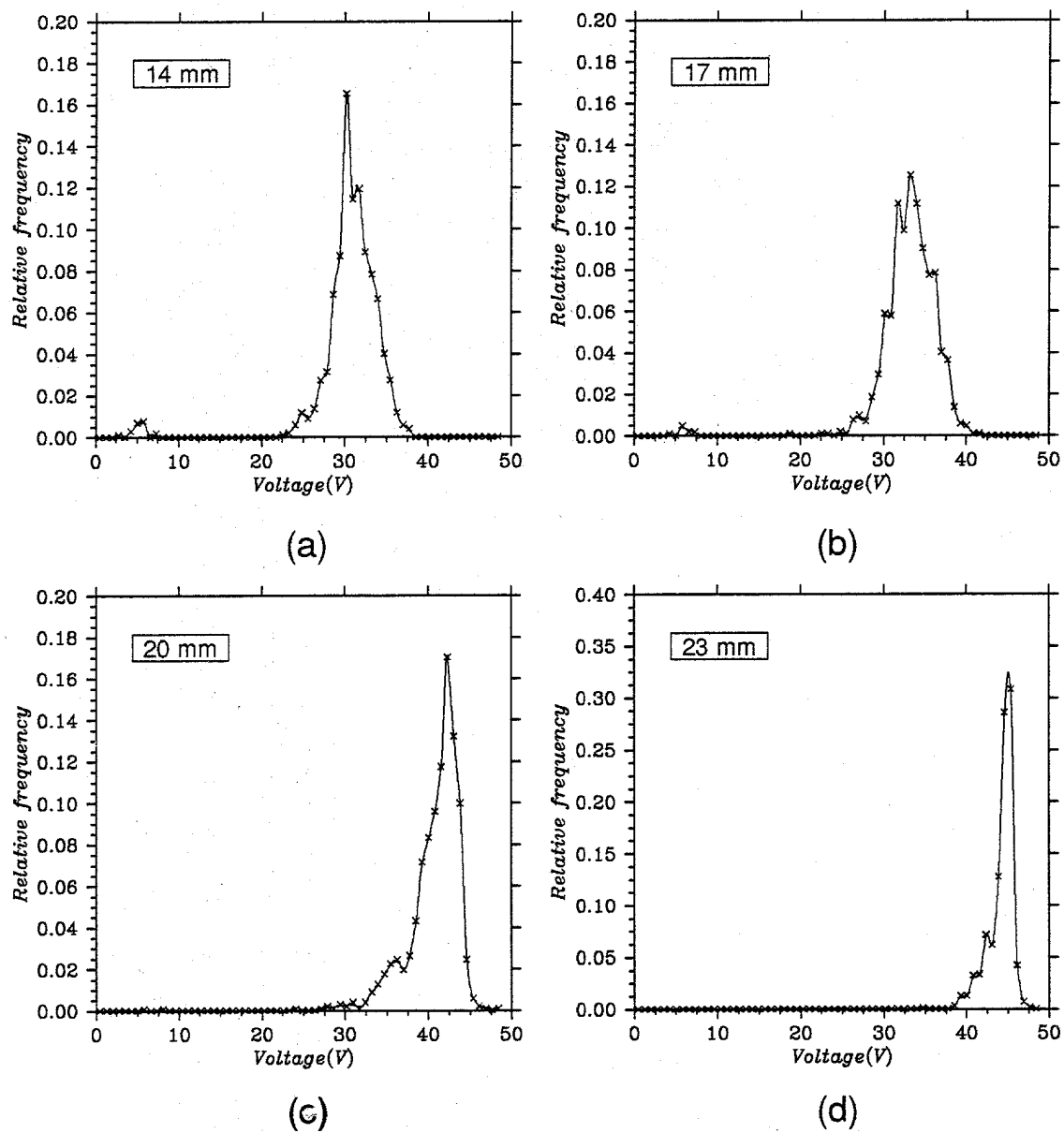


Figure 7.18

Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: Ar-2%O₂. Current: 260A.

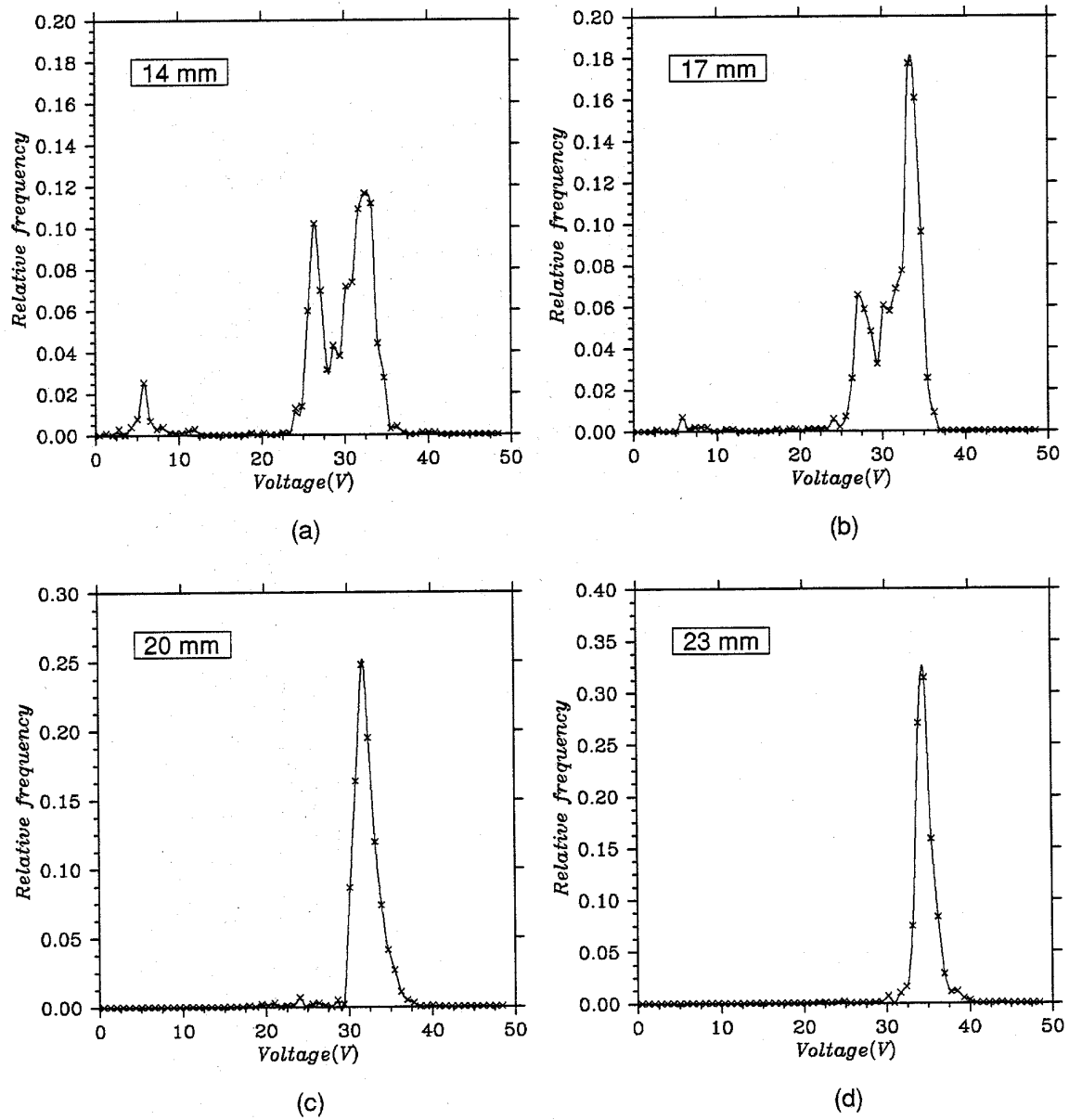


Figure 7.19

Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: argon. Current: 300A.

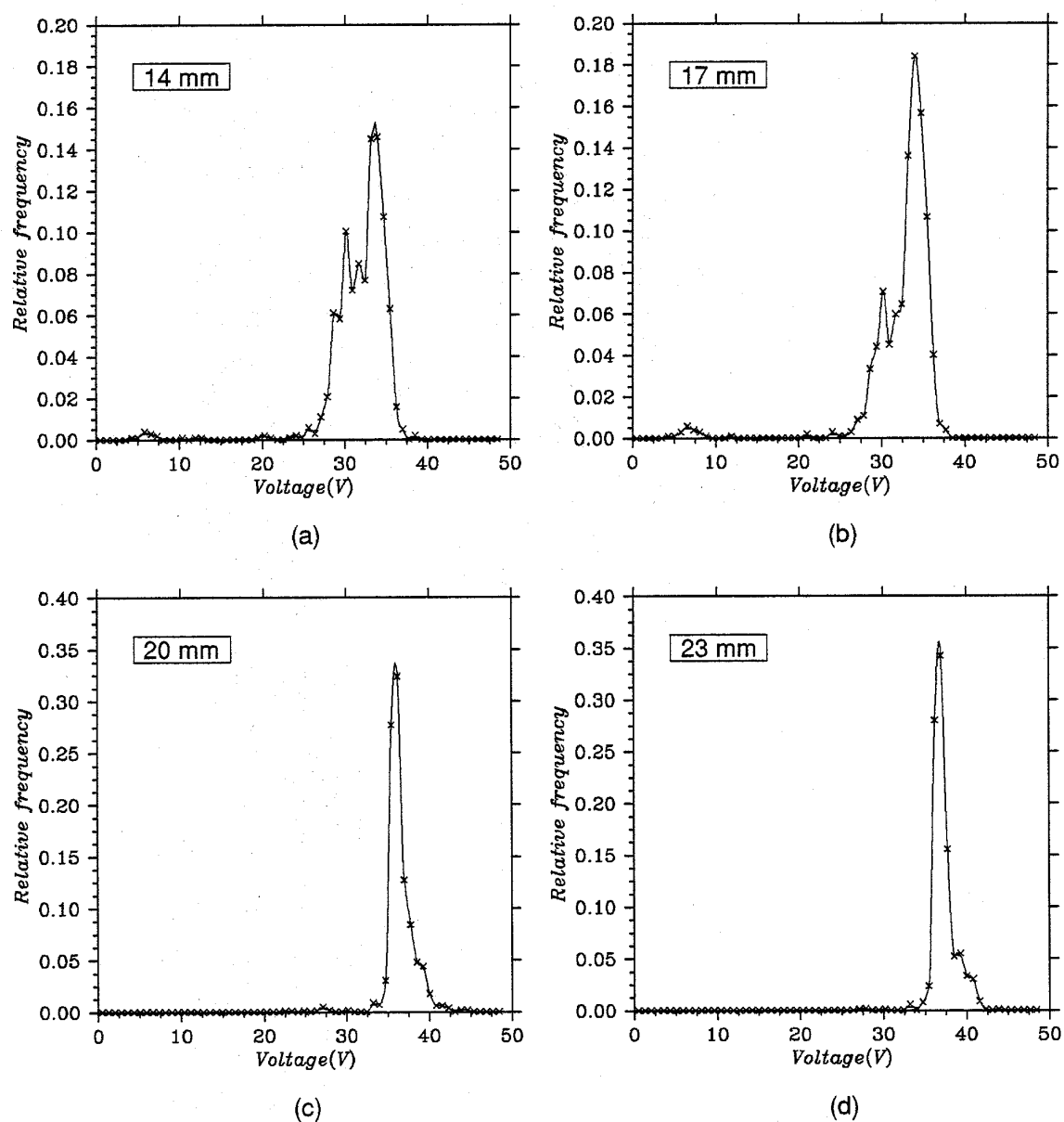


Figure 7.20

Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: Ar-25%He. Current: 300A.

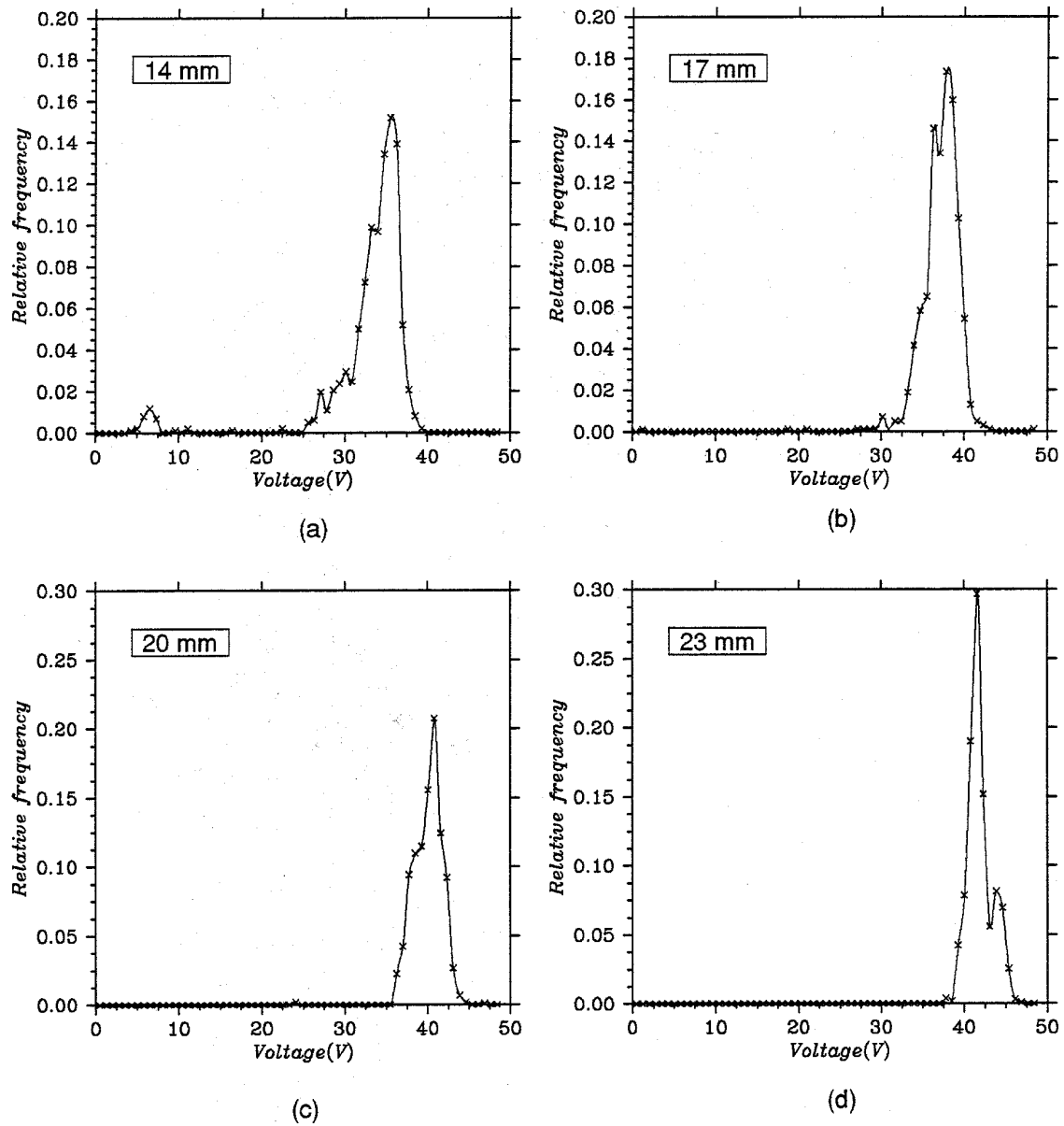


Figure 7.21

Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: Ar-75%He. Current: 300A.

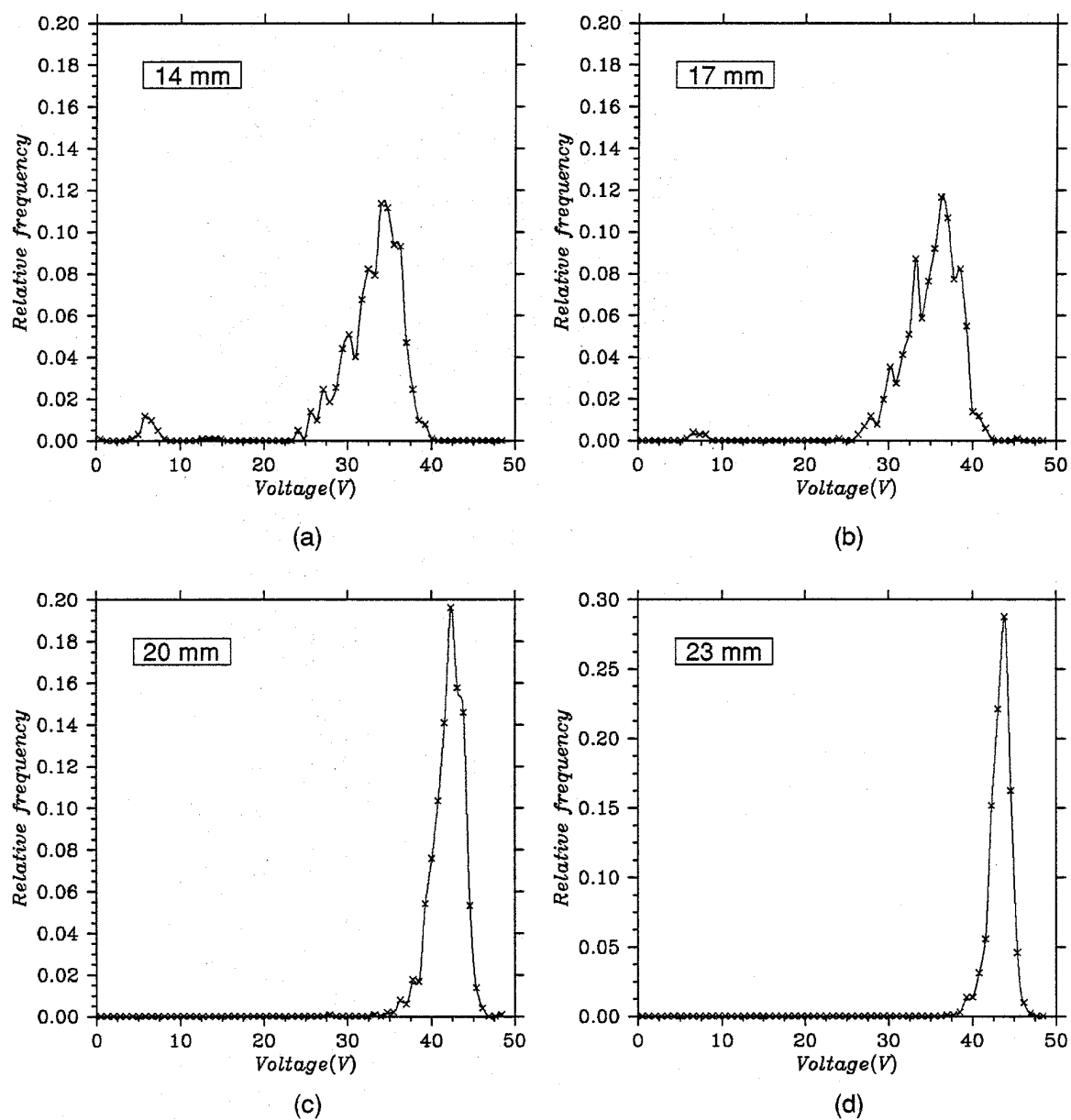


Figure 7.22

Frequency polygon plot of the voltage trace from CC stability trials with different standoff distances. Gas: He. Current: 300A.

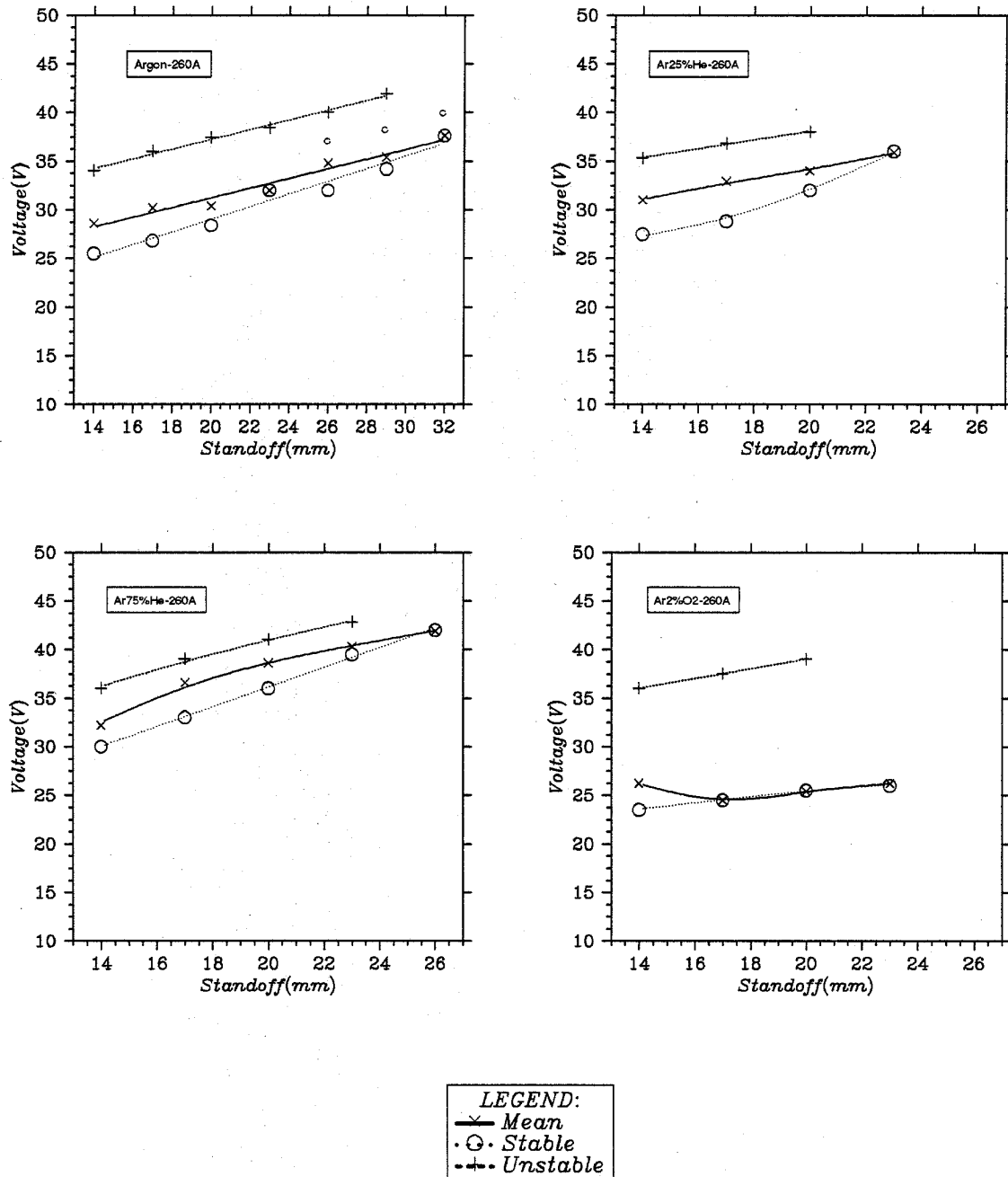


Figure 7.23 Mean voltage, V_{st} and V_{uns} levels for welding trials with $I = 260A$ and $w = 8m/min$. C - Trials performed in the hyperbaric chamber.

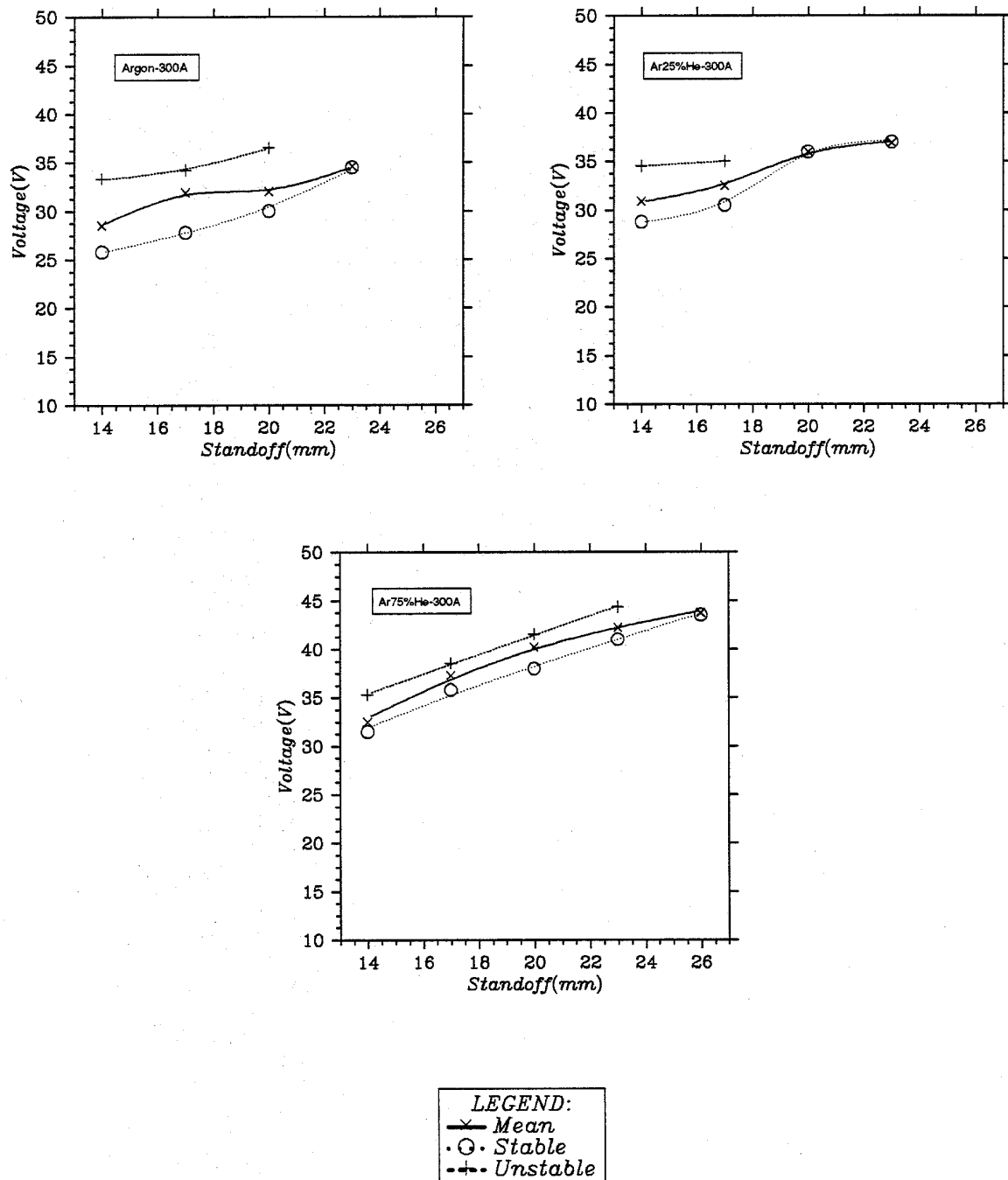


Figure 7.24

Mean voltage, V_{st} and V_{uns} levels for welding trials with $I = 300A$ and $w = 10m/min$.

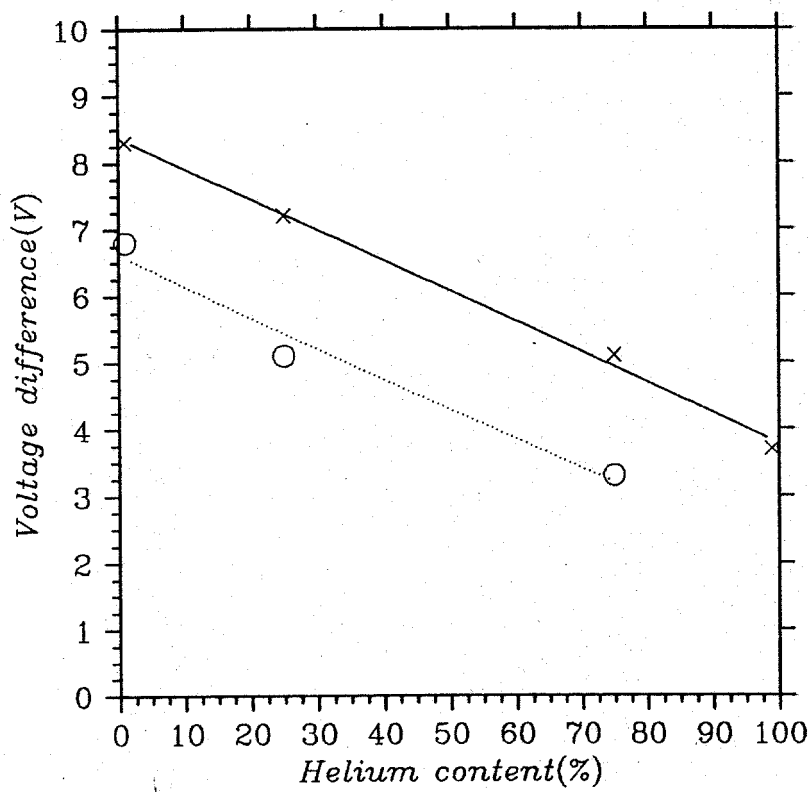


Figure 7.25 Effect of current level and gas composition on the difference between V_{uns} and V_{st} levels.

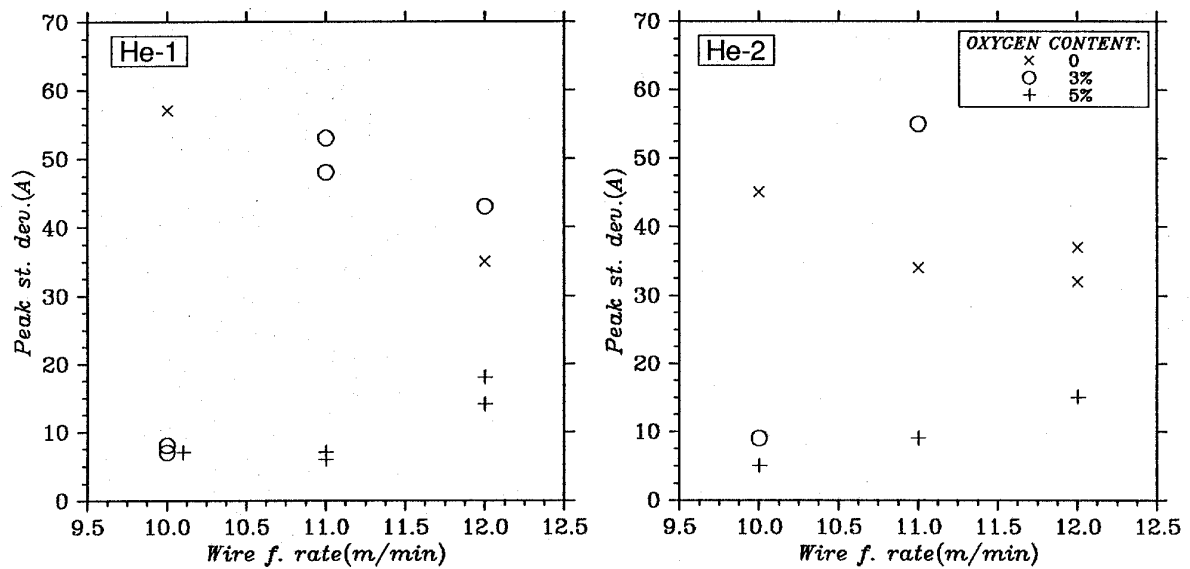


Figure 7.26 Effect of oxygen content and wire feed rate on arc stability in pulsed GMA welding.

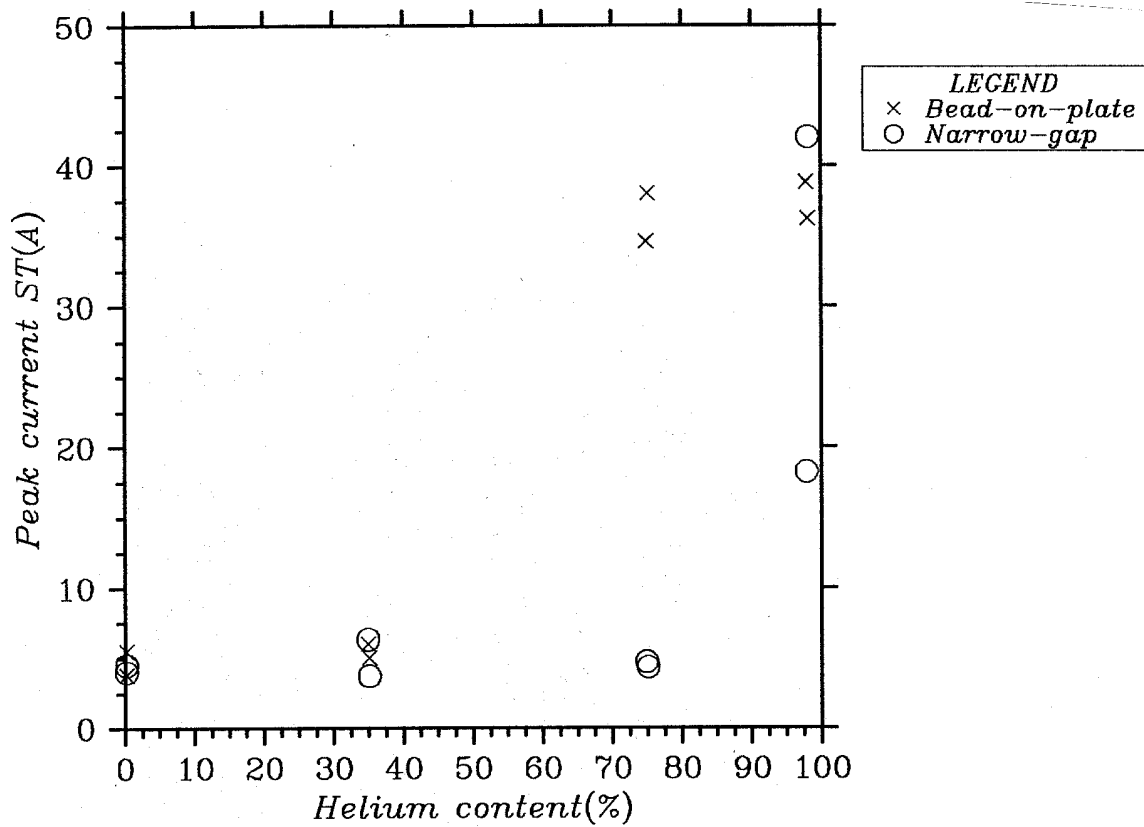


Figure 7.27

Effect of He content on arc stability in pulsed current welding. Arc stability measured by the standard deviation of peak current.

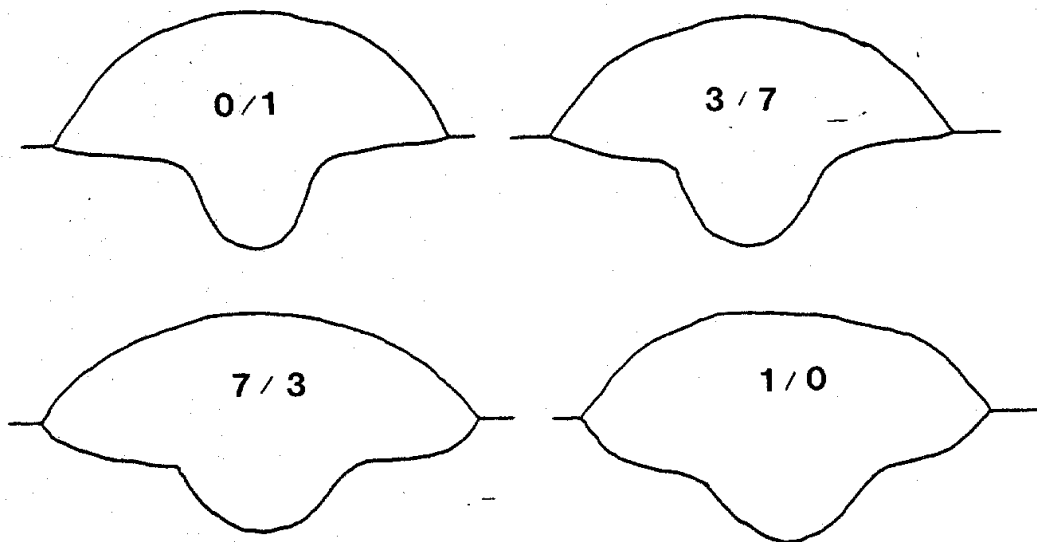
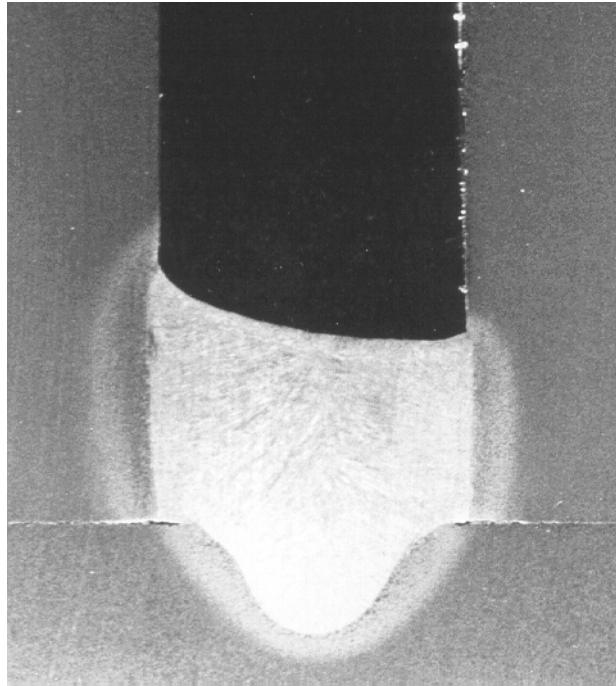
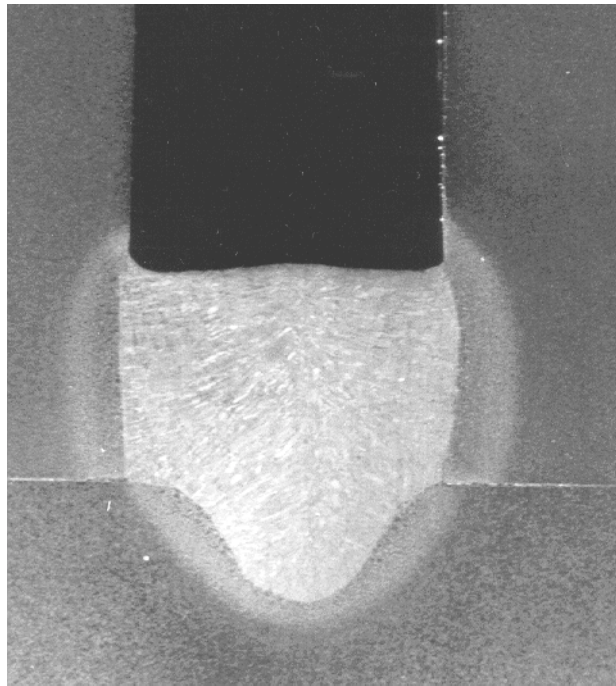


Figure 7.28

Transverse section of bead-on-plate welds performed with different He/Ar ratios. Magnification: 3.5X. Pulsed current welding. Mean current: 250A.



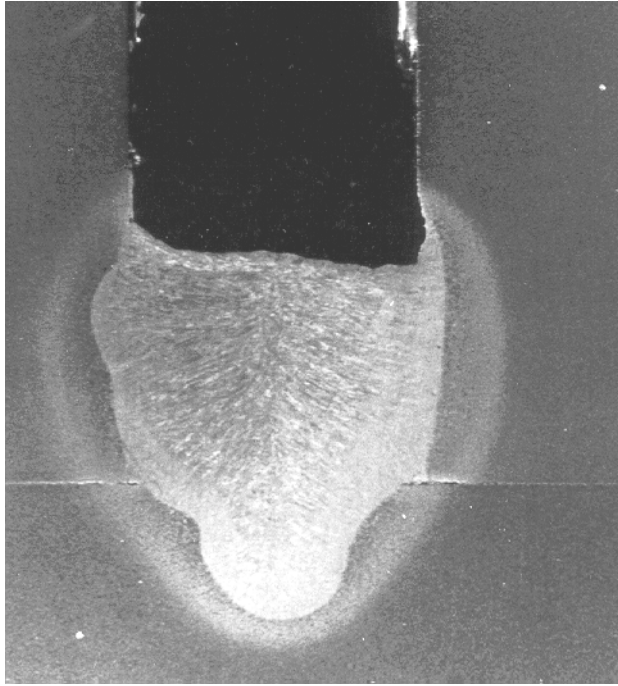
(a)



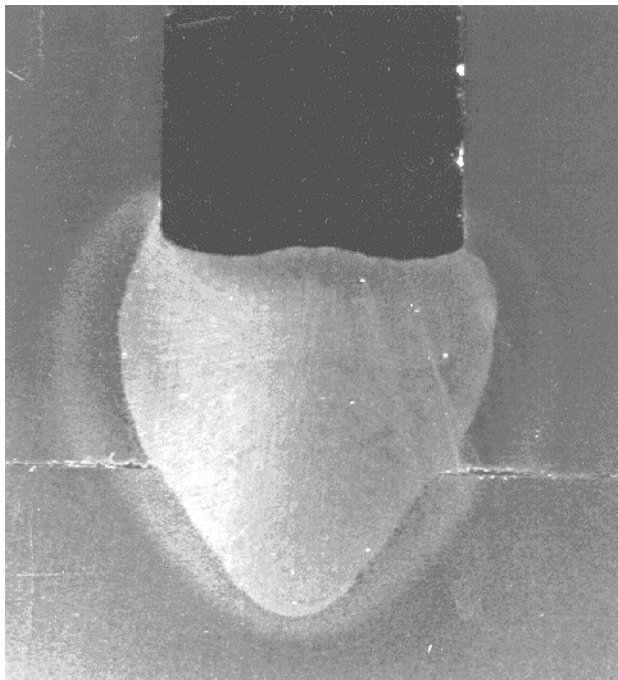
(b)

Figure 7.29

Transverse section of narrow gap specimens performed with different He/Ar ratios. Shielding gases: (a)Ar, (b)Ar-25%He. Magnification: 6X.



(c)



(d)

Figure 7.29(cont.)

Transverse section of narrow gap specimens performed with different He/Ar ratios. Shielding gases: (c)Ar-75%He, (d)He. Magnification: 6X.

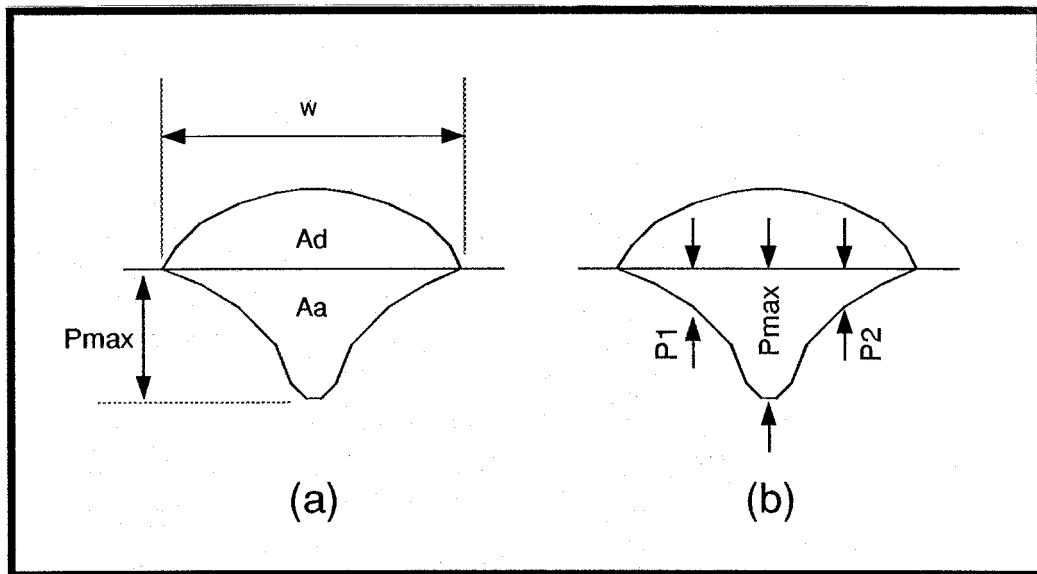


Figure 7.30 Some geometric parameters considered for bead-on-plate specimens. (a) A_a : axial penetration area, A_d : deposited area, w : bead width and P_{max} : maximum axial penetration. In (b), the marginal penetrations p_1 and p_2 are measured half-distance between the maximum penetration and the bead edges.

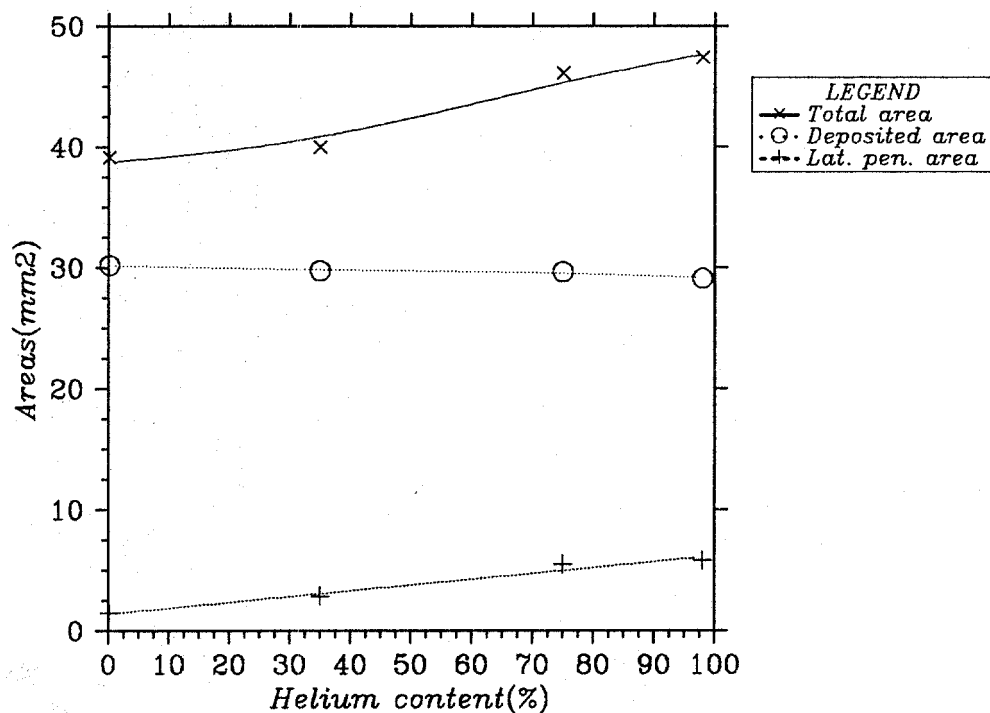


Figure 7.31 Effect of He content in the shielding gas on bead characteristics of narrow gap welds.

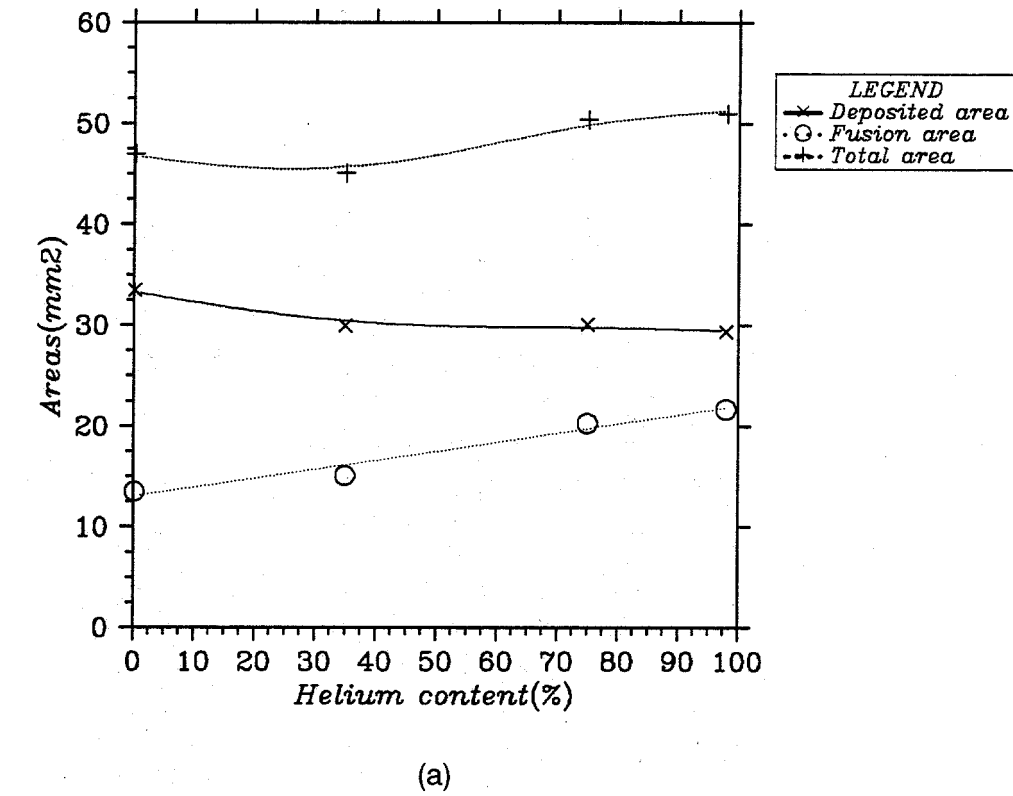
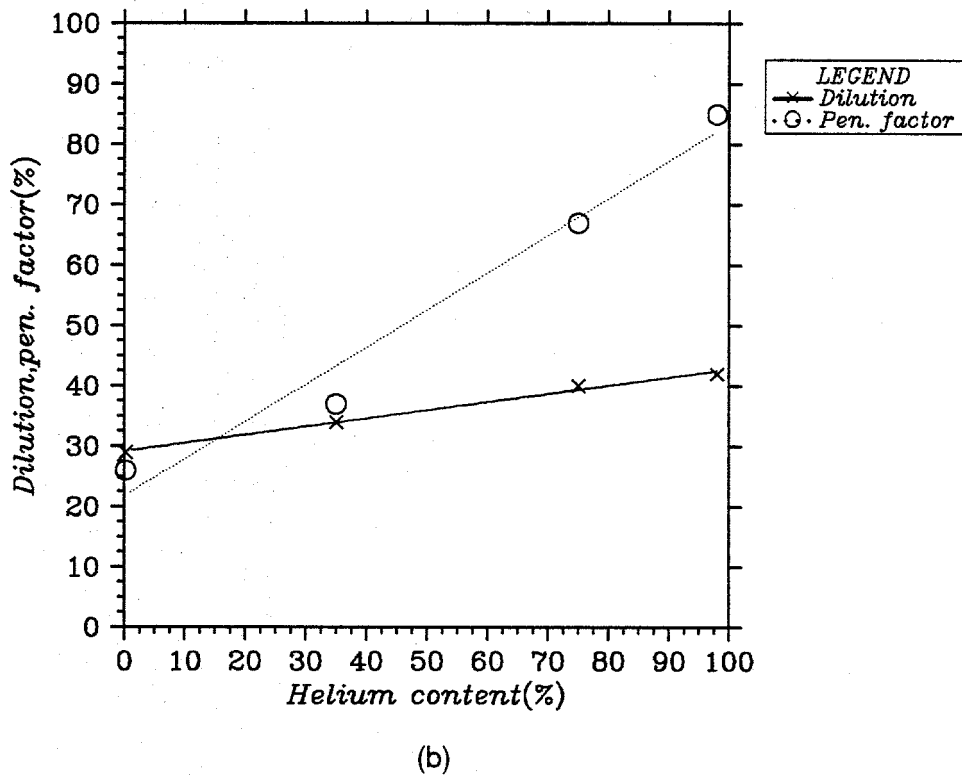


Figure 7.32

Effect of He content in the shielding gas on bead characteristics of bead-on-plate welds. (a) A_d , A_a and A_t , (b) $\bar{u}$ and f_p .

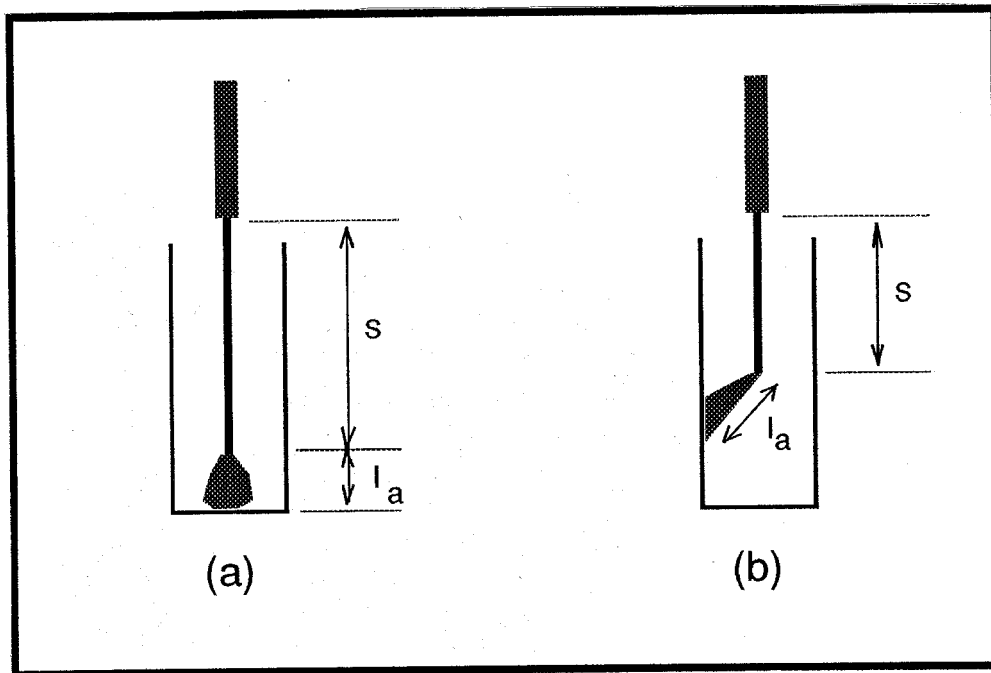


Figure 7.33 Limit arc configurations in a very narrow groove. (a) Short arc, (b) long arc.

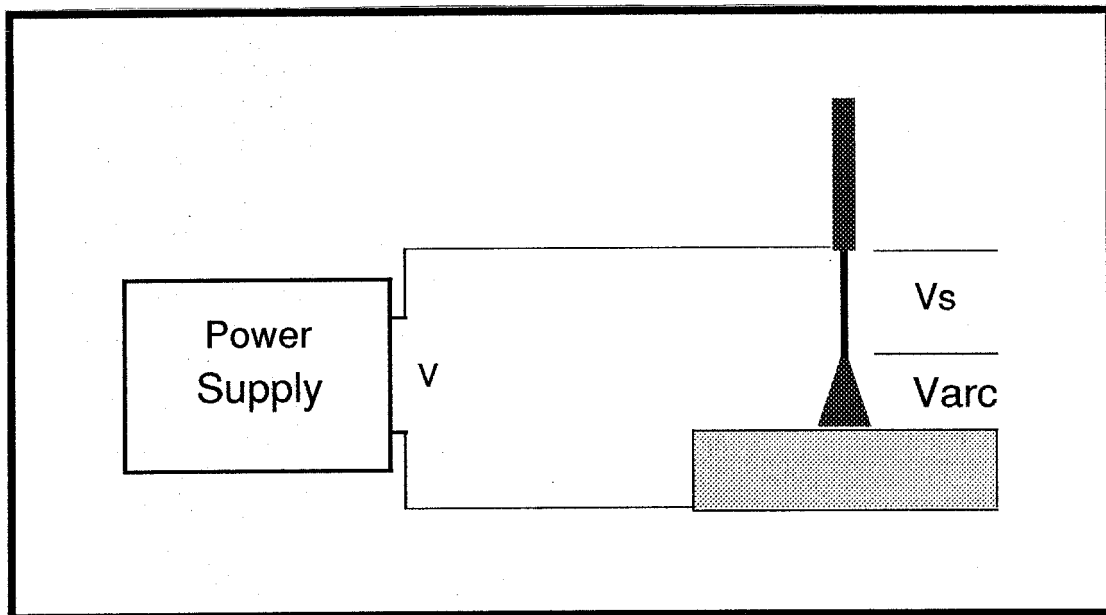


Figure 7.34 Voltage drop along the welding circuit.

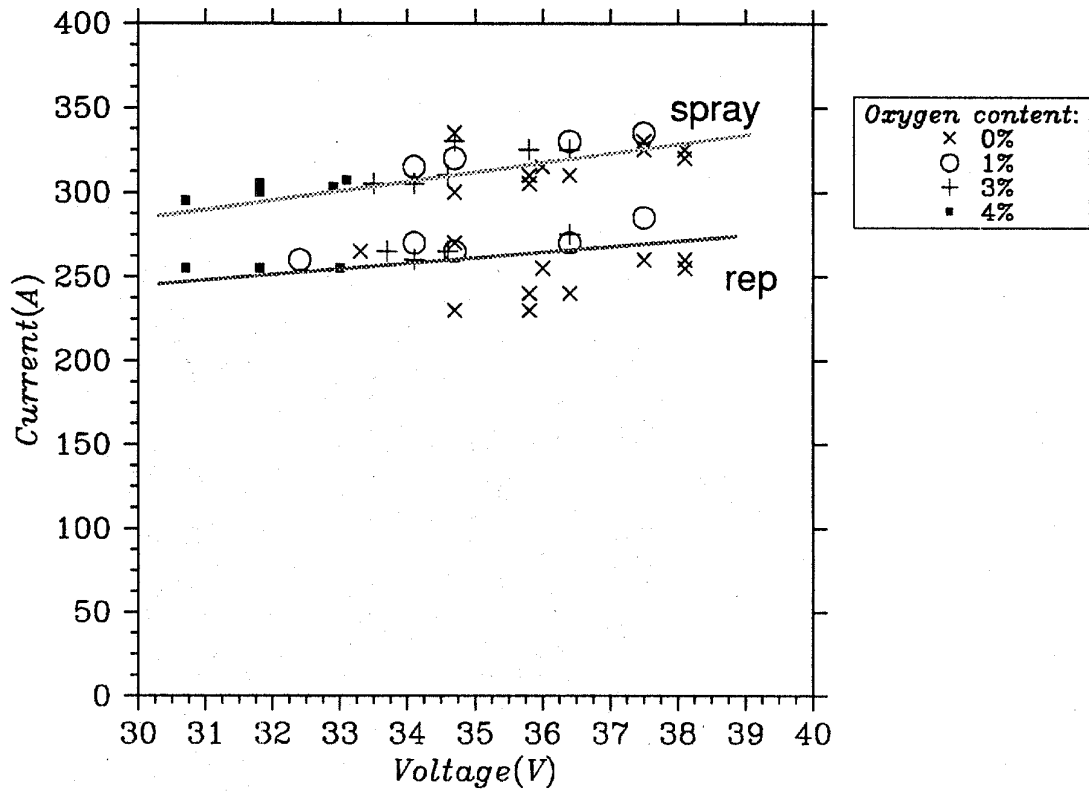


Figure 7.35

The difference in current level for stable (spray) and unstable (repulsive) modes in constant voltage. Shielding gas: He-101 + oxygen.

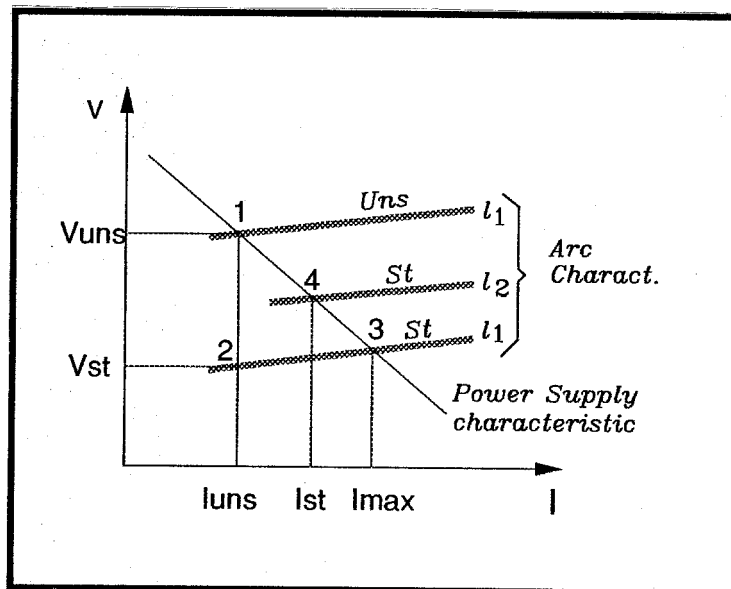


Figure 7.36

Schematic diagram presenting the relationship between power supply characteristic and the transition from unstable (1) to stable (4) operation. l : arc length, $l_1 < l_2$.

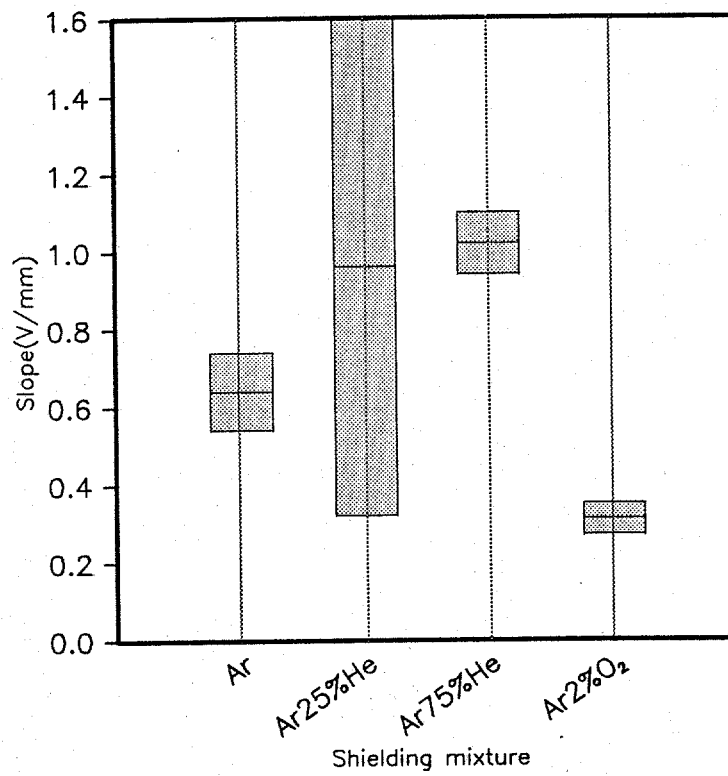


Figure 7.37

Slope of the $V \times$ standoff lines, with its 95% confidence interval, for different shielding gas compositions. $I=260A$.

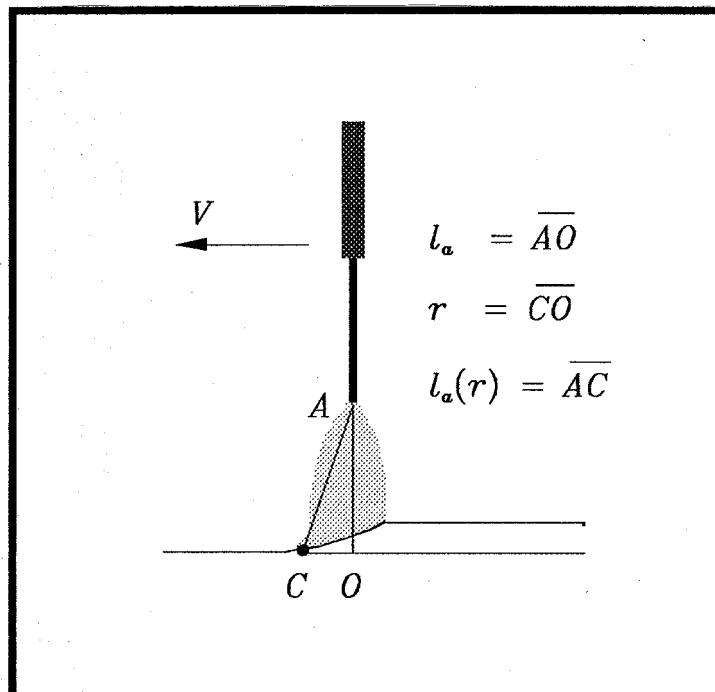


Figure 7.38

Schematic representation of the GMAW arc region.

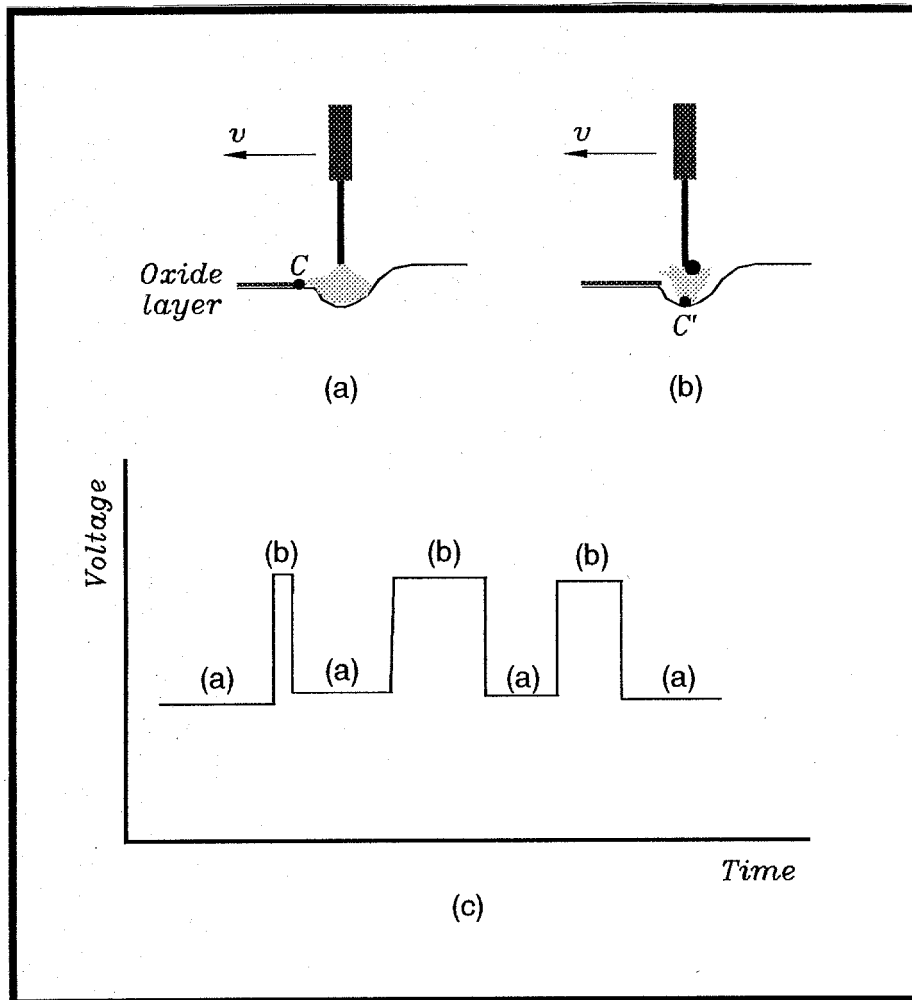


Figure 7.39

Proposed mechanism for arc length dependent instability.

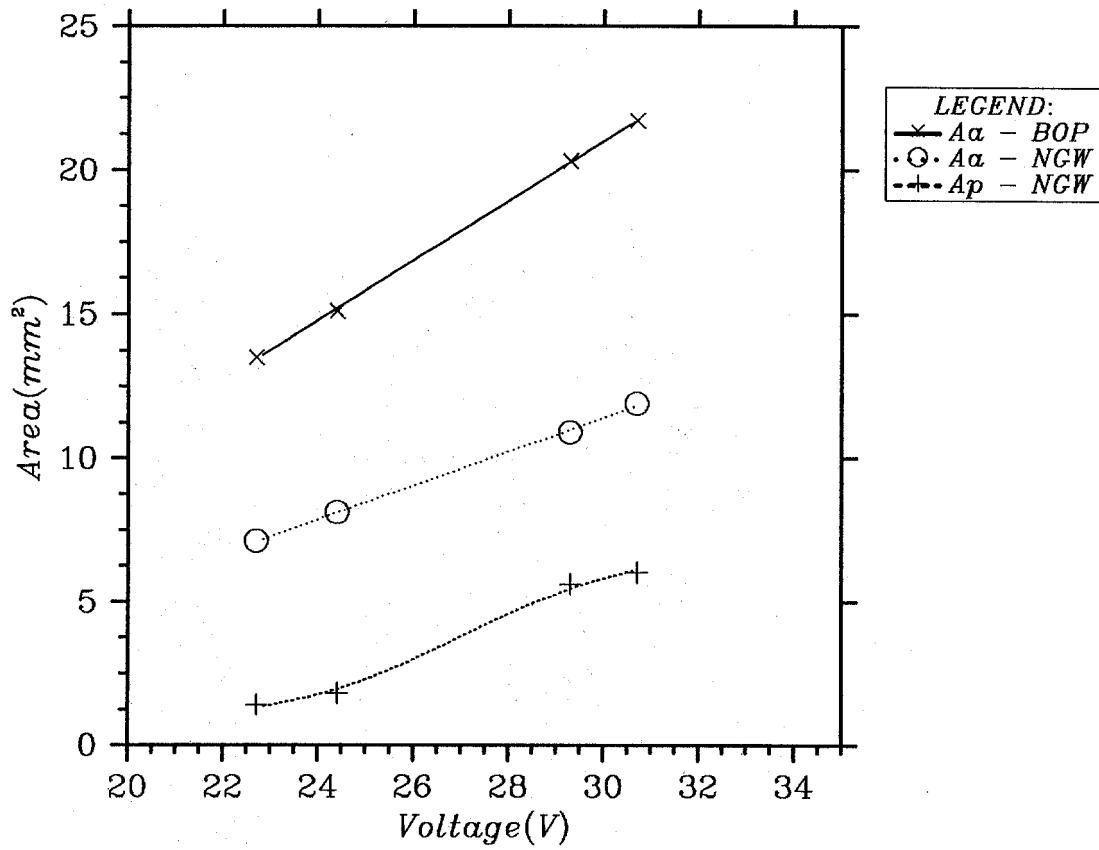


Figure 7.40 The effect of arc voltage on plate fusion in BOP and NG welding trials.

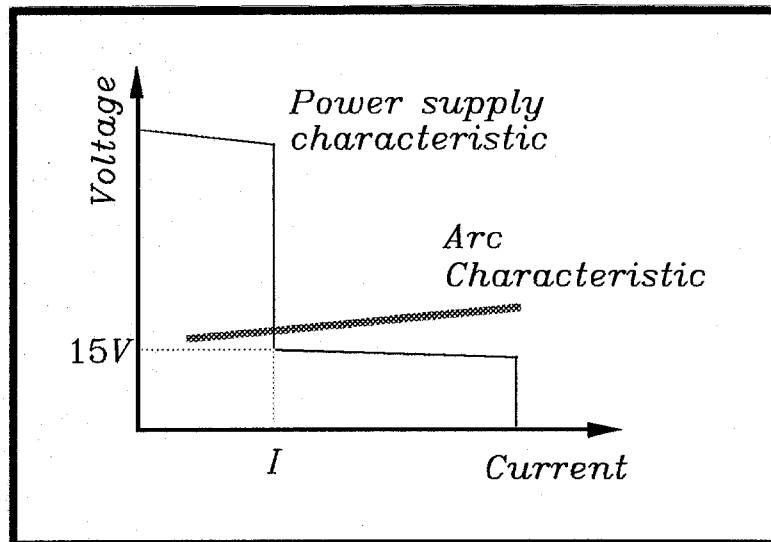


Figure 7.41 Idealised power supply characteristic for narrow gap welding.

CHAPTER 8

8. CONCLUSIONS

1. Statistical experimental analysis can provide a powerful tool for the analysis and modelling of welding processes. The present programme demonstrated that these techniques can be a more efficient and adequate tool than the usual one-variable-at-a-time approach to investigate the influence of welding parameters on the weld bead characteristics. However, caution is important to avoid misleading conclusions from an improper use of these techniques. The strong interdependence between input variables that was found in the GMAW-NG process made it difficult to apply a factorial experiment in its analysis. This forced the use of a distorted factorial which introduced some collinearity into the input data. Careful data analysis, however, allowed the development of adequate models by multiple linear regression.
2. Modelling results depend strongly on both the experimental design and the initial set of input variable candidates, and this should be taken into account during result analysis. For example, modelling equations for bead characteristics related to wire fusion can be reduced to a very simple form by properly selecting input variables. The objectives of modelling and the experimental conditions should influence this selection.
3. Plate melting efficiency decreases in NGW with decreasing gap width and is always lower than in bead-on-plate welding. The chance of sidewall fusion defects at the bottom of the joint generally decreases with decreasing gap width.
4. For the downhand position, the best results in terms of a lack of welding defects were associated with non-pulsed, constant current operation, Ar-He-O₂ shielding and a 7mm gap width. The optimized shielding gas mixture and the use of a non-pulsed current enlarged considerably the space for acceptable operation of the process. This improvement was demonstrated by a multiplot diagram in which the influence of four different input variables could be analyzed at the same time. In horizontal-vertical welding, the main process feature was non-uniform plate fusion by the arc. In order to minimize this effect by forcing a more effective arc action, measures such as narrower gap widths or off-centre wire positioning should be used.
5. Helium additions to the shielding gas improve both lateral and axial penetration in NGW. The increase in plate fusion is related to an increase in secondary fusion while finger penetration remains approximately unchanged. Results indicate that up to 75%He can be used in the shielding gas without process stability deteriorating appreciably in NGW provided an adequate balance of oxidizing components is present.

6. Helium additions to the shielding gas can enlarge the area of acceptable operation in NG-GMA welding by improving its fusion characteristics. A shielding mixture containing approximately 75%He and 2%O₂ was considered to provide, in the ternary Ar-He-O₂ system, the best compromise in terms of fusion and process stability.
7. Narrow gap beads relatively free from fusion defects can be obtained for both the downhand and the horizontal-vertical positions. However, the process can be rather sensitive to minor changes in welding parameters and, therefore, its application in production will depend on the availability of effective control systems. For instance, the results indicate that a variation of less than 1mm in the gap width can strongly influence the formation of defects such as lack of fusion and undercutting. Current level and welding speed changes also affect strongly the bead shape and the likelihood of defects.
8. An arc/metal transfer process instability that depends on arc length, oxidizing potential of the shielding gas and the power supply characteristic was demonstrated. The instability process is associated with abrupt changes in arc current or voltage level and can seriously affect operation for short arc conditions such as those necessary for the process studied.
9. Mathematical modelling of the voltage drop along the welding circuit in the GMAW process demonstrated that, inside a very narrow gap, the self-adjusting arc property of the constant voltage operation can become inoperative and result in an unstable process in which the arc tends to climb up along the side walls of the joint. In order to prevent this effect, a power supply with constant current characteristic and capable of detecting and responding to short circuit was used in the present programme.

CHAPTER 9

9. Recommendations for further work

Although optimization of shielding gas composition and other parameters significantly improved the fusion characteristics of the process, this is still rather sensitive to variations in process parameters, particularly in the H-V position. However, it should be possible to further improve fusion characteristics by changing the solid electrode for a metal cored wire. This sort of consumable would certainly require important changes in electric polarity, shielding gas composition, welding current levels, etc.

As far as welding with solid wire is concerned, further improvements in the shielding gas composition could be expected from an investigation of the Ar-He-CO₂-O₂ system. Carbon dioxide may effectively substitute for some of the helium in the optimized mixture, reducing its cost.

One of the major obstacles for the use of the process in an industrial application could be its narrow operational envelope. In order to overcome this, adequate and reliable control systems to guarantee process operation in an industrial environment would have to be developed and tested.

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APPENDIX A

This is a binary-to-ascii files translator programme. It was used to create ASCII versions of the VELA data files to be transferred from the BBC microcomputer to other computers.

```

10MODE7:CLS:DIM NAME$(31),DT(31),CHANNEL%(31),AD%(7),DAT 2050:
COR1$=CHR$132+CHR$157+CHR$131:COR2$=CHR$130+CHR$157+CHR$129
20PRINT TAB(5,10);CHR$130;"BIN-ASCII TRANSLATOR"
30FOR I=1TO3000:NEXT
40PROCSETUP
50START%=1
60IF START%>FILES% THEN 140
70FOR I%=START% TO FILES%
80CLS:OSCLI"*DR."+BINDR$
90PROCINTRO
100OSCLI"*DR."+ASDR$
110PROCCREATE
120NEXT
130OSCLI"*."+ASDR$
140PRINT:PRINT:PRINT CHR$130;CHR$136;"          ** BYE BYE **":END
150DEFPROCSETUP
160CLS:LOCAL I%
170PRINT COR1$:PRINT COR1$;" SELECT FILE TYPE: (1)Vela(WITH t)": PRINT
COR1$;"          (2)Graphitek":PRINT COR1$;"
(3)Vela(NO t)":PRINT COR1$
180INPUT" YOUR CHOICE";FTY%:IF FTY%<1 OR FTY%>3 THEN 180
185PRINT:PRINT:IF FTY%=3 THEN FTY%=1:FTX$="TRUE" ELSE FTX$="FALSE"
190PRINT COR2$:PRINT COR2$;" SPECIFY BINARY FILES DRIVE(0-3)":PRINT
COR2$
200INPUT BINDR$:IF BINDR$>"3" OR BINDR$<"0" THEN 200 ELSE CLS:OSCLI "*."
+ BINDR$
210 PRINT:PRINT COR2$;" NUMBER OF FILES TO BE TRANSLATED":INPUT
FILES%:IF FILES%<1 THEN STOP ELSE IF FILES%>31 THEN 210
220PRINT:IF FTY%=1 THEN PRINT COR1$;"SELECT FILES" ELSE PRINT COR1$;
"SELECT FILES,NUMBER OF CHANNELS AND":PRINT COR1$;"          LOGGING TIME(ms)"
230PRINT:IF FTY%=1 THEN FOR I%=1 TO FILES%:PRINT"FILE ";I%:INPUT
NAME$(I%):NAME$(I%)="D."+NAME$(I%):CHANNEL%(I%)=1:NEXT
240IF FTY%=2 THEN FOR I%=1 TO FILES%:PRINT("";I%;") FILE NAME,NB OF
CHANNELS,TIME":INPUT NAME$(I%),CHANNEL%(I%),DT(I%):NEXT
250CLS:PRINT COR2$:PRINT COR2$;" SPECIFY ASCII FILES DRIVE(0-3)": PRINT
COR2$
260INPUT ASDR$:IF ASDR$>"3" OR ASDR$<"0" THEN 260
270CLS:ENDPROC

280DEF PROCINTRO
290ON ERROR GOTO 540
300X=OPENUP(NAME$(I%))
320PRINT TAB(0,6);COR2$;"          READING:";NAME$(I%)
330IF FTY%=1 THEN FOR J%=1 TO 7:AD%(J%)=BGET#X:NEXT:NB%=AD%(1)+256
*AD%(2):DT(I%)=AD%(4)*256+AD%(5) ELSE NB%=2047
335ON ERROR OFF
340IF FTY%=1 AND AD%(3)=1 THEN DT(I%)=DT(I%)*0.05:IF DT(I%)=0 THEN
DT(I%)=0.034
350J%=0
360REPEAT:DAT?J%=BGET#X:J%=J%+1
370UNTIL J%=NB% OR EOF#X
380NB%=J%:CLOSE#X
390ENDPROC

400DEF PROCCREATE
410CLS:PRINT COR1$;"          CREATING ASCII FILE":IF FTY%=1 THEN ASFI$=
RIGHT$(NAME$(I%),LEN(NAME$(I%))-2) ELSE ASFI$=NAME$(I%)
420IF DT(I%)<=10 THEN PRINT COR2$;"          LOGGING TIME IN ms" ELSE
DT(I%)=DT(I%)/1000:PRINT COR2$;"          LOGGING TIME IN SEC!!":PRINT CHR$7

```

```

4300N ERROR GOTO 510
4400SCLI"*SPOOL "+ASFI$
4500N ERROR OFF
460IF FTX$="TRUE" THEN PRINT NB%,DT(I%)
470N%=NB%/CHANNEL%(I%)-1:FOR J%=0 TO N%:@%=&20210:IF FTX$<>"TRUE" THEN
PRINT; DT(I%)*J%;
480@%=&10:FOR K%=1 TO CHANNEL%(I%):PRINT ;" ";DAT?(J%*CHANNEL%(I%) +
K%);:NEXT:PRINT:NEXT
490*SPOOL
500ENDPROC

5100N ERROR OFF:PRINT:PRINT COR1$
520IF ERR=&BE OR ERR=&C6 THEN PRINT COR1$;"      DISK OR CATALOG FULL!
":PRINT COR1$;"      CHANGE DISK AND HIT C":PRINT COR1$;"      TO
CONTINUE"
530PRINT COR1$:PRINT:PRINT CHR$7:REPEAT UNTIL GET$="C":START%=I%: GOTO
60 ELSE PRINT COR2$;"      ERROR IN OPENING FILE ";NAME$(I%):PRINT CHR$7:END
5400N ERROR OFF:IF ERR=&D6 OR ERR=222 THEN PRINT COR1$:PRINT COR1$;
"      FILE NOT FOUND!":PRINT COR1$:PRINT CHR$7:START%=I%+1:FOR X=1 TO
3000:NEXT:GOTO 60
550PRINT COR2$;"      ERROR IN OPENING FILE ";NAME$(I%):PRINT CHR$7:END

```

APPENDIX B

```

C *****
C *
C *          This program studies welding data recorded
C *                      by the VELA.
C *                      By P. J. Modenesi
C *                      LINK MYPROGRAM, 'UNIRASLIB'
C *
C *****

C MAIN VARIABLES IN PROGRAM:

C VARIABLE NAME          TYPE          CHARACTERISTICS
C  NOME  ----- CHAR  ----- DATA FILE NAME
C  Y(1023) ----- REAL  ----- DATA VECTOR(NOT FILTERED)
C  YF(1023) ----- REAL  ----- DATA VECTOR
C  YPEAK(100) ----- REAL  ----- PEAK CURRENT VALUES
C  YBASE(100) ----- REAL  ----- BASE CURRENT VALUES
C  PTIME(100) ----- REAL  ----- PEAK TIMES
C  YMEAN  ----- REAL  ----- MEAN CURRENT
C  NB  ----- INT  ----- NB OF POINTS(FILTERED DATA)
C  NP  ----- INT  ----- NB OF POINTS
C  IMIN  ----- INT  ----- FIRST FILTERED DATA POINT
C  DT  ----- REAL  ----- TIME INTERVAL
C  COEF  ----- REAL  ----- CALIBRATION FACTOR
C  FACTOR ----- REAL  ----- VOLTAGE DIVISOR FACTOR
C  IDEV  ----- INT  ----- PLOTTING TERMINAL NB

C *****

CHARACTER*40 NOME,A*1,LABEL*30
DIMENSION Y(1023),YF(1023),YPEAK(100),YBASE(100),PTIME(100)

EXTERNAL DISP,GRAFV,FILTER,STATS,PEAK,CREATE,CUVAL,INTRO
COMMON /DATT/YF,YMEAN,Y
COMMON /PARAM/NB,IMIN,DT,NP
COMMON /COEFT/COEF,COEF0,ICOEF,ISETUP,Y_MIN,Y_MAX,LABEL

C SET UP INITIAL CONDITIONS
DO I=1,15
  PRINT*, ' '
END DO

Y_MIN=0
Y_MAX=600.
LABEL=' Weld. current(A)$'
COEF=250./128./0.43
COEF0=0.

C OPEN REPORT FILE(VELA.DAT)
OPEN(UNIT=IU,FILE='VELA.DAT',STATUS='NEW')
WRITE(IU,100)
100 FORMAT(18X,' WELD CURRENT STRUCTURE ANALYSIS'//)
NB=0
IDEV=0

C *****MAIN MENU*****
10 PRINT*, ' '
PRINT*, ' '
PRINT*, ' ***** '
PRINT*, '          MAIN MENU '
PRINT*, ' ***** '
PRINT*, ' '
PRINT*, ' (0) CHANGE SET UP '
PRINT*, ' (1) INPUT DATA FILE '
PRINT*, ' (2) DISPLAY DATA '

```

```

PRINT*, ' (3) PLOT DATA(GRAFIC TERMINAL)'
PRINT*, ' (4) FILTER SIGNAL'
PRINT*, ' (5) CALCULATE CURRENT CHARACTERISTICS'
PRINT*, ' (6) CALCULATE AREA UNDER PEAK'
PRINT*, ' (7) CREATE DATA FILE'
PRINT*, ' (8) CALCULATE STATISTICS'
PRINT*, ' '
PRINT*, ' YOUR CHOICE'
READ(*,*) IC
IF((IC.LT.0).OR.(IC.GT.8)) GO TO 30
IF(IC.EQ.0) CALL SET_UP
IF((IC.NE.1).AND.(NB.EQ.0)) GO TO 10
PRINT*, ' '

IF(IC.EQ.1) THEN
    CALL INTRO(NOME, IFILTER)
    CALL STATS(YF, IMIN, NB, YMEAN, SD, 0)
    WRITE(IU, 110) NOME
    WRITE(IU, 170) YMEAN, SD
END IF

IF(IC.EQ.2) CALL DISP
IF(IC.EQ.3) CALL GRAFV(IDEV)
IF(IC.EQ.4) CALL FILTER(IFILTER)

IF(IC.EQ.5) THEN
    PRINT*, ' CURRENT STRUCTURE: '
    WRITE(*, 120) YMEAN, SD
    CALL PEAK(YPEAK, YBASE, YMAX, YMIN, NPEAK, NBASE, PER, PTIME)
    IF((NPEAK.LE.1).OR.(NBASE.LE.1)) THEN
        PRINT*, ' '
        PRINT*, ' INSUFICIENT PEAKS AND/OR BASES. '
    END IF
    CALL STATS(YPEAK, 1, NPEAK, YPMEAN, SDP, 0)
    CALL STATS(YBASE, 1, NBASE, YBMEAN, SDB, 0)
    CALL STATS(PTIME, 1, NPEAK, TMEAN, SDPT, 0)
    PRINT*, ' *PEAK VALUES*'
    PRINT*, ' '
    WRITE(*, 140) (YPEAK(I), I=1, NPEAK)
    WRITE(*, 150) YPMEAN, SDP, NPEAK, YMIN
    WRITE(*, 140) (YBASE(I), I=1, NBASE)
    WRITE(*, 160) YBMEAN, SDB, NBASE
    FREQ=1000./PER
    WRITE(*, 200) PER, FREQ, TMEAN, SDPT
    CALL REPORT(I)
    IF(I.EQ.1) THEN
        WRITE(IU, 130) IFILTER, YMAX
        WRITE(IU, 180) (YPEAK(I), I=1, NPEAK)
        WRITE(IU, 190) YPMEAN, SDP, NPEAK, YMIN
        WRITE(IU, 180) (YBASE(I), I=1, NBASE)
        WRITE(IU, 210) YBMEAN, SDB, NBASE
        WRITE(IU, 220) PER, FREQ, TMEAN, SDPT
    END IF
END IF

IF(IC.EQ.6) THEN
    PRINT*, ' AREAS UNDER PEAK: '
    WRITE(*, 120) YMEAN, SD
    CALL PAREA(YPEAK, YMAX, NPEAK)
    IF(NPEAK.LE.1) THEN
        PRINT*, ' '
        PRINT*, ' INSUFICIENT NUMBER OF PEAKS '
        GO TO 25
    END IF
    CALL STATS(YPEAK, 1, NPEAK, YPMEAN, SDP, 0)
    PRINT*, ' *PEAK AREAS*'
    PRINT*, ' '

```

```

WRITE(*,145) (YPEAK(I), I=1, NPEAK)
WRITE(*,230) YPMEAN, SDP, NPEAK
CALL REPORT(I)
IF(I.EQ.1) THEN
  WRITE(IU,240) IFILTER, YMAX
  WRITE(IU,185) (YPEAK(I), I=1, NPEAK)
  WRITE(IU,250) YPMEAN, SDP, NPEAK
END IF
END IF

IF(IC.EQ.7) CALL CREATE

IF(IC.EQ.8) THEN
  YEFF=1
  CALL STATS(YF, IMIN, NB, YMEAN, SD, YEFF)
  CALL BOUND(YF, 1023, NB, IMIN, VMAX, VMIN)
  PRINT*, ' '
  PRINT*, ' DATA STATISTICS: '
  WRITE(*,260) YMEAN, SD, VMAX, VMIN, YEFF
END IF

25 PRINT*, ' '
PRINT*, ' CONTINUE(C/c) OR STOP(S)? '
READ(*, '(1A)') A
IF(A.NE.'S') GO TO 10
30 CLOSE(IU)
STOP

110 FORMAT(/11X, '*****')
1  *****'//11X, 'DATA FILE:', 15A//)
120 FORMAT(/' MEAN CURRENT(A):', F8.1, 13X, 'ST. DEV.(A) :', F8.1/)
130 FORMAT(17X, '*****CURRENT STRUTURE:'//32X, 'FILTER FACTOR :',
1  I4//20X, ' PEAK REF.(A):', F8.1//40X, '*PEAK VALUES*')
140 FORMAT(6F10.1)
145 FORMAT(6F10.4)
150 FORMAT(/' MEAN PEAK(A) :', F8.1, 13X, 'ST. DEV.(A) :', F8.1/
1  ' NUMBER PEAKS :', I8//' BASE REF.(A):', F8.1//
2  28X, '*BASE VALUES*')
160 FORMAT(/' MEAN BASE(A) :', F8.1, 13X, 'ST. DEV.(A) :', F8.1/
1  ' NUMBER BASES :', I8//)
170 FORMAT(21X, 'MEAN CURRENT(A):', F8.1, 13X, 'ST. DEV.(A) :', F8.1//)
180 FORMAT(10X, 10F10.1)
185 FORMAT(10X, 10F10.4)
190 FORMAT(/20X, ' MEAN PEAK(A) :', F8.1, 13X, 'ST. DEV.(A) :', F8.1/
1  20X' NUMBER PEAKS :', I8//23X, 'BASE REF.(A):', F8.1//
2  40X, '*BASE VALUES*')
200 FORMAT(' PULSE TIME(ms):', F8.2, 13X, 'FREQUENCY(Hz):', F7.1/
1  ' PEAK TIME(ms) :', F8.2, 13X, 'ST. DEV.(ms):', F8.2/)
210 FORMAT(/20X, ' MEAN BASE(A) :', F8.1, 13X, 'ST. DEV.(A) :', F8.1/
1  20X, ' NUMBER BASES :', I8//)
220 FORMAT(21X, 'PULSE TIME(ms):', F8.2, 13X, 'FREQUENCY(Hz):', F7.1/
1  21X, 'PEAK TIME(ms) :', F8.2, 13X, 'ST. DEV.(ms):', F8.2/)
230 FORMAT(/' MEAN AREA(A*s):', F8.4, 13X, 'ST. DEV.(A*s):', F8.4/
1  ' NUMBER PEAKS :', I8//)
240 FORMAT(17X, '*****PEAK AREAS:'//32X, 'FILTER FACTOR :', I4//
1  20X, ' REF. CUR.(A):', F8.1//40X, '*AREA VALUES*')
250 FORMAT(/20X, ' MEAN AREA(A.s):', F8.4, 13X, 'ST. DEV.(A*s):', F8.4/
1  20X, ' NUMBER PEAKS :', I8//)
260 FORMAT(/' MEAN :', F10.2, 10X, 'STANDART DEV.: ', F10.2/
1  ' MAXIMUM: ', F10.2, 10X, 'MINIMUM : ', F10.2/
2  ' EF. MEAN:', F10.2//)
END

```

C *****

SUBROUTINE GRAFV(IDEV)

```

C      This routine plots a Y x time graphic
C      IDEV --- Graphic terminal number
C
C      *****
C
C      MAIN VARIABLES IN PROGRAM:
C
C      TLABEL(2)  ----- CHAR -----  AXIS LABELS
C      TEXT  ----- CHAR -----  TEXT LINE(ENDING IN $)
C      VMIN(2)/VMAX(2) -- REAL -----  AXIS LIMITS
C      X(1100),Y(1100) -- REAL -----  POINTS COORDINATES
C      FX0,FY0 ----- REAL -----  RELATIVE ORIGIN POSITION
C      X0,Y0 ----- REAL -----  ORIGEM COORDINATES
C      FTEX ----- REAL -----  RELATIVE TEXT POSITION
C      YTEX ----- REAL -----  TEXT POSITION
C      FDX,FDY ----- REAL -----  RELATIVE AXIS LENGTH
C      DX,DY ----- REAL -----  AXIS LENGTH
C      FLABEL ----- REAL -----  RELATIVE CHARACTER SIZE
C      HT ----- REAL -----  CHARACTER SIZE
C      WL ----- REAL -----  LINE WIDTH
C      IBACK ----- INT -----  BACKGROUND COLOUR
C      ILINE ----- INT -----  LINE COLOUR
C
C      *****
C      CHARACTER*20 TLABEL(2),TEXT*100,LABEL*30
C      CHARACTER*1 DEC
C      DIMENSION VMIN(2),VMAX(2),X(1100),Y(1100),V(1100)
C      DATA FDX,FDY,FTEX/0.75,0.51,0.57/,FX0,FY0/1.79,1.57/,
C      1      YLASER/195.08/,WL/-2./
C      DATA IBACK,ILINE/7,4/
C
C      COMMON /DATT/V
C      COMMON /PARAM/NB,IMIN,DT
C      COMMON /COEFT/COEF,COEF0,ICOEF,ISETUP,Y_MIN,Y_MAX,LABEL
C
C      DEFINE GRAPHIC SETTINGS
C      FLABEL=3.0/YLASER
C      TLABEL(2)=LABEL
C      VMIN(2)=Y_MIN
C      VMAX(2)=Y_MAX
C
C      IF(NB*DT.LT.2000) THEN
C          TLABEL(1)='Time(ms)$'
C          FTIME=1.0
C      ELSE
C          TLABEL(1)='Time(sec)$'
C          FTIME=0.001
C      END IF
C
C      IF((IDEV.LE.0).OR.(IDEV.GE.5)) THEN
C          PRINT*, ' '
C          PRINT*, '*****'
C          PRINT*, 'SELECT TERMINAL: (1) LT4109'
C          PRINT*, '                (2) VT4014'
C          PRINT*, '                (3) DUMMY DRIVER'
C          PRINT*, '                (4) VAXSTATION'
C          PRINT*, '                (5) RETURN'
C          READ(*,*)IDEV
C          PRINT*, ' '
C          IF((IDEV.LT.1).OR.(IDEV.GT.4)) RETURN
C      END IF
C
C      SELECT DATA INTERVAL AND INITIALIZE X AND Y
10  WRITE(*,200) IMIN
C      READ(*,*) ISTART
C      IF((ISTART.LT.IMIN).OR.(ISTART.GE.NB)) GO TO 10

```

```

11  WRITE(*,210) NB-ISTART+1
    READ(*,*) NP
    IF((NP.LE.0).OR.(NP.GT.NB-ISTART+1)) GO TO 11

    PRINT*, ' '
    PRINT*, ' '
    PRINT*, ' '
    PRINT*, '*VALUES FOR Y AXIS:'
    PRINT*, ' '
    WRITE(*,220) TLABEL(2)
    PRINT*, '*MAX.Y: ', VMAX(2)
    PRINT*, '*MIN.Y: ', VMIN(2)
    PRINT*, ' '
    PRINT*, ' CHANGE SETTINGS?[ N ]'
    READ(*, '(A)') DEC
    IF((DEC.EQ.'Y').OR.(DEC.EQ.'y')) THEN
        PRINT*, ' INPUT NEW LABEL (END=$): '
        READ(*, '(A)') TLABEL(2)
12    PRINT*, ' '
        PRINT*, ' INPUT MIN. Y'
        READ(*,*) Y_SMALL
        PRINT*, ' INPUT MAX. Y'
        READ(*,*) Y_LARGE
        IF(Y_SMALL.GE.Y_LARGE) THEN
            PRINT*, ' ** Y_MIN < Y_MAX **'
            GO TO 12
        ELSE
            VMIN(2)=Y_SMALL
            VMAX(2)=Y_LARGE
        END IF
    END IF

    IFLAG=0
125 DT0=0
    J=ISTART-1

    DO I=1,NP
        Y(I)=V(J+I)
        X(I)=DT0
        DT0=DT0+DT*FTIME
    END DO
    VMAX(1)=X(NP)
    VMIN(1)=X(1)

C   CALL DEVICE
    IF(IFLAG.EQ.0) THEN
        IF(IDEV.EQ.1) THEN
            CALL GROUTE('SEL LT4109;EX')
        ELSE IF(IDEV.EQ.2) THEN
            CALL GROUTE('SEL VT4014;EX')
        ELSE IF(IDEV.EQ.3) THEN
            CALL GROUTE('SEL MDUMDR;EX')
        ELSE IF(IDEV.EQ.4) THEN
            CALL GROUTE('SEL MGPX;EX')
        END IF
    END IF

C   START UNIRAS AND DETERMINE DEVICE SIZE
    CALL GOPEN
    CALL GRPSIZ(XDEV,YDEV)

C   SET PLOTTING DIMENSIONS
    HT=FLABEL*YDEV
    DX=FDX*XDEV
    DY=FDY*YDEV
    X0=(XDEV-DX)/FX0

```

```

Y0=(YDEV-DY)/FY0
YTEX=FTEX*Y0
X1=VMIN(1)
X2=VMAX(1)
Y1=VMIN(2)
Y2=VMAX(2)

C   DRAW AXES AND GRID
CALL BGRAF(X0,Y0,DX,DY)
IF((IFLAG.EQ.0).AND.((IDEV.EQ.1).OR.(IDEV.EQ.4)))
1   CALL BGRAFB(IBACK)
CALL GCHARF('SOFT')
CALL GCHARF('ITAL')
DO I=1,2
    CALL BAXLAB(HT,HT,999,999)
    CALL BTICKM(4)
    CALL BAXIS(I,VMIN(I),VS,VMAX(I),TLABEL(I))
    IF(I.EQ.1) THEN
        CALL BAXORI(X0,Y0+DY)
    ELSE
        CALL BAXORI(X0+DX,Y0)
    END IF
    CALL BAXLAB(0.,0.,999,999)
    CALL BAXIS(-I,VMIN(I),VS,VMAX(I),'$')
END DO

C   DRAW CURVE
CALL GLIMIT(X1,X2,Y1,Y2,0.,0.)
CALL GVPORT(X0,Y0,DX,DY)
CALL GWBOX(DX,DY,0.)
CALL GSCALE
IF(((IDEV.EQ.1).OR.(IDEV.EQ.4)).AND.(IFLAG.EQ.0))
1   CALL GWICOL(-1,ILINE)
IF(IFLAG.GT.0) CALL GWICOL(WL,1)
CALL GVECT(X,Y,NP)

C   WRITE TEXT
CALL GSCAMM
IF(IFLAG.GT.0) THEN
    XJUS=XDEV/2
    CALL GCHARF('TRIP')
    CALL GCHARJ(1)
    CALL GCHART(1)
    CALL GCHAR(TEXT,XJUS,YTEX,HT)
    CALL GSEGCL(IFLAG)
END IF

C   STOP UNIRAS
CALL GCLOSE

PRINT*, '   DEVICE PLOT AREA LENGTHS(MM)'
PRINT*, 'X= ',XDEV, ' Y= ',YDEV

130 PRINT*, ' '
PRINT*, ' SELECT OPTION: '
PRINT*, '           (1) MODIFY PLOT'
PRINT*, '           (2) HARDCOPY'
PRINT*, '           (3) RETURN'
READ(*,*)I
IF(I.EQ.1) GO TO 10
IF(I.EQ.2) THEN
    PRINT*, ' '
    PRINT*, ' INPUT SEGMENT NUMBER(1-99)'
    READ(*,*) IFLAG
    PRINT*, ' '
    IF((IFLAG.LT.1).OR.(IFLAG.GT.99)) GO TO 130

```

```

        PRINT*, ' INPUT TEXT(MAX. 100 CHAR.)'
        READ(*, '(100A)') TEXT
        CALL CONCAT(TEXT, 100)
C        CALL GROUTE('SEL GLN03A;EX')
        CALL GROUTE('SEL HPOSTA4L;EX')
        CALL GSEGWK(0)
        CALL GSEGCR(IFLAG)
        GO TO 125
    END IF
200  FORMAT(' INPUT STARTING POINT( >', I4, ')')
210  FORMAT(' INPUT NUMBER OF POINTS( <', I4, ')')
220  FORMAT(' *Y LABEL :', A/)
    RETURN
    END

C *****

C        SUBROUTINE FILTER(IFILTER)
C        IFILTER -----FILTER FACTOR

C *****

C        MAIN VARIABLES:

C        C00(6), COX(6,6) ---- REAL ---- FILTER COEFICIENTES

C *****
    DIMENSION YF(1023), Y(1023), C00(6), COX(6,6)
    COMMON /DATT/YF, YMEAN, Y, /PARAM/NB, IMIN, DT, NP
    DATA C00/2., 6., 20., 70., 252., 924./
    DATA COX/1., 0, 0, 0, 0, 4., 1., 0, 0, 0, 0, 15., 6., 1., 0, 0, 0, 56.,
1      28., 8., 1., 0, 0, 210., 120., 45., 10., 1., 0, 792., 495., 220.,
2      66., 12., 1./
    PRINT*, ' '
    PRINT*, ' INPUT FILTER FACTOR(0-6)'
    READ(*, *) IFILTER
    IF((IFILTER.LE.0).OR.(IFILTER.GT.6)) THEN
        IMIN=1
        NB=NP
        DO I=IMIN, NB
            YF(I)=Y(I)
        END DO
        RETURN
    END IF
    IMIN=IFILTER+1
    NB=NP-IFILTER
    N=4.*IFILTER
    DO I=IMIN, NB
        YF(I)=Y(I)*C00(IFILTER)
        DO J=1, IFILTER
            YF(I)=YF(I)+(Y(I-J)+Y(I+J))*COX(J, IFILTER)
        END DO
        YF(I)=YF(I)/N
    END DO
    RETURN
    END

C *****

C        SUBROUTINE INTRO(NAME, IFIL)
C        NAME ----- DATA FILE NAME
C        IFIL ----- FILTER FACTOR(0)

C *****

```

```

CHARACTER*40 NAME, DEC*1, LABEL*30
DIMENSION CF(1023), C(1023)
COMMON /DATT/CF, CMEAN, C
COMMON /PARAM/NB, IMIN, DT, NP
C   COMMON /COEFT/COEF, COEF0, ICOEF, ISETUP, Y_MIN, Y_MAX, LABEL

998 PRINT*, ' '
PRINT*, ' ***** '
PRINT*, ' INPUT FILENAME '
READ(*, '(A)') NAME
OPEN(UNIT=20, ERR=999, FILE=NAME, STATUS='OLD')
READ(20, *) NB, DT
READ(20, *) (C(I), I=1, NB)
CLOSE(20)

DO I=1, NB
    C(I)=CUVAL(C(I))
    CF(I)=C(I)
END DO
IFIL=0
IMIN=1
NP=NB
CMEAN=0
RETURN

C   *****
C   ERROR DURING FILE OPENNING!!
C   *****
999 PRINT*, ' ***THIS FILE CANNOT BE OPENED!*** '
PRINT*, ' DO YOU WANT TO TRY ANOTHER? (1)YES '
PRINT*, '                                     (2)NO '
READ(*, *) I
IF(I.EQ.1) GO TO 998
C   *****
RETURN
END

C   *****

SUBROUTINE DISP

C   *****

DIMENSION CF(1023)
COMMON/DATT/CF, /PARAM/NB, IMIN
PRINT*, ' '
PRINT*, ' FIRST AVAILABLE POINT:', IMIN
PRINT*, ' LAST AVAILABLE POINT:', NB
10 PRINT*, ' '
PRINT*, ' INPUT LOWER LIMIT '
READ(*, *) ILOW
IF((ILOW.LT.IMIN).OR.(ILOW.GT.NB)) GO TO 10
20 PRINT*, ' UPPER LIMIT '
READ(*, *) IUP
IF((IUP.LT.ILOW).OR.(IUP.GT.NB)) GO TO 20
PRINT*, ' '
WRITE(*, 100) (CF(I), I=ILOW, IUP)
100 FORMAT(6F10.1)
RETURN
END

C   *****

```

```

SUBROUTINE PEAK(YPEAK,YBASE,YMAX,YMIN,NPEAK,NBASE,PER,PTIME)
C  YPEAK ----- PEAK CURRENT VALUES
C  YBASE ----- BASE CURRENT VALUES
C  YMAX ----- REFERENCE CURRENT(FOR YPEAK)
C  YMIN ----- " " (FOR YBASE)
C  NPEAK ----- NB OF PEAKS
C  NBASE ----- NB OF BASES
C  PER ----- MEAN PERIOD
C  PTIME ----- PEAK TIMES

C  *****

C  MAIN VARIABLES:

C  IIP(100) ---- INT ----- PEAK/BASE STARTING POINTS
C  IEP(100) ---- INT ----- PEAK/BASE ENDING POINTS
C  *****

DIMENSION YF(1023)
DIMENSION IIP(100), IEP(100), YPEAK(100), YBASE(100), PTIME(100)
COMMON /DATT/YF, YMEAN, /PARAM/NB, IMIN, DT

C  SEARCH FOR PEAKS
10 PRINT*, ' '
PRINT*, ' INPUT REFERENCE FOR PEAK CURRENT '
READ(*,*) YMAX
K=1
CALL LIMIT(YMAX,N1,N2,K)
IF(K.EQ.0) THEN
    PRINT*, ' REFERENCE TOO LOW! '
    GO TO 10
END IF
CALL PEAKSEARCH(YMAX,N1,N2,IIP,IEP,NPEAK,1)
IF(NPEAK.LE.1) GO TO 50
PER=DT*(IIP(NPEAK)-IIP(1))/(NPEAK-1)
DO I=1,NPEAK
    YPEAK(I)=YF(IIP(I))
    PTIME(I)=DT*(IEP(I)-IIP(I))
    DO J=IIP(I)+1,IEP(I)
        IF(YF(J).GT.YPEAK(I)) YPEAK(I)=YF(J)
    END DO
END DO

C  SEARCH FOR BASE CURRENT VALUES
30 PRINT*, ' '
PRINT*, ' INPUT REFERENCE FOR BASE CURENT '
READ(*,*) YMIN
K=-1
CALL LIMIT(YMIN,N1,N2,K)
IF(K.EQ.0) THEN
    PRINT*, ' REFERENCE TOO HIGH! '
    GO TO 30
END IF
CALL PEAKSEARCH(YMIN,N1,N2,IIP,IEP,NBASE,-1)
IF(NBASE.LE.1) GO TO 50
DO I=1,NBASE
    YBASE(I)=YF(IIP(I))
    DO J=IIP(I)+1,IEP(I)
        IF(YF(J).LT.YBASE(I)) YBASE(I)=YF(J)
    END DO
END DO
IF(NPEAK.EQ.0) THEN
    PRINT*, ' TOO HIGH REFERENCE CUR. FOR PEAK CURRENT! '
    RETURN
END IF
50 RETURN

```

```

END

C *****

      SUBROUTINE LIMIT(YREF, ISTART, IEND, IFLAG)
C      YREF ----- REFERENCE VALUE
C      ISTART ----- STARTING POINT
C      IEND ----- FINNISHING POINT
C      IFLAG ----- RESULT FLAG

C *****

      DIMENSION YF(1023)
      COMMON /DATT/YF, /PARAM/NB, IMIN

      REF=IFLAG*YREF
      K=IFLAG
      IFLAG=0
      DO I=IMIN, NB
          P1=K*YF(I)
          IF(P1.LT.REF) THEN
              ISTART=I
              IFLAG=1
              GO TO 15
          END IF
      END DO
      IF(IFLAG.EQ.0) GO TO 30
15      DO I=IMIN, NB
          J=NB-I+1
          P1=K*YF(J)
          IF(P1.LT.REF) THEN
              IEND=J
              GO TO 30
          END IF
      END DO
30      RETURN
      END

C *****

      SUBROUTINE CREATE
C      THIS ROUTINE SAVES DATA IN FILE

C *****

      CHARACTER*40 NOME, VARIABLE
      DIMENSION DADO(1023)
      COMMON /DATT/DADO, /PARAM/NB, IMIN, DT

      PRINT*, ' INPUT NAME OF FILE TO BE CREATED '
      READ(*, '(A)') NOME
      PRINT*, ' INPUT VARIABLE NAME(END=$) '
      READ(*, '(A)') VARIABLE
      OPEN(UNIT=15, FILE=NOME, STATUS='NEW')
      I=NB-IMIN+1
      WRITE(15,*) I, DT
      WRITE(15,100) (DADO(I), I=IMIN, NB)
      WRITE(15, '(A)') VARIABLE
      CLOSE(15)
      RETURN
100  FORMAT(7F10.1)
      END

```

```

C *****

      SUBROUTINE REPORT(I)

C *****

CHARACTER*1 NAME
I=0
PRINT*, ' DO YOU WANT TO SAVE THESE DATA? (Y/y)YES '
PRINT*, '                                     (N/n)NO '
READ(*, '(1A)') NAME
IF((NAME.EQ. 'Y').OR.(NAME.EQ. 'y')) I=1
RETURN
END

C *****
      FUNCTION CUVAL(X)
C *****

COMMON /COEFT/FT,F0
IF(X.LT.128) X=128.
IF(X.GT.255) X=256
CUVAL=FT*(X-128.)+F0
RETURN
END

C *****

      SUBROUTINE STATS(DAT, IMIN, NUB, YMEAN, STD, YEFF)
C   DAT(1100)----- DATA
C   IMIN ----- FIRST POINT NB
C   NUB ----- NUMBER OF POINTS
C   YMEAN ----- MEAN(999.9 -> ERROR CONDITION)
C   STD ----- ST. DEV.(999.9 -> ERROR CONDITION)
C   YEFF ----- EFFECTIVE MEAN
C *****

DIMENSION DAT(1100)
IF(NUB.LE.1) THEN
  YMEAN=-999.9
  STD=-999.9
  RETURN
ELSE
  IMAX=IMIN+NUB-1
  YMEAN=0
  STD=0
END IF
DO I=IMIN, IMAX
  YMEAN=YMEAN+DAT(I)
END DO
YMEAN=YMEAN/NUB
DO I=IMIN, IMAX
  STD=STD+(DAT(I) - YMEAN)**2
END DO
STD=SQRT(STD/(NUB-1))
IF(YEFF.NE.0) THEN
  YEFF=0
  DO I=IMIN, IMAX
    YEFF=YEFF+DAT(I)*DAT(I)
  END DO
  YEFF=SQRT(YEFF/NUB)
END IF
RETURN
END

```

```

C *****

SUBROUTINE PEAKSEARCH(YREF,N1,N2,ISTART,IEND,NV,ISIG)
C   YREF ----- REFERENCE VALUE
C   N1 ----- FIRST POINT
C   N2 ----- LAST POINT
C   ISTART(100) --- PEAK/BASE STARTING POINT
C   IEND(100) ---- PEAK/BASE FINNISHING POINT
C   NV ----- NUMBER OF PEAKS/BASES
C   ISIG -----( 1) -> PEAK
C               (-1) -> BASE

C *****

DIMENSION DAT(1023)
DIMENSION ISTART(100),IEND(100)

COMMON /DATT/DAT

IFLAG=0
NV=0
REF=ISIG*YREF
DO 10 I=N1,N2
  YTEST=ISIG*DATT(I)
  IF((YTEST.GT.REF).AND.(IFLAG.EQ.0)) THEN
    NV=NV+1
    IFLAG=1
    ISTART(NV)=I
    GO TO 10
  END IF
  IF(IFLAG.EQ.0) GO TO 10
  IF(YTEST.LT.REF) THEN
    IFLAG=0
    IEND(NV)=I
  END IF
10 CONTINUE
RETURN
END

C *****

SUBROUTINE PAREA(AREA,YREF,NV)
C   AREA(100) ----- PEAK AREAS
C   YREF ----- REFERENCE CURRENT
C   NV ----- NUMBER OF PEAKS

C *****

DIMENSION DAT(1023)
DIMENSION IIP(100),IEP(100),AREA(100)
COMMON /DATT/DAT,/PARAM/NB,IMIN,DT

10 PRINT*, ' '
PRINT*, ' INPUT REFERENCE CURRENT '
READ(*,*) YREF
K=1
CALL LIMIT(YREF,N1,N2,K)
IF(K.EQ.0) THEN
  PRINT*, ' REFERENCE TOO LOW! '
  GO TO 10
END IF
CALL PEAKSEARCH(YREF,N1,N2,IIP,IEP,NV,1)
IF(NV.LE.1) GO TO 40

```

```

DO 30 I=1,NV
  AREA(I)=0
  DO 20 J=IIP(I), IEP(I)
    AREA(I)=AREA(I)+2.*DAT(J)
20  CONTINUE
  AREA(I)=DT/2000.*(AREA(I)-DAT(IIP(I))-DAT(IEP(I)))
30  CONTINUE
40  RETURN
END

C *****

      SUBROUTINE BOUND(DATA, IDIM, NP, IMIN, VMAX, VMIN)

C *****

  DIMENSION DATA(IDIM)
  VMAX=DATA(IMIN)
  VMIN=DATA(IMIN)
  DO I=IMIN+1, IMIN+NP-1
    IF(DATA(I).GT.VMAX) VMAX=DATA(I)
    IF(DATA(I).LT.VMIN) VMIN=DATA(I)
  END DO
  RETURN
END

C *****

      SUBROUTINE CONCAT(XIN,N)

C *****

  CHARACTER*100 XIN,XOUT
  I=N+1
10  I=I-1
  IF(I.EQ.0)THEN
    I=1
  ELSE
    IF(XIN(I:I).EQ.' ')GOTO 10
  END IF
  XOUT=XIN(:I)//'$'
  XIN=XOUT
  RETURN
END

C *****

      SUBROUTINE SET_UP

C *****

  COMMON /COEFT/COEF, COEF0, ICOEF, ISETUP, Y_MIN, Y_MAX, LABEL
  CHARACTER*30 LABEL, NAME, DEC*1, DEC1*1, DEC2*1

  PRINT*, ' '
  PRINT*, '*CALIBRATION FACTORS : '
  PRINT*, '* '
  PRINT*, '*SLOPE      : ', COEF
  PRINT*, '*INTERCEPT: ', COEF0
  PRINT*, '* '
  PRINT*, '*Y_MIN      : ', Y_MIN

```

```

PRINT*, ' *Y_MAX      : ', Y_MAX
PRINT*, ' * '
WRITE(*, 100) LABEL

PRINT*, ' '
PRINT*, ' CHANGE CALIBRATION COEFICIENTS? [N] '
  READ(*, ' (A) ') DEC
IF((DEC.EQ.'Y').OR.(DEC.EQ.'y')) THEN
  PRINT*, ' '
  PRINT*, ' READ SET UP FROM FILE? [N] '
  READ(*, ' (A) ') DEC1
  PRINT*, ' '
  IF((DEC1.EQ.'Y').OR.(DEC1.EQ.'y')) THEN
    PRINT*, ' INPUT FILE NAME: '
    READ(*, ' (A) ') NAME
    OPEN(UNIT=20, ERR=999, FILE=NAME, STATUS='OLD')
    READ(20, *) COEF, COEF0
    READ(20, *) Y_MIN, Y_MAX
    READ(20, ' (A) ') LABEL
    CLOSE(20)
    PRINT*, ' ** DONE! ** '
  ELSE
    PRINT*, ' INPUT NEW SLOPE '
    READ(*, *) COEF
    PRINT*, ' INPUT NEW INTERCEPT '
    READ(*, *) COEF0
    PRINT*, ' CHANGE Y LABEL? (Y/N) '
    READ(*, ' (A) ') DEC2
    IF((DEC2.EQ.'Y').OR.(DEC2.EQ.'y')) THEN
      PRINT*, ' INPUT NEW LABEL FOR Y (END $) '
      READ(*, ' (A) ') LABEL
    END IF
10  PRINT*, ' '
    PRINT*, ' CHANGE MAXIMUM AND MINIMUM VALUES OF '
    PRINT*, ' Y (FOR PLOTTING)? (Y/N) '
    READ(*, ' (A) ') DEC
    IF((DEC.EQ.'Y').OR.(DEC.EQ.'y')) THEN
      PRINT*, ' INPUT YMIN '
      READ(*, *) Y_SMALL
      PRINT*, ' INPUT YMAX '
      READ(*, *) Y_LARGE
      IF(Y_SMALL.GE.Y_LARGE) THEN
        PRINT*, ' ** Y_MIN < Y_MAX ** '
        GO TO 10
      ELSE
        Y_MIN=Y_SMALL
        Y_MAX=Y_LARGE
      END IF
    END IF
    END IF
    ISETUP=1
    ICOEF=1
  ELSE
    ISETUP=0
    ICOEF=0
  END IF
  RETURN

999 PRINT*, ' ***** CANNOT OPEN SETUP FILE! ***** '
PRINT*, ' '
RETURN
100 FORMAT(' *Y LABEL :', 2X, A/)
END

```

APPENDIX C

This appendix exemplifies the use of the SPSS^X language to write programmes for statistical modelling.

A) PROGRAMME:

```

TITLE                REGRESSION MODELS-HE2+O2 HORIZ. WELDING
FILE HANDLE MODEL NAME='[IS931.MATH2]MODEHOR.DAT'
DATA LIST FILE=MODEL LIST
      / WFR IARC SPEED Y1 TO Y8
COMPUTE Y9=Y6*SPEED
COMPUTE Y10=Y2-(Y3+Y4)
DO REPEAT Y=Y1 TO Y10/L=LY1 TO LY10
.      COMPUTE L=LN(Y)
END REPEAT
DO REPEAT Y=Y1 TO Y10/R=RY1 TO RY10
.      COMPUTE R=1./Y
END REPEAT
VARIABLE LABELS Y2   'BEAD AREA(MM2) - At'
                Y3   'DEPOSITED AREA(MM2) - Ad'
                Y4   'LAT. PEN. AREA(MM2) - Ap'
                Y5   'LAT. PEN.(MM) - p'
                Y6   'MEAN HEIGHT(MM) - h'
                Y7   'HEIGHT/WIDTH RATIO - R'
                Y8   'Aau/Aal - Ralu'
                Y9   'PRODUCTIVITY(MM2/S) - tp'
                Y10  'ARC VOLTAGE(V)'
                LY2  'LN(At)'
                LY3  'LN(Ad)'
                LY4  'LN(Ap)'
                LY5  'LN(p)'
                LY6  'LN(h)'
                LY7  'LN(R)'
                LY8  'LN(Ralu)'
                LY9  'LN(tp)'
                LY1  'LN(V)'
                LY10 'LN(Aa)'
                RY2  'INV(At)'
                RY3  'INV(Ad)'
                RY4  'INV(Ap)'
                RY5  'INV(p)'
                RY6  'INV(h)'
                RY7  'INV(R)'
                RY8  'INV(Ralu)'
                RY9  'INV(tp)'
                RY1  'INV(V)'
                RY10 'INV(Aa)'
                WFR  'W. F. R.(M/MIN)'
                SPEED 'WELD. SPEED(MM/S)'
                IARC 'CURRENT(A)'
DESCRIPTIVES VARIABLES= IARC WFR SPEED
      /SAVE
REGRESSION DESCRIPTIVES=DEFAULTS/
      VARS= ZIARC ZWFR ZSPEED Y1 TO Y10/
      STATISTICS=DEFAULTS CI/
      DEP=Y1 TO Y10/BACKWARD/
      CASEWISE=DEFAULTS/
      SCATTERPLOT (*RES,*PRE)/
REGRESSION DESCRIPTIVES=DEFAULTS/
      VARS= ZIARC ZWFR ZSPEED LY1 TO LY10/
      STATISTICS=DEFAULTS CI/
      DEP=LY1 TO LY10/BACKWARD/
      CASEWISE=DEFAULTS/
      SCATTERPLOT (*RES,*PRE)/
REGRESSION DESCRIPTIVES=DEFAULTS/
      VARS= ZIARC ZWFR ZSPEED RY1 TO RY10/
      STATISTICS=DEFAULTS CI/
      DEP=RY1 TO RY10/BACKWARD/
      CASEWISE=DEFAULTS/
      SCATTERPLOT (*RES,*PRE)/

```

```

COMPUTE IXW=ZIARC*ZWFR
COMPUTE IXS=ZIARC*ZSPEED
COMPUTE WXS=ZWFR*ZSPEED
REGRESSION DESCRIPTIVES=DEFAULTS/
           VARS=ZIARC ZWFR ZSPEED
           IXW IXS WXS Y1 TO Y10/
           STATISTICS=DEFAULTS CI/
           DEP=Y1 TO Y10/STEPWISE/
           CASEWISE=DEFAULTS/
           SCATTERPLOT (*RES,*PRE)/
REGRESSION DESCRIPTIVES=DEFAULTS/
           VARS=ZIARC ZWFR ZSPEED
           IXW IXS WXS LY1 TO LY10/
           STATISTICS=DEFAULTS CI/
           DEP=LY1 TO LY10/STEPWISE/
           CASEWISE=DEFAULTS/
           SCATTERPLOT (*RES,*PRE)/
REGRESSION DESCRIPTIVES=DEFAULTS/
           VARS=ZIARC ZWFR ZSPEED
           IXW IXS WXS RY1 TO RY10/
           STATISTICS=DEFAULTS CI/
           DEP=RY1 TO RY10/STEPWISE/
           CASEWISE=DEFAULTS/
           SCATTERPLOT (*RES,*PRE)/
FINISH

```

B) PRINTOUT SAMPLE:

19-Oct-89 REGRESSION MODELS-HE2+02 HORIZ. WELDING
 10:48:50 CRANFIELD INSTITUTE on CDVA:: VMS V5.1

Correlation:

	ZIARC	ZWFR	ZSPEED	LY3
ZIARC	1.000	.635	-.107	.303
ZWFR	.635	1.000	.000	.318
ZSPEED	-.107	.000	1.000	-.944
LY3	.303	.318	-.944	1.000

* * * * M U L T I P L E R E G R E S S I O N * * * *

Equation Number 1 Dependent Variable.. LY3 LN(Ad)

Beginning Block Number 1. Method: Enter

Variable(s) Entered on Step Number 1.. ZSPEED Zscore: WELD. SPEED(MM/S)
 2.. ZWFR Zscore: W.F.R.(M/MIN)
 3.. ZIARC Zscore: CURRENT(A)

Multiple R .99619
 R Square .99240
 Adjusted R Square .99064
 Standard Error .02162

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	3	.79365	.26455
Residual	13	.00608	.00047

F = 565.73062 Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	95% Confdnce	Intrvl B	Beta
ZSPEED	-.211067	.005459	-.222860	-.199274	-.944080
ZWFR	.070950	.007022	.055780	.086121	.317353
ZIARC	1.46911E-04	.007063	-.015111	.015405	6.571E-04
(Constant)	3.345168	.005245	3.333838	3.356499	

T Sig T

-38.666	.0000
10.104	.0000
.021	.9837
637.812	.0000

Beginning Block Number 2. Method: Backward

Variable(s) Removed on Step Number 4.. ZIARC Zscore: CURRENT(A)

Multiple R .99619
 R Square .99240
 Adjusted R Square .99131
 Standard Error .02084

Analysis of Variance

DF	Sum of Squares	Mean Square
----	----------------	-------------

Regression	2	.79365	.39683
Residual	14	.00608	.00043

F = 913.84189 Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	95% Confdnce	Intrvl B	Beta
ZSPEED	-.211083	.005210	-.222257	-.199910	-.944151
ZWFR	.071044	.005210	.059870	.082217	.317769
(Constant)	3.345168	.005054	3.334328	3.356008	

T Sig T

-40.518	.0000
13.637	.0000
661.878	.0000

----- Variables not in the Equation -----

Variable	Beta In	Partial	Min Toler	T	Sig T
ZIARC	6.571E-04	.005769	.585908	.021	.9837

End Block Number 2 POUT = .100 Limits reached.

0 Outliers found. No casewise plot produced.

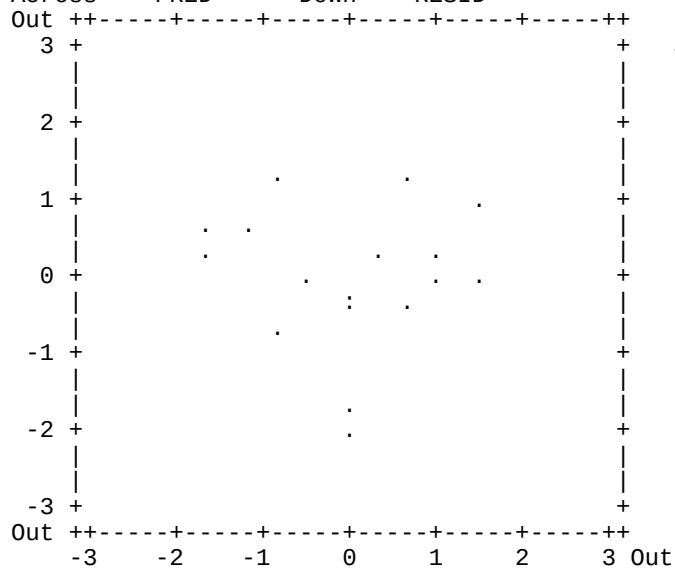
Residuals Statistics:

	Min	Max	Mean	Std Dev	N
*PRED	2.9850	3.6753	3.3452	.2227	17
*RESID	-.0418	.0264	.0000	.0195	17
*ZPRED	-1.6170	1.4822	.0000	1.0000	17
*ZRESID	-2.0036	1.2664	.0000	.9354	17

Total Cases = 17

Standardized Scatterplot

Across - *PRED Down - *RESID



Symbols:

Max N

.	1.0
:	2.0