

CRANFIELD UNIVERSITY



KONSTANTINOS PAPADOPOULOS

PROCESS PARAMETER SENSING

FOR

REMOTE HYPERBARIC WELDING

SCHOOL OF APPLIED SCIENCES [SAS]

MSc by RESEARCH THESIS

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KONSTANTINOS PAPADOPOULOS

**Process Parameter Sensing for Remote Hyperbaric
Welding**

Supervisor: Mr. D. Yapp

**This thesis is submitted in partial fulfilment of the requirements
for the degree of Master of Science by Research.**

Abstract

Pipeline ovality and equipment set-up variations pose a challenge for offshore remote hyperbaric welding operations using a fillet welded sleeve for pipeline repair. The distance from the torch to the pipe should be kept as constant as possible to maintain optimum welding process stability. The work of this research project was focused on using through-the-wire sensing and the establishment of the feasibility of Dip Resistance measurement as a suitable method for real time contact tip to work-piece distance estimation and control under Hyperbaric Welding conditions.

Analysis of cases of Dip Resistance application in 1 Atm and factors of influence has been performed and their relevance and importance for the RPRS program is examined. Suitability of the Dip Resistance is concluded and verification of this under hyperbaric conditions is tested. For this purpose, a data acquisition hardware system was built and software was written using LabVIEW 7.1 in order to acquire and analyse the welding signals in real-time and store the signals for later analysis. A second program focused on the analysis of the Dip Resistance information was written using LabVIEW 7.1 in order to analyse the experimental data off-line and to evaluate the results in more detail.

Experiments were made using various welding patterns so as to determine the feasibility of the method of the use of Dip Resistance information as a method for real-time estimation and control of the weld process. Based on these results, three detection algorithms were evaluated and the most suitable one was selected for further investigation. Initial investigation on other factors of influence like the length of the welding current's path and resistance variation with temperature is examined. The results from the experiments and their off-line analysis are presented and a discussion of the results is presented.

It is concluded that real-time control of the contact tip to work-piece distance torch may be achieved in real-time using dip resistance monitoring if it used in conjunction with the welding current and welding voltage signals allows achievement of robust control. Suggestions for further study and achievement of a complete solution are presented.

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1 Introduction

The world as we know it for the last few decades is totally oil dependent. This fact means that everybody and everything needs oil in a direct or indirect manner in order to cover everyday needs. However, after long periods of oil addiction and usage, the time has come that two main problems arise. The first one is that the easily accessible oil reserves of the planet that we are currently using are becoming less and less every day. The second one is that the main collection and distribution system is made from pipelines that inevitably need repair and expansion to new destinations day after day. In order to deal with the first problem, we need to explore oil reserves that currently wait for a technology breakthrough that will allow their exploitation. These reserves are mainly located underwater and in depths that are very hard for humans to work safely and effectively. The solution of the first problem though, is another reason for the second problem to grow. Even if we construct deep-sea pipeline networks that will allow us to use these reserves, these constructions will inevitably need maintenance, like the current underwater pipeline networks, only this time things will be even more difficult.

Current Maintenance and Repair Technology

Current maintenance and repair technology predominantly includes the use of support clamps [35, 38] to weakened sections, or cutting away the damaged sections and replacing them with new sections using mechanical connectors [35, 38] installed in the wet [6] or dry [6] hyperbaric welding [35, 38] for joining [38]. The term hyperbaric welding is used to describe the process of dry welding in a pressure equalised habitat on the seabed by evacuating the water using gas which is pumped in the habitat [4, 8, 37, 46], although the actual meaning of the term “Hyperbaric Welding” can be used to describe any welding process that takes place in high pressure. In most cases hyperbaric welding is preferred and in the Norwegian sector, dry, remotely controlled, hyperbaric welding [8]. The main difference between the mechanical and the weld-based maintenance approaches, for the depths where the pipelines are located, lies purely in the need for a dry habitat in which the hyperbaric welding is performed compared to the operation in the wet for the installation of a

mechanical connector [6]. The reason for preference of hyperbaric welding over remotely installed mechanical connectors for subsea repair is purely economical [8]. More specifically, the overall cost for the use of mechanical connectors is very expensive because of the requirement for their contingency storage together with connector unit cost for larger-diameter pipelines [8].

Diver Assisted Welding

The literature is somewhat confusing when it comes to the depth limit of using diver assisted hyperbaric welding; various sources mention the range to be from the splash zone [5] down to 250 m [5, 37], or 300 m [4], or 360 m [36] or even 500 m [9]. Whatever the actual limit, although divers have been historically employed for inspection, manipulation and repair tasks this is not a viable solution in depths greater than about 400 m [6]. The supporting divers for set-up tasks operate in helium based atmosphere which causes their voice to be distorted impeding communication with the surface [8]. In depths greater than 400 m the ambient pressure has an incapacitating effect on the human body resulting in significant functionality and coordination deterioration caused by rapid fatigue [1, 5, 6]. Currently divers are employed for depths up to 250 m for various pipeline operations like fully manual or semi automated repair welding, essential tie ins and hot taps [37]. However, the human limits and the labour intensive nature make it an extremely dangerous and expensive job requiring many divers and shift changes due to diving time limitations [8]. In addition, although Heliox mixtures reduce the possibility for nitrogen pick-up [4], helium can lead to higher cooling rates [4] and in hyperbaric conditions the oxygen pick-up from the Heliox mixture could influence the resulting material properties [4, 5, 38] and for non-manned, below 300 m, operations [4] a pure argon atmosphere can be used [4].

Current Diver Assisted Systems and Future Plans

For all the reasons presented previously, the Norwegian oil companies plan to remove the divers altogether for operations below 180 m [8] and this has led to the development of the Pipeline Repair System [PRS] from Norsk Hydro and Statoil which limits, but does not eliminate [5], the use of divers below 180 m [4]. This system is now planned to be substituted by the Remote Pipeline Repair System [RPRS] and this thesis describes work study to support the development of the fully

remote welding repair equipment system using hyperbaric Gas Metal Arc [GMA] welding and a fillet-welded sleeve. More specifically, the work that is presented here aimed at exploring the use of short-circuiting dip resistance as feedback information for control of the Contact Tip to Workpiece Distance [CTWD]. The results, although encouraging, suggest that further studies should be made and [perhaps] it would be advantageous to couple the dip resistance information with another welding parameter.

1.1 The Cranfield Hyperbaric Welding Program

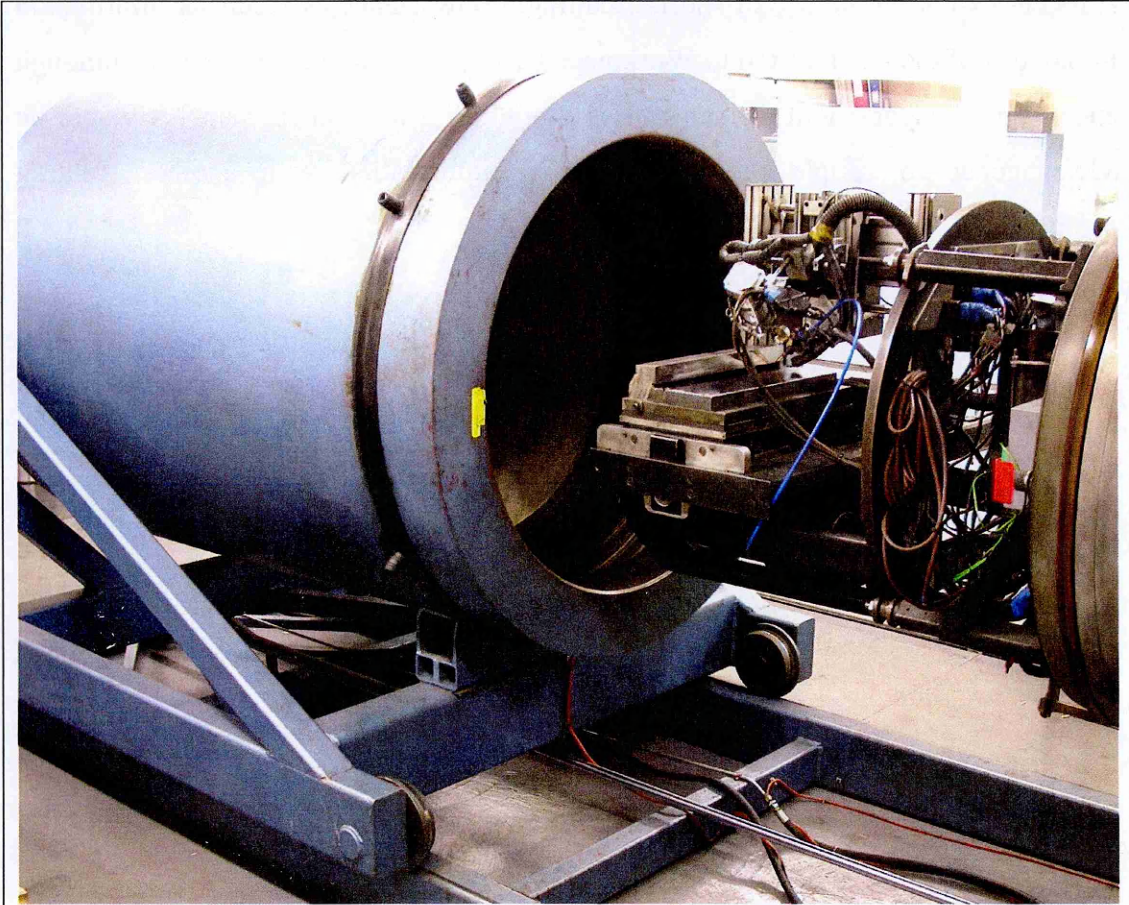
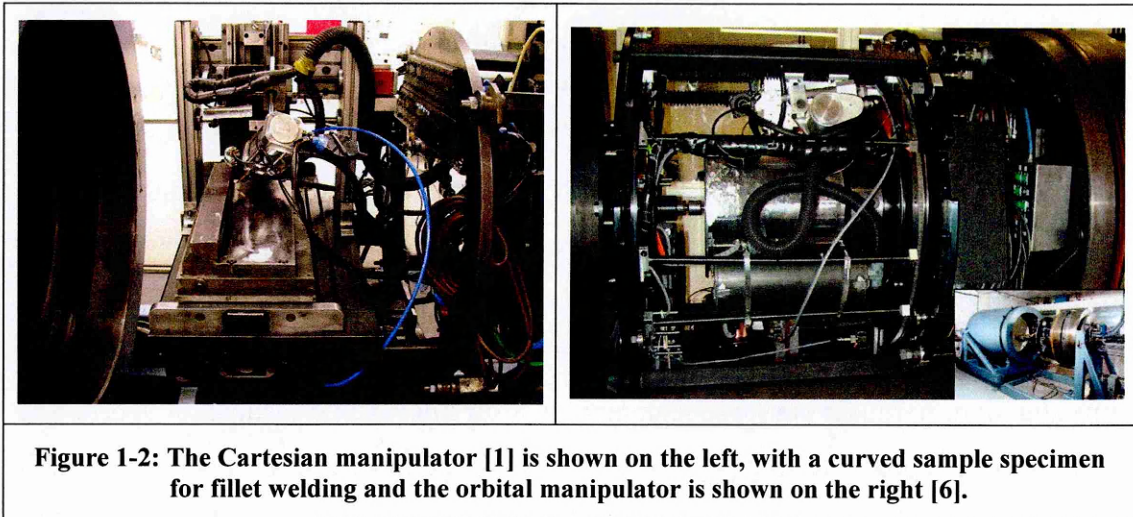


Figure 1-1: The Cranfield Hyperweld 250 vessel used to emulate hyperbaric conditions up to 250 Atm.

For the last three decades, Cranfield University has conducted a substantial research programme on hyperbaric welding, and has firmly established the feasibility of deep water hyperbaric welding using the Metal Inert Gas [MIG] / Gas Metal Arc Welding [GMAW] process with ambient pressure of 250 Atm, equivalent to a depth of 2,490 m [4, 5, 6, 7, 38]. This was achieved using Cranfield University's unique facility of a pressure vessel, shown in Figure 1-1, capable of emulating the pressure at these depths. This system is used for the research and development of the procedures and technologies that the Statoil RPRS will adopt and put in operation.

1.1.1 Pressure Vessel & Subsystems

The pressure vessel has approximately 1.2 m³ internal volume [5, 6, 38] and can emulate dry hyperbaric conditions up to 250 Atm ambient pressure [4, 5, 6, 7, 38]. It includes two robotic manipulator systems, a Cartesian -linear motion- for linear welds in all positions [5, 6, 38] and a four axis orbital head for welding in the 5G position [5, 6, 38], shown in Figure 1-2, both of which are remote controlled through a computerized system giving the ability to perform hyperbaric welds in every position.



The pressure vessel is equipped with all subsystems necessary to allow emulation of a subsea hyperbaric habitat in operation. These subsystems include supply of water from an external cooling system, clean gas recirculation [5, 6, 7, 38], fume extraction [5, 6, 7, 38], shielding gas [5, 6, 7, 38] from a fresh gas external unit pre-pressurised at 350 Atm [7] and electrical supplies [5, 6, 7, 38]. Optical inspection of the weld pool is done via a camera housed in a modified pressure housing designed and built to withstand the 250 Atm ambient pressure [7].

1.1.2 Power Sources & Other Instrumentation

For the GMAW experiments a set of three Fronius Transpocket TP 450s inverter power sources is used [5, 6, 38] connected in series capable of delivering up to 450 A at up to 200 V [6, 38]. The power sources are controlled by a combination of digital and analogue computerised systems [5, 6, 7, 38]. The analogue subsystem is responsible for producing the output characteristic of the power sources [5, 6, 38]. The digital subsystem is responsible for providing the user interface and pulse generation capabilities [5, 6, 7, 38]. The output values are updated at the pre-fixed

frequency of 10 kHz [5, 6, 7, 38]. Data logging systems are used to capture the arc voltage and arc current values [5, 7, 38].

Control of the welding operation is achieved using hardware and software similar to the ones used in the THOR [6] and Pipeline Repair System [PRS] by Statoil [7]; it is comprised of a top station user interface [6] and a real time bottom station computer [6], responsible for all sequencing and welding procedures [6].

1.1.3 Previous Work & Landmark Achievements

Work in Cranfield University has been focused in the quality, robustness and capabilities of the welding processes via welding under different configurations [V-Butts and fillets, on variable and constant gaps] and various positions like overhead, vertical-down, vertical-up and others [4]. A metallurgical investigation has also been carried out, including chemical analysis, inclusion counting, metallographic investigation, hardness surveys, scanning-electron microscope evaluation and tensile and impact-toughness testing [4]. From this work, the mechanical properties of welds produced under hyperbaric conditions of 160 Atm were improved [4], as well as the metal impact toughness [4] and the use of metal-core consumables [with optimised chemical composition] was proved to be a good adequate alternative to solid wire GMAW [4].

During the first two phases of the Deepwater Hyperbaric Welding Programme at Cranfield University, progressive welding process development took place, culminating in an ability to orbitally weld soundly at pressures equivalent to water depths of 2,490 m [8,200 ft] and equivalent pressure of 250 Atm [5, 19]. In the previous phase of the program *“Deepwater Hyperbaric Welding - An Initial Feasibility Study for Hot Tapping and Riser Repair Applications”* work has focused on mechanical properties of fillet and butt welds. Research has shown that GMA fillet welding is practically insensitive to fillet weld root gap [5] and the parameter selection could practically be invariant during all position welding [5].

Welding Consumables Development

Previous work has tended to concentrate on achieving satisfactory mechanical properties in welds made under the special conditions of high pressure argon using commercially available consumables, designed for pipeline welding at 1 Atm [surface conditions]. A breakthrough in this area has been realisation that together with the nickel [5] and titanium [5] concentration, wire oxygen content plays a key role in determining the weld metal toughness [4, 5]. Reducing oxygen content constantly improves toughness by positively affecting the upper shelf energy and the transition temperature [5]. Care must be taken however, since in 1978 it was shown [38] that too low oxide inclusions [especially those containing titanium] [38], and oxygen particle contents, are insufficient for acicular ferrite nucleation [4, 38]. In other words, the acicular ferrite content is reduced, which results in reduced toughness [4] and lower temperature transformation products with higher strength and poorer toughness [38]. It has now been shown that special cored welding electrodes and wires can be made to deliver high, consistent toughness in the weld metal [3, 4, 5]. An evaluation of mechanical properties was made by Marino *et al.* [4] and the microstructural characteristics of welds produced at 160 Atm with ten different commercial and experimental consumables [4]. More specifically, there were three commercial wires [4], the Thyssen K-Nova, ESAB XTI, ESAB Spoolarc 120, and seven experimental wires [4] from the ESAB HBX series. The use of the experimental wires enabled to control the oxygen content by controlling the addition of iron oxide powder to the powdered metal core in parallel with two different target levels of nickel and titanium [4]. This optimisation of the welding wires lasted for more than twenty years with tubular wires specially formulated for hyperbaric welding, some of which have become commercial products [38].

The results obtained so far have provided key information on the procedures necessary to complete fillet welds, and on the properties achieved [2].

1.2 The current PRS and the evolving RPRS programs

The PRS is the main repair contingency for approximately 10,000 km of underwater pipeline networks with diameters from 8 inches up to 44 inches located in depths down to 600 msw [35, 38], although this is to be extended down to 1,000 meters sea water [msw] depth due to new networks coming in operation [35, 38]. Statoil was appointed in 1987 to operate it [38] on behalf of more than forty members [5, 37]. The PRS is a comprehensive suite of underwater pipeline construction and repair tools [35, 38]. Its spread includes isolation plugs, cleaning tools, manipulation and installation frames and welding habitat enclosures [35, 38] as illustrated in Figure 1-3. The selected repair method depends on the case and it ranges from the application of support clamps in weakened sections to cutting-off damaged sections and replacement with new pipe segments with the joints being made either via mechanical connections in the wet [6] or utilising dry [6] hyperbaric welding [35, 38]. The PRS diver assisted Gas Tungsten Arc [GTA] hyperbaric welding system [5, 37] applies V-groove welds technology for repair and tie-in operations [37] in the North Sea underwater pipeline network [5].

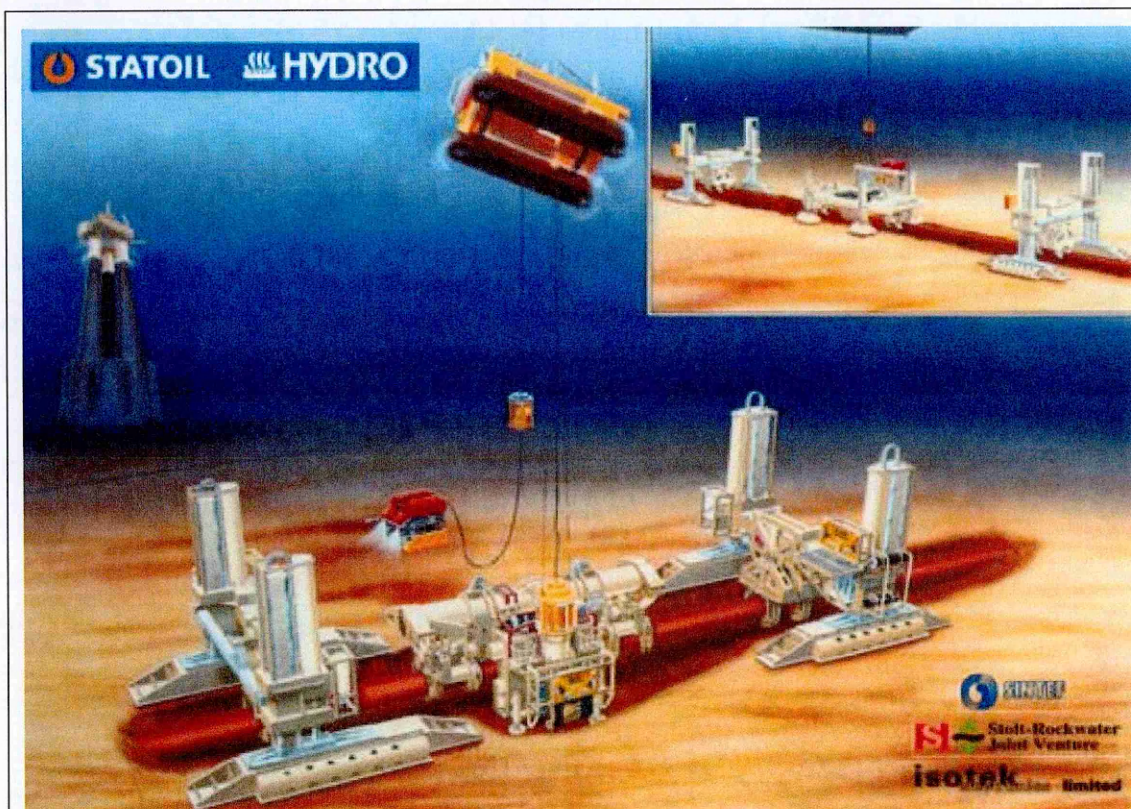


Figure 1-3 [35, 37, 38]: Artistic view of the spread of a PRS operation.

1.2.1 PRS's Operation Description

Non-Diver Assisted Tasks

A typical underwater PRS operation involving hyperbaric GTA welding repair consists of the following stages. Firstly, the pipeline region for the repair must be prepared for lifting, thus it is excavated and cleared from debris [1, 5]. Then, an 'H' frame is lowered on each side of the repair area [5]. Each 'H' frame weighs 70 tonnes and has a lifting capacity of 120 tonnes [1, 5]. The two 'H' frames are working together for pipeline manipulation and provide the ability to move the pipeline in every direction in the lateral, vertical and axial planes [1, 5]. In the sequel, a combined tool with a high pressure water-grit jet is used to cut the damaged section of the pipe [5]. With the pipeline cut, the next step is to cut and remove the weight coating [1]. For this, the tooling is changed and two longitudinal cuts and a full circumferential cut are made in the weight coating [1]. The anti-corrosion coating is also removed using a high-pressure water jet [1]. The preparation is now complete and the next step is to lower the replacement part [spool piece] into position [1, 5]. The two 'H' frames are used so as to roughly align the spool with the pipeline [1, 5].

The welding habitat is then lowered over the pipe and the remotely operated integral doors with the flexible sealing skirts are closing so as to seal around the pipe [5]. The next step is to inject pressurised gas inside the habitat which equalises the ambient pressure and expels the water [1, 5].

Diver Assisted Tasks

The following steps involve assistance from the divers. An Integral Modular Tool [IMT] is used so as to minimise the pipe out-of-roundness by squeezing the pipe circumferentially using hydraulic clamps [5]. After that, a machine tool which is attached to the IMT is used to machine a bevel preparation on the pipe ends which matches the one in the spool piece [5]. The orbital movement of the tool around the pipeline is provided by the IMT [5].

A fine alignment frame is integrated to the habitat and its operation is crucial for a successful repair [1, 5]. Its purpose is to align the prepared pipe ends to within 0 to +1 mm root gap and 0 to +2 mm high/low on both ends under diver control [1, 5]. Been within this tolerance is crucial for the integrity of the butt welding procedure which will follow [1, 5]. After the alignment is complete, the diver has to set-up the welding head, the pre-heat mats and the degaussing coils so as to be ready to commence welding [1, 5].

The welding operation then begins controlled by surface operators [1, 5]. Each weld pass' parameters are predetermined based on weld tests completed on-shore in an emulating hyperbaric chamber prior to deployment [1, 5]. Completion of welding follows a Non Destructive Testing [NDT] phase [1, 5]. For this reason, an NDT assembly is mounted onto the IMT and using ultrasonic NDT principles the joints integrity is checked and verified [5]. The repair process is completed by covering the repaired region with a protective coating [1]. Finally, the chamber is flooded and all pieces of equipment are recovered to the surface [1].

1.2.2 Limitations of the PRS & Reasons for RPRS

The increased pressure limits the capability for the use of divers [6]. The human body is greatly affected by the hyperbaric environment. The use of the air we breathe everyday is limited to depths down to 30 msw. After that depth, nitrogen narcosis becomes very significant. Just like with every "drug", diver welders can slowly develop increased tolerance to nitrogen narcosis which and become able to work sufficiently for longer, the increased presence of nitrogen in the blood stream could lead to paralysis or even death especially in emergency ascent situations, controlled or not. Even worse, oxygen content of atmospheric levels in the breathing gas mixture becomes toxic to the human body below 70 m and even a few minutes below this depth could be fatal. Successful diving is therefore achieved by the substitution of the breathing gas [4, 34], consequently the habitat environment, with Heliox [4], a mixture of helium mixed with 0.5 Atm of oxygen [34]. This is required since nitrogen [as mentioned previously] exhibits narcotic and other side-effects and also can have a detrimental effect on the welds [4]. The use of helium based mixtures gives the ability for the use of divers up to 250 msw but, as said, the process is

extremely dangerous and careful decompression is still required to safeguard the diver's health [34] which can be very long in duration. The equipment required together with the decompression arrangements increase the cost of the application of the process [34]. For that reason, Norsk Hydro and Statoil developed the RPS program that involves a semi-automated system that limits the presence of divers below 180 m [4]. Nevertheless, for deeper [non-manned] operations below 300 msw [4], a pure argon atmosphere can be used [4] which will prevent the increased cooling rates caused by the presence of helium which could affect the quality of the welds produced [4], but will also make the use of divers impossible [4] since argon causes asphyxiation. This is why Statoil and other partners are developing the RPRS, which will be completely automated and controlled from the sea surface.

The restrictions in diver performance [37], the complexity of the operation caused by the high degree of accuracy for achieving the fine alignment required in V-groove welds in butt joints [37], as in the case of the PRS, prohibits the full automation of the technology [37] and its use on higher diameter pipelines and/or in deeper waters.

The Emerging RPRS

For the reasons above, Statoil's future plans are to replace the diver assisted PRS dry hyperbaric welding system with the RPRS, an unmanned remotely operated repair system initially targeted to operate between 180 m and 370 m [37], which will also enable the maintenance of the existing pipeline network with a design capability of 1,000 msw depth for future deeper operations [37]. The new approach is to use a slightly over-sized sleeve and fillet welds at the sleeve ends by applying dry hyperbaric GMA welding [37]. This is a more straightforward approach which makes it easier to be fully automated and remotely controlled since the pipe ends do not have to be fine aligned and abutted closely [37]. This approach allows alignment of the pipes and installation of the repair sleeve to be completely performed on the wet [37].

Selection of Repair Strategy

As mentioned earlier, the fundamental difference between the mechanical connectors and the weld-based repairs is the need for a dry habitat in which to perform the weld compared to the ability to install the mechanical connectors in wet [6]. Because of the

complexity in fully automating tasks inside the habitat [6], the current dominant conceptual approach is to use mechanical connectors for joining tasks in deeper waters [6]. Using the fillet welded approach the use of the dry habitat is minimised in the period required to perform the weld simplifying part of the process. The best joint integrity and long term performance is offered by the welded connections [6, 9], although the practical considerations make the use of mechanical connectors more attractive especially for small to medium size pipelines [6]. Nonetheless, the problems of mechanicals connections associated with sealing performance for large diameter pipelines and complex joint geometries enhance the need for parallel deepwater welding capabilities [6]. It is possible that combination of mechanical joining and hyperbaric welding can offer the optimum result in some cases [6], for example using mechanical connectors to form the primary seal [6]. In such cases the manufacturing cost of the connectors can be reduced since complex sealing arrangements and actuation mechanisms will not be implemented [6]. In addition, *“the mechanical connector can readily furnish weld head tracking and guidance systems so as to ensure alignment without involving complex metrology tasks”* [6], simplifying the repair task and reducing the overall cost.

Remotely installed mechanical connectors may also be employed [37] independently of the use of welding in the future. The overall rational is to use the established diver-assisted GTA welding for depths down to 180 m [37], mechanical connectors for pipelines below 30 inches in diameter [37] and fully remotely controlled repair(s) using fillet welded sleeve(s) for water depths greater than 180 m and pipe diameters greater than 30 inches [37].

Supported by the Cranfield Hyperbaric research program, the Remote Pipeline Repair System [RPRS] is currently being constructed by a number of sub-contractors, including Isotek Electronics Ltd., Statoil and Stolt-Subsea 7 Joint Venture. This will be completely automated and remotely controlled from the sea surface.

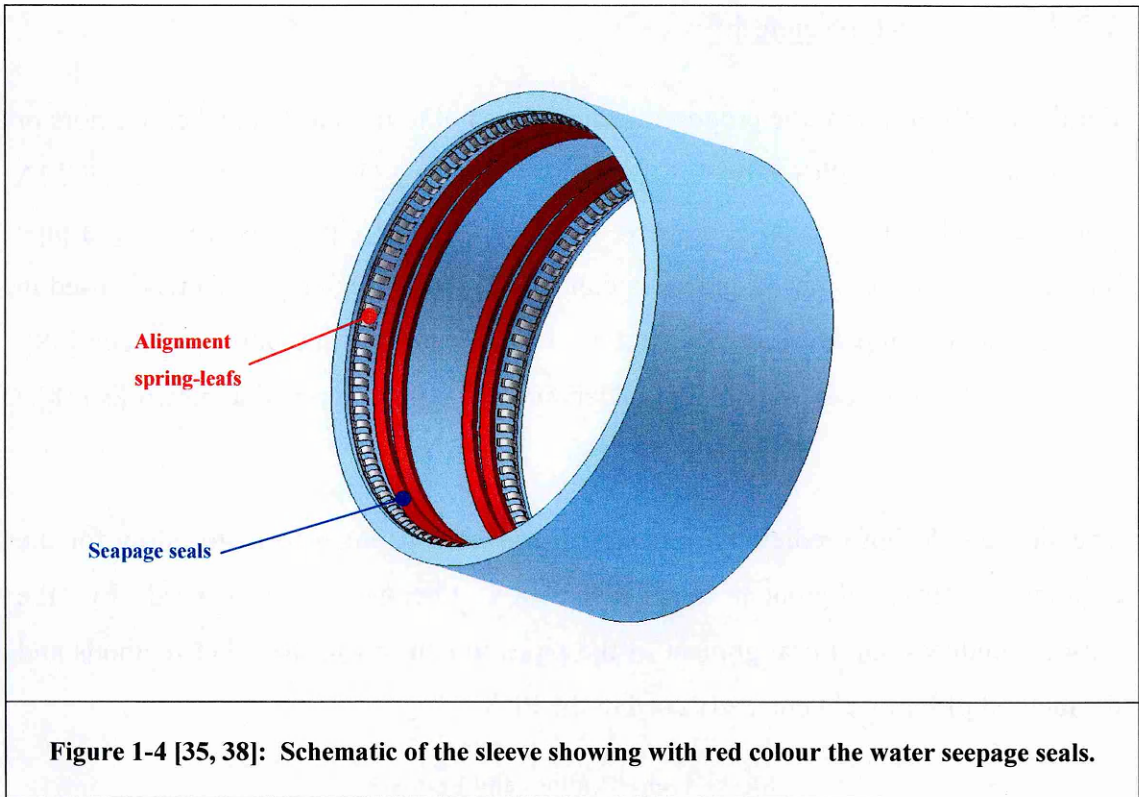
1.2.3 Sleeve-On-Pipe concept

For the RPRS program, the proposed technique is not to use mechanical connectors or butt welds, like the PRS program, but to use a Sleeve-On-Pipe concept and GMA fillet welds [1] on the ends of a sleeve installed over the pipe ends, covering a pipe diameter even bigger than 42 inches in diameter [1]. This technique is already used in smaller diameter pipelines onshore and is part of the tools of the plumbing trade [38]; however, it has not been used before underwater for repair on pipeline networks [38].

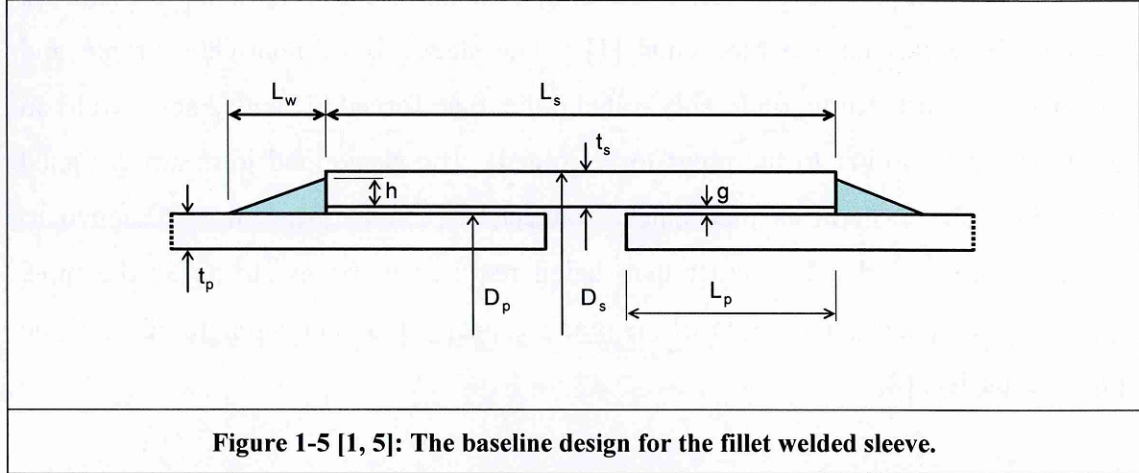
The sleeve's design predicts the internal diameter to be such so as to allow for the required ovality, alignment and installation tolerances [5] caused by the out-of-roundness and misalignment of the pipes in contrast to the other methods and the method of butt weld currently used in the PRS.

Sleeve's Specifications and Features

A schematic of the sleeve is shown in Figure 1-4. As shown, the internal part of the sleeve includes water seepage seals on both ends, shown as a double barrier, to prevent water from the pipes to flow on the welding area during welding [5] and the gas filled habitat [35] and that gas from the habitat will not escape into the pipeline [35, 38]. Also shown, is the sleeve's self-alignment mechanism on each end to ensure that the sleeve will be evenly spaced around the pipe [35, 38], although its weight will cause a variation [1] with the bottom opening to be the widest and the top the shortest as the sleeve lies on the pipe ends [1]. The sleeve is of relatively simple and inexpensive construction, preferably rolled rather than forged [2] with a seam weld on the pipe seam, similar to the pipes to be joined. The sleeve and joint are designed using the same criteria as mechanical connectors (which means it is designed to accommodate actual loads rather than being required to be as strong as the pipe, typically moment capacity 30 % of the pipe's capacity and axial strength 50 % of the pipe's capacity) [2].



The baseline for the sleeve geometry is shown in Figure 1-5. It is envisaged that the sleeve's length, L_s , will be 600 mm [1, 5, 37, 39], the root gap, g , will be 5 mm [5] [worst case scenario value to be 6.4 mm [1, 37, 39]], and the pipe extension inside the sleeve, L_p , will be 250 mm [1, 5, 37, 39]. These dimensions will allow for a 100 mm gap between the two pipe's ends [1, 5, 35, 37, 38, 39] with a radial offset tolerance of approximately 2 mm [5, 35, 38] between the two pipe ends and an angular offset of 2° [5, 35, 38].



Sleeve's Installation

The sleeve is made slightly oversized to the pipe and can be threaded over one end in the wet and been dragged back over the two pipe ends to be joined [35, 38] by a suitable tooling arrangement [2] [shown in Figure 1-6 and Figure 1-8], or, in the case that a large part of the pipe is to be substituted, two sleeves on a spool can be used [2, 35, 38] -typically installed on the spool on shore and dragged into location as [2, 35, 38], shown in Figure 1-7.

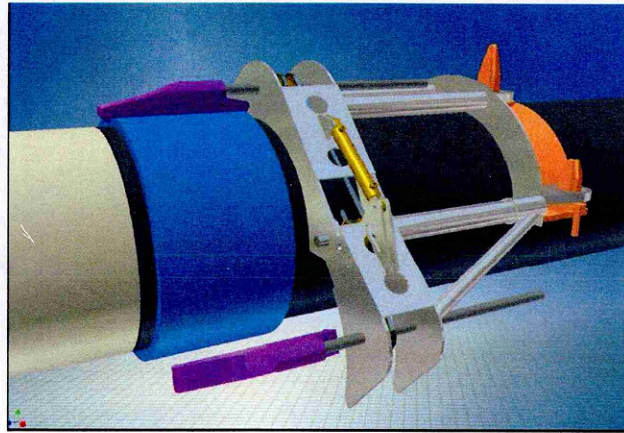


Figure 1-6 [1]: Schematic representation of the mechanism to drag the sleeve on location.

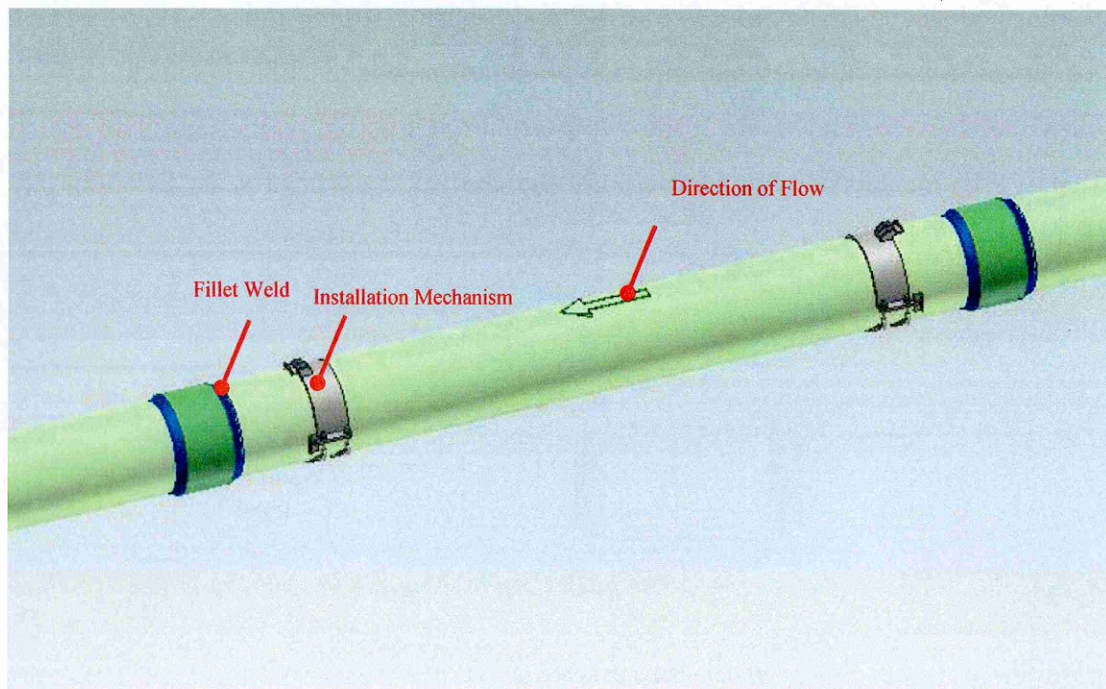


Figure 1-7 [35, 38]: A spool piece joining the two ends of a pipeline using two sleeves already located and welded.

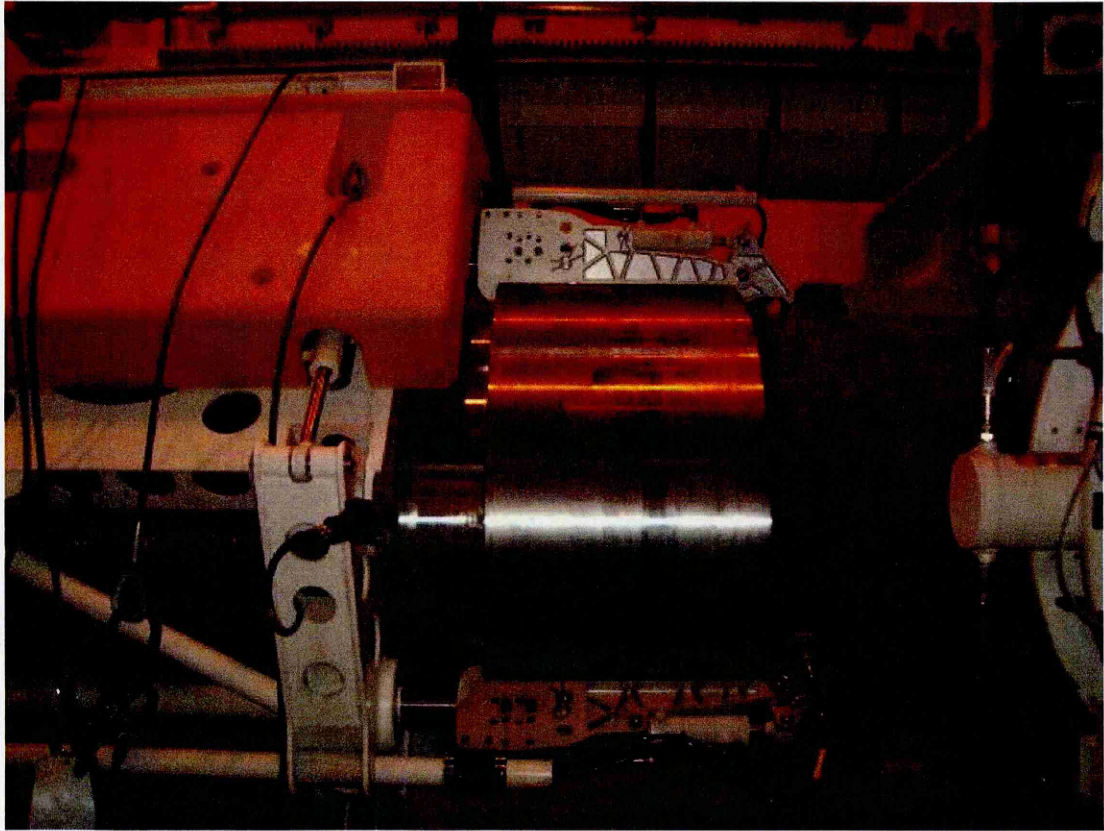


Figure 1-8 [38]: Photograph of the actual installation mechanism illustrated in Figure 1-6.

The use of the sleeve avoids the requirement for butt-to-butt closure [35, 38] and threading of the sleeve limits the need for precision alignment [35, 38]. An example of a located sleeve is shown in Figure 1-9 and Figure 1-10; in Figure 1-10, the sleeve is dragged from right to left and the edge of the left pipe is machined in such a way to allow the sleeve to slide even if the two pipes are not perfectly aligned. The orbital fillet welds are shown with blue colour and the water seepage seals locations are visible.

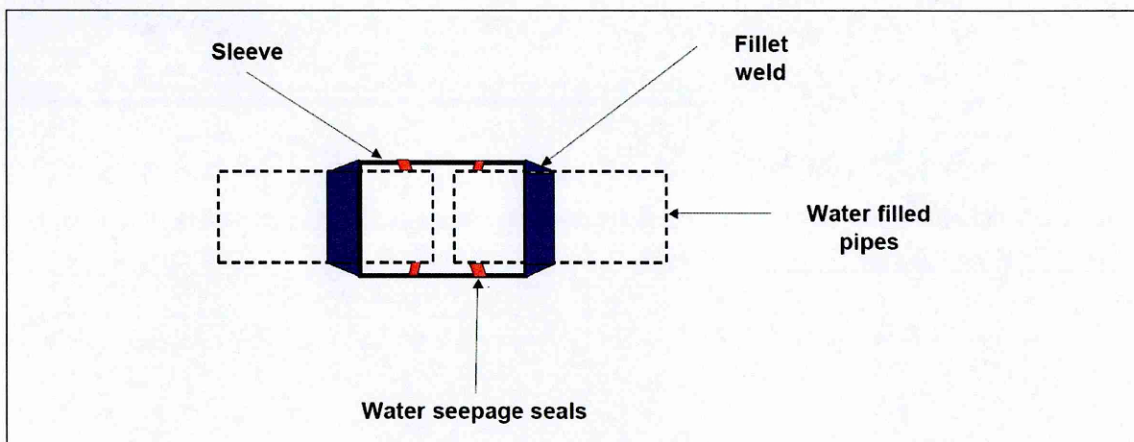


Figure 1-9 [35, 38]: Schematic representation of the welded sleeve on the pipeline.

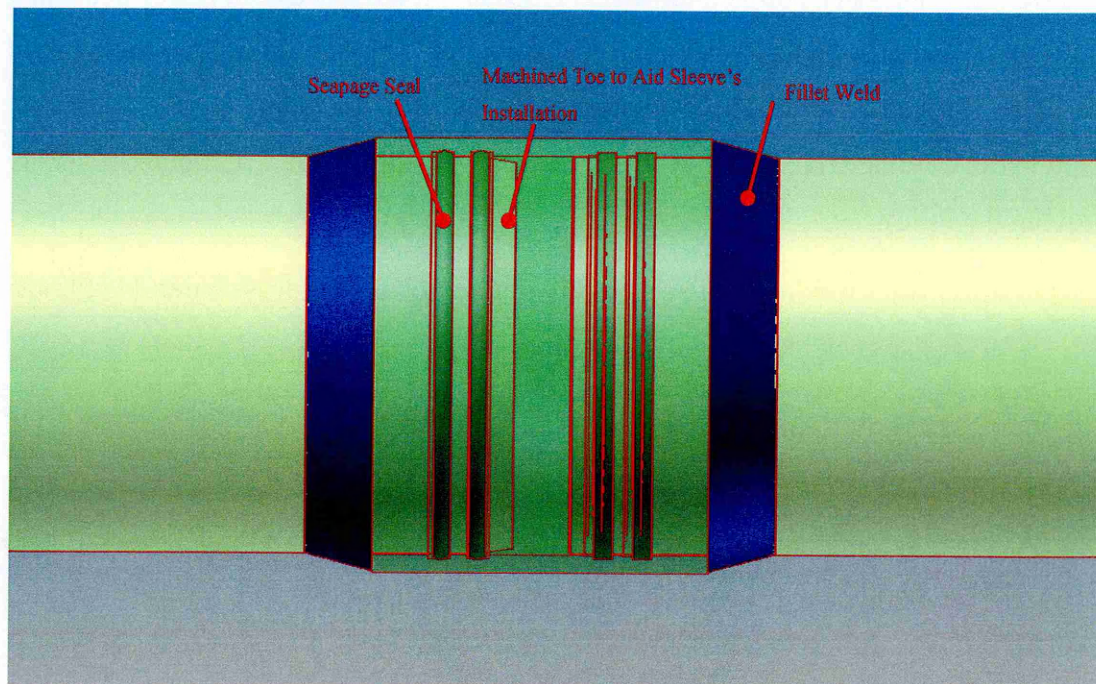


Figure 1-10 [37, 39]: Schematic of a complete Sleeve-On-Pipe construction.

Challenges of the Sleeve-On-Pipe Approach

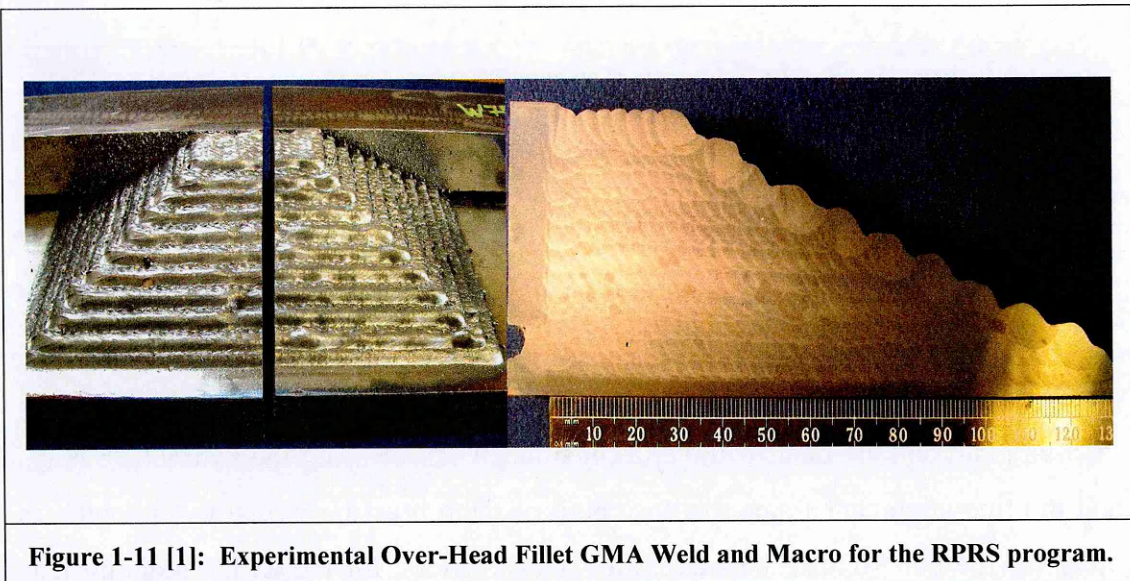
“Because of the installation tolerances, the fillet weld design, and the need for a root gap which in practise it will probably be variable because the sleeve rests on the pipes, it is expected that an inherent root flow will be present” [1]. The pipe out-of-roundness and the pipe misalignment are present in the current diver assisted PRS program and are dealt with [1] as mentioned earlier using the hydraulic clamps and the fine alignment frame, because both of them must be virtually eliminated in order for the butt weld to be successful. Nevertheless, for the RPRS program it is necessary a way to be found to minimise during welding the effect of the inherent root flow, the pipe out-of-roundness and the pipe misalignment without having to implement any difficult or diver assisted strategy because of the fact that with absence of divers, everything must be able to be successfully accomplished remotely. This can be done by controlling the position of the welding torch so as to eliminate process variations due to CTWD and stick-out variation.

1.2.4 RPRS Welding Technology

The weld that has been adopted for the RPRS is an orbital fillet weld performed using the GMA process, which has a higher deposition rate [1] than the GTA process used on diver assisted PRS welding, and is much more water depth tolerant. Remote hyperbaric welding trials have been successfully performed at Cranfield University proving the following:

- 1) GMA fillet welding can successfully cover a gap of at least 5 mm [1, 5], and larger gaps can be closed by buttering [2],
- 2) GMA fillet welding is robust and tolerant to position parameters from 150 msw [2] to 2,500 msw [1, 2, 35],
- 3) GMA welding parameters are relatively depth and position independent [1, 5] beyond 800 msw [2] with no sign of upper depth limit [1].

Examples of Experimental Results



The left side of Figure 1-11 shows a sample result produced after parameter development with use of Cranfield University's facilities sized for the RPRS in the over-head position [1]. The specimen's leg length is 120 mm by 43 mm height including a 5 mm root gap [1]. The fillet weld was made on steel plate with ambient pressure of 30 Atm [equivalent to 290 msw depth] using 255 passes. The macro in the right picture of Figure 1-11 shows the shape of the fillet and the sound weld profile it has [1]. On the weld toe a smooth blend has been achieved owing to the use of a final pulsed stringer pass on each layer [1]. As shown in the macro, satisfactory

penetration has been achieved into the representative sleeve material and only few defects exist [1]. Figure 1-12 shows a typical overlap region [at 12 o'clock or 6 o'clock] where a small 0.2 mm inclusion exists at the root of the start of the two passes [1].



Figure 1-12 [1]: A typical overlapping region of two beads, either at 12 o'clock or 6 o'clock.

Example of Experimental Modelling

Figure 1-13 shows a 2-D finite element analysis used to determine the optimum volume and shape the fillet welds should have for the RPRS. The model shown is the result of using design parameters required by an actual pipeline application.

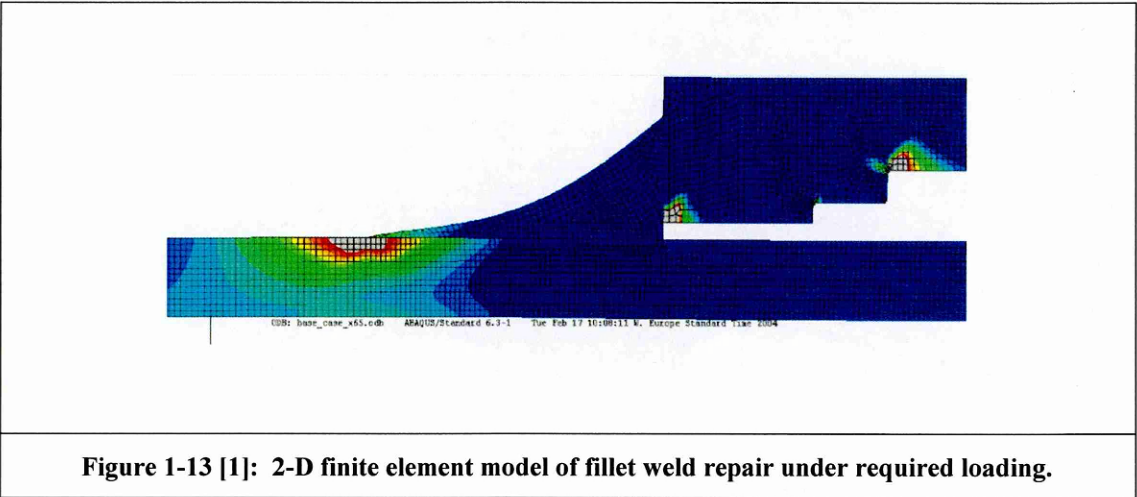


Figure 1-13 [1]: 2-D finite element model of fillet weld repair under required loading.

In this case the resultant stresses are in the fillet weld “root” region, and, in the pipeline itself at the toe of the weld [1]. A long weld leg length helps in spreading the load more evenly back into the pipeline [1]. As seen, the majority of the fillet weld is not particularly stressed [1] allowing for the concave shape which reduces the time, hence the cost of the repair, and the down-time of the pipeline itself. The appropriate critical pressure [system pressure test] used was 242 Atm [1] and bending design loadings equivalent to a real scenario were used [1].

1.2.5 Underwater Hardware System Overview

Two main units constitute the underwater part of the RPRS, the tool basket and the welding module –or habitat-. Both of them are remotely controlled by the operators on the sea surface [1, 2, 5, 37] using equipment like user-interface control [1, 5], a top station [1, 5] and camera panels [1, 5] all of which are similar to the ones employed in current surface controlled hyperbaric welding [1]. The ship that contains all the necessary hardware and software support systems, communicates with the tool basket through an umbilical [2] as shown in Figure 1-14.

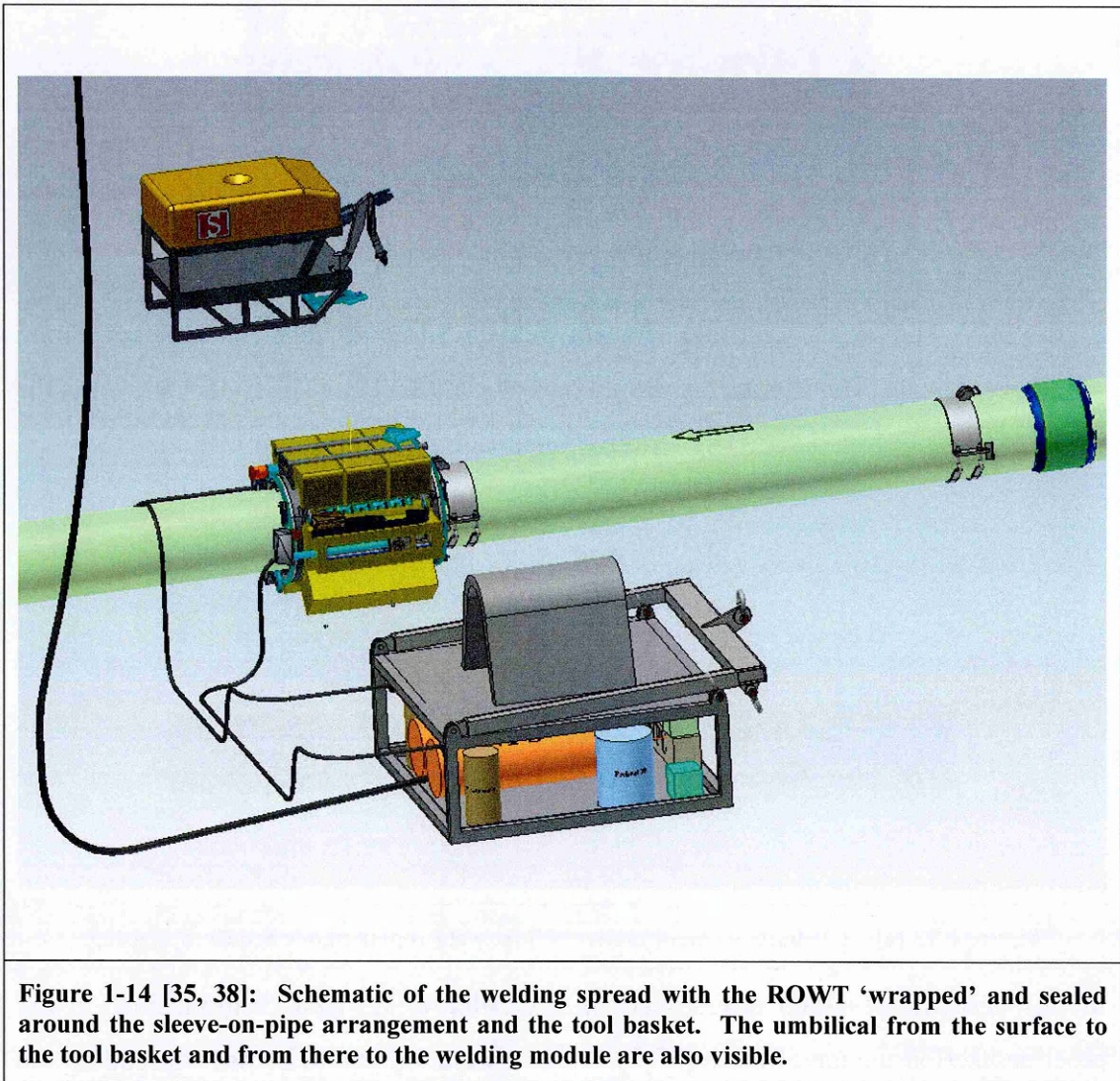


Figure 1-14 [35, 38]: Schematic of the welding spread with the ROWT ‘wrapped’ and sealed around the sleeve-on-pipe arrangement and the tool basket. The umbilical from the surface to the tool basket and from there to the welding module are also visible.

The umbilical is the medium used to provide gas, power and data communications to the tool basket [2]. The tool basket is approximately 10 m away and by accommodating all the services required for the chamber’s operation the weight and complexity of the chamber are reduced and maintenance is a lot easier [35, 38].

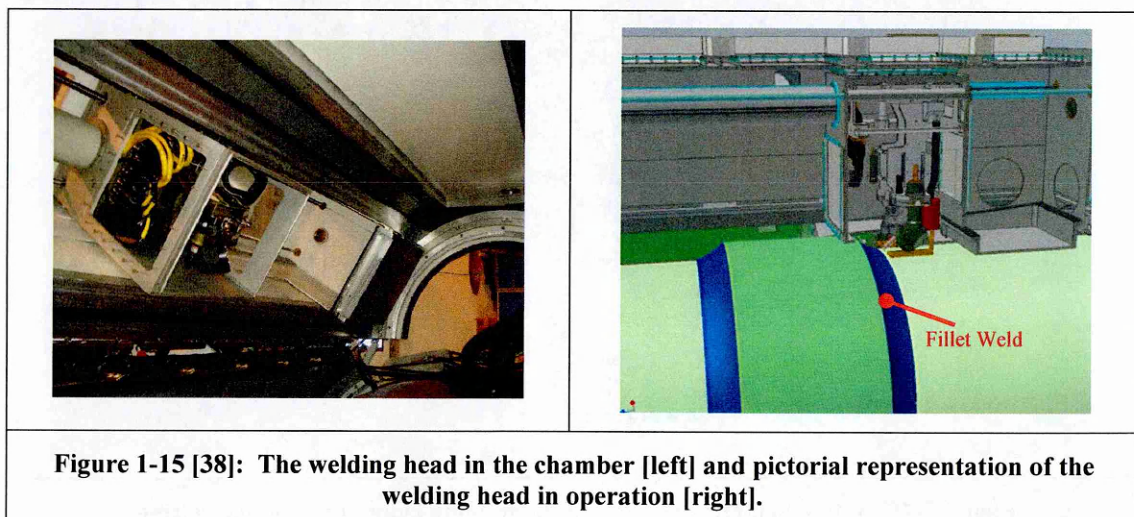
Tool Basket

The tool basket in turn provides the welding module with all the necessary services it needs in order to perform the welding operation, such as filler wire feed and welding power and contains the following:

- 1) Welding [1, 2, 5, 35, 38] and preheat power sources [2],
- 2) Hydraulic power sources [2],
- 3) Process Control equipment [1, 2, 5],
- 4) Bulk wire storage on wire spools [2, 5, 35, 38] [capable of accommodating large amounts of welding wire [2]],
- 5) Wire feeding [5, 35, 38],
- 6) Backup gas services [2, 35, 38] and possibly fumes extraction and gas cleaning [2] and drying,
- 7) Pipe stand for welding module deployment [2].

Welding Module

In order to avoid excessive stress in the sleeve-pipe arrangement as well as to avoid the risk of a malfunction, the welding head module, also called Remotely Operated Welding Tool [ROWT] [1, 5, 37], shown in Figure 1-15 and Figure 1-18, is kept as small and as simple as possible. The enclosure has static seals which grip around the pipe and dynamic seals to allow the body of the enclosure to rotate about the static gripping parts [35, 38].



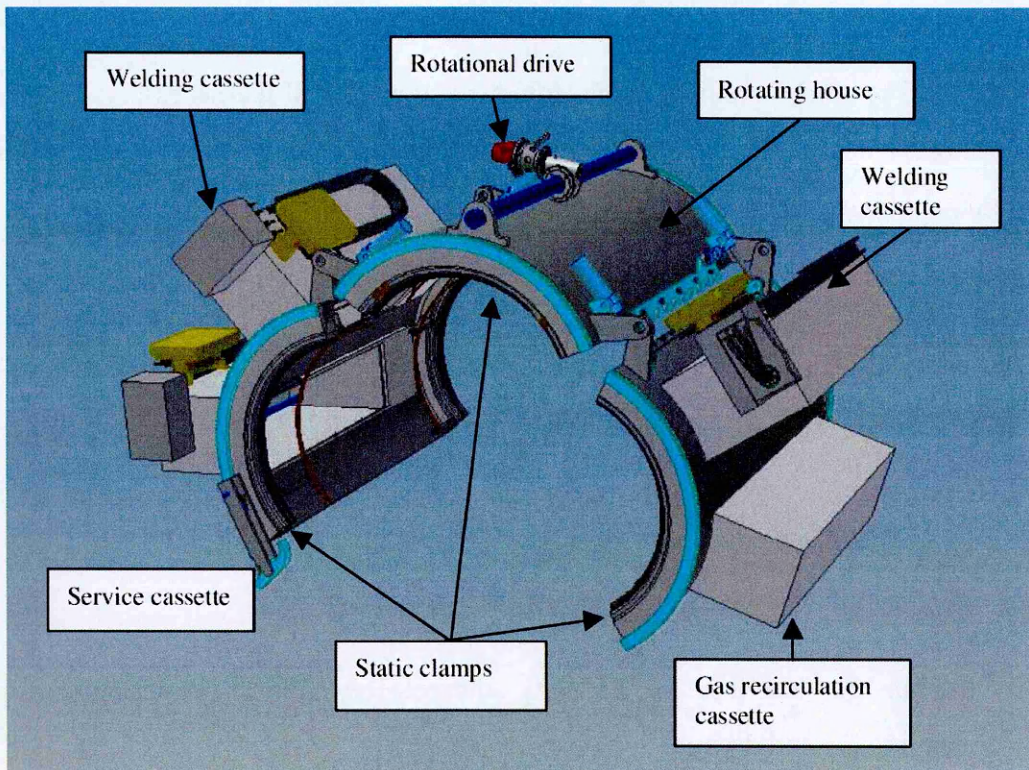


Figure 1-16 [35]: Simplified schematic overview of the ROWT with its main sections.

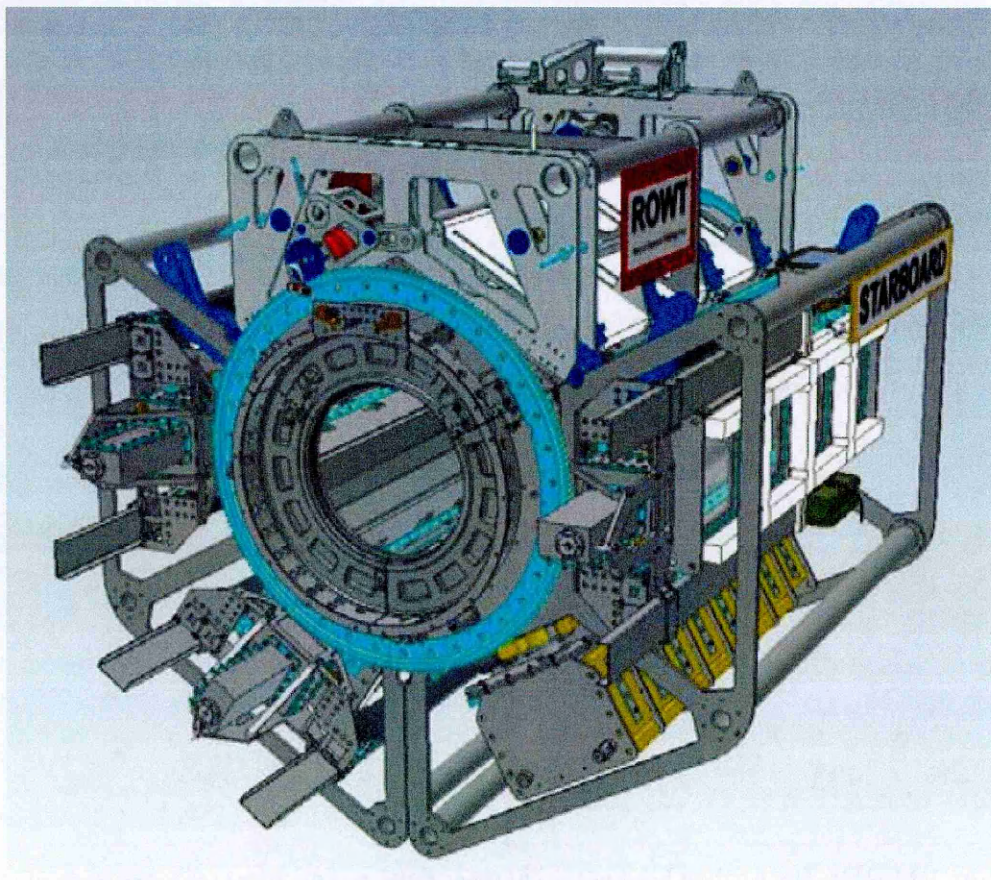


Figure 1-17 [38]: Schematic overview of the welding chamber in closed setting.

The ROWT contains the following:

- 1) Two weld heads [1, 2, 5, 35, 37, 38] [one main and one backup providing 100 % redundancy [35, 38]], with a gas-cooled Binzel GMA welding torch [1, 2, 5, 37], able to move on an angular wristed weave axis [1, 2, 5, 37],
- 2) Local contact tip cleaning tool [1, 2, 5, 37],
- 3) Two separate arc viewing and weld inspection cameras[1, 2, 5, 35, 37, 38],
- 4) Pencil grinder in the same cassette as the observation equipment [35, 38] for cosmetic tasks,
- 5) Preheat mechanism,
- 6) Separate fume extraction [5, 35] and gas re-circulation drying cassette [35, 38].

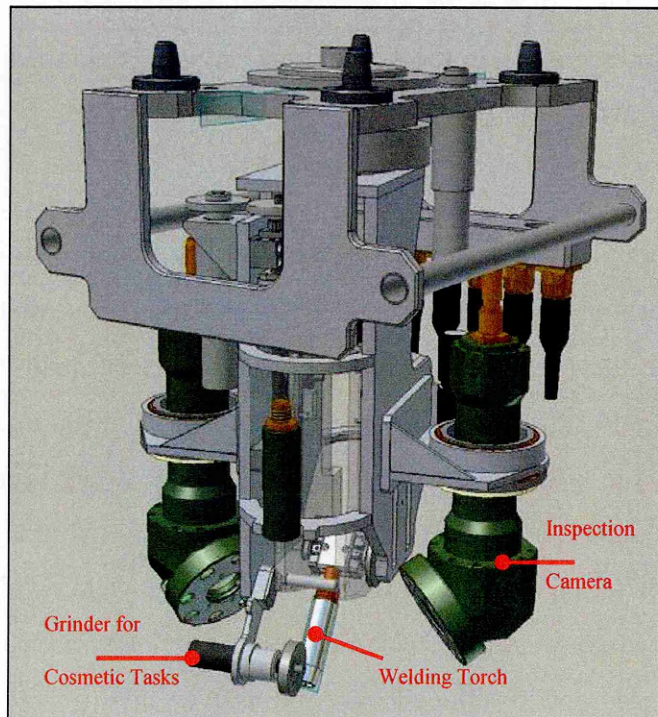


Figure 1-18 [1, 5]: The welding head module showing the two arc viewing and weld inspection cameras.

1.2.6 RPRS System Operation

The preparation of the pipeline area where the operation will take place is similar to the one used for the PRS system which has been described earlier in 1.2.1. For the case of a spool repair where a pipe length will be replaced using two sleeves [35, 38], the operation after preparations have finished is as follows [35, 38]. The sleeve is placed on the spool ends on the surface [35, 38]. The spool is deployed and the pipe ends and the spool are then aligned to each other with a tolerance of 2° angular misalignment and approximately 2 mm horizontal misalignment, with maximum allowed gap of 100 mm between the spool and pipe ends [35, 38]. The sleeve is then dragged over the pipe and spool ends [35, 38] using specialized equipment so as to cover the gap which is to be approximately equidistant from either end of the sleeve [35, 38]. Once the sleeve is properly located, the welding habitat is lowered with the use of a Remotely Operated Vehicle [ROV] from an equipment basket and is installed over the sleeve making a tight water sealed enclosure around it [35, 38], as shown in Figure 1-19 and Figure 1-20. In the sequel, gas [argon] is pumped in the habitat in order to force the seawater out [35, 38].

After water extraction is complete, the pressurised gas is continuously re-circulated and the heating systems are used to dry the gas and the parent metals [35, 38] and sleeve and to raise their temperature to achieve satisfactory quality during welding since parent metal and sleeve temperature and moisture contents in the shielding gas play a significant role. As Woodward *et al.* reports [1], it has been experimentally established in the lab that a pre-heat of 50 °C is required to avoid Hydrogen Induced Cold Cracking [HICC] particularly in the root area of the weld. This drying process may take about two days. The welding heads are then moved from their dry transportation garages and positioned over the sleeve ends [35, 38]. For the large fillet welding equipment, many welding passes are required to complete the desired fillet weld shape. The welding process used is GMAW fillet welding [35, 38]. For achieving 360° welding coverage the chamber has to be rotated by approximately 200° in either direction [35, 38], effectively performing a slow oscillation until the required amount of weld material has been deposited [35, 38]. Welding is always performed in the down-hill direction [35, 38]. After completion of the welding, the

weld heads are retracted into the gas-tight transportation garages and the chamber is opened and flown back to the basket ready for recovery [35, 38]. The equipment is designed for a relatively easy recovery, such that recovery and development systems during operation [for any essential equipment maintenance] are commercially available or of known technology [36]. Finally, the equipment is salvaged or moved to another location.

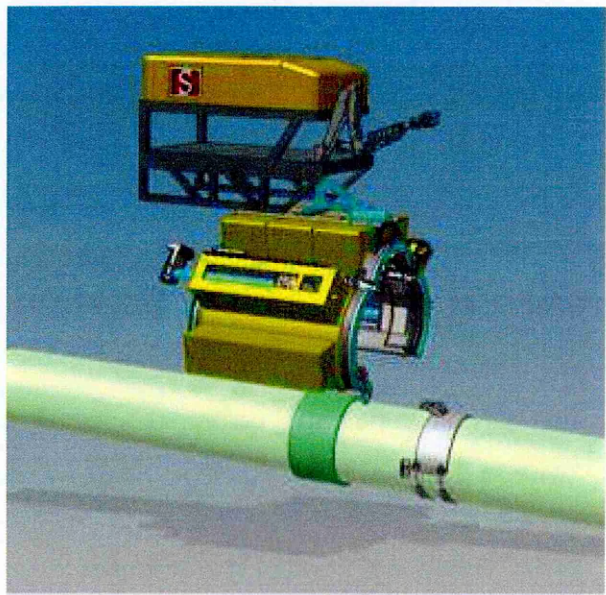


Figure 1-19 [35]: The Welding habitat as it is positioned around the sleeve-on-pipe arrangement with the aid of a ROV.

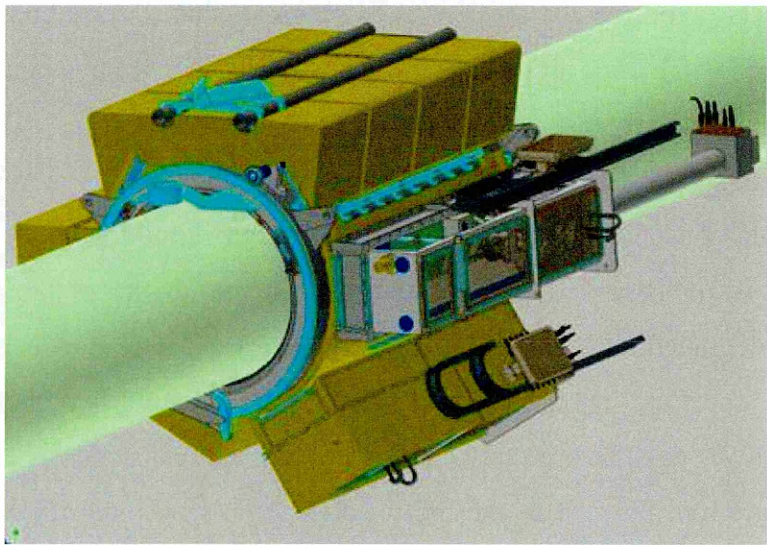


Figure 1-20 [5]: The welding habitat wrapped around the pipes and closed so as to seal and isolate the welding area from the sea.

1.3 Needs for Future Automation

The work at Cranfield University and the construction of the system have reached a stage where further development is required, most importantly the potential for full automation in order to produce high quality welds in the repair system environment.

Operator's Tiredness

Although the system is going to be remotely controlled from the sea surface, it is best that there will be some automation and control systems locally [submerged]. One of the reasons is that the duration of the welds will be a process that will take hours to be completed. The system's operators will work in shifts monitoring and controlling the process with the aid of the video cameras and the instrumentation that will monitor the process parameters, for example voltage, current, temperature. It is inevitable that this creates tiredness that can cause potential errors. The errors may cause delays in the completion of the work, which will lead to the cost being increased.

CTWD and Reasons for the Project's Work

One of the most important variables to be controlled hyperbarically is to maintain a constant CTWD to achieve satisfactory welding quality. During the initial process and parameter development, the geometry used in the laboratory was ideal. However, this is not to be expected for the real case scenario, due to variations of the pipe ovality or the inevitable misalignment of the sleeve-on-pipe arrangement and the fact that the sleeve practically rests on the pipe ends as mentioned earlier. Also, there will be some change in the sleeve-pipe geometry as the welding head moves around them, causing a slight constant change in the centre of gravity resulting slight variations in the CTWD. If all these variations are large, then the quality of the weld will be significantly degraded since the geometry will be varied. As it will be mentioned later in 2.2.2, short arc lengths of 1 mm, or less, are required hyperbarically which means that CTWD must be precisely controlled. The vertical stand-off of the welding torch is set at 5 mm but due to the the welding torch's weaving the actual CTWD [stick-out when dipping in the weld pool] is 8 mm to 9 mm. The work in this project was focused towards estimating this in real time and providing a signal suitable for control of the welding torch's position so as to maintain the CTWD within ± 1.5 mm.

Sensors for CTWD Control

There are various different sensor types to measure or estimate the CTWD, these are:

- 1) Tactile Sensors
- 2) Optical Sensors
- 3) Temperature Sensors
- 4) Acoustic Emission Sensors
- 5) Proximity Sensors
- 6) Arc Phenomena Sensors

The technology and application of these sensors is described extensively in 2.4 and for each one a summary with the reasons that limit their prospect of application in the RPRS is given. In sort, the above sensors require additional hardware to be installed on or near the welding torch and the point of measurement [with the exception of the optical Infrared Radiation [IR] and the arc phenomena sensors] is near but not on the welding point. The need for additional hardware might not be an “extreme” demand in 1 Atm applications, however, it is most desired to avoid adding components in the welding head assembly since the risk of a malfunction is increased; consequently, the risk of having to aboard an operation for emergency maintenance is increased with potentially extreme consequences in the overall cost.

In the case of the arc phenomena sensors for torch positioning [61] and arc length control [62], the additional hardware can be kept to a minimum [61] as the wire oscillation alone can be enough. However, for increased sensitivity to be provided so as better control to be achieved, the process involves angular weaving of the welding torch and the dip transfer method to be used for the biggest part of the welding. Consequently, the arc length and stick-out is continuously varying due to the nature of the process. Additionally, periods where the welding arc is fully extinct can be relatively long in duration, as discussed in 2.2.1, and welding torch control could be lost because as a result of the following two scenarios. Firstly, the control system might recognise them as step change input, which means that it will instruct the torch to move towards the parent metal resulting in torch crashing. Secondly, if hysteresis is used so as to avoid the first scenario, it will limit the response time of the system

which again can result to less satisfactory welding or, again, in the torch to crash on the parent metal. These unwanted possibilities make the successful application of an arc phenomena sensor to be doubtful.

At the moment [for the laboratory experiments], the CTWD control around the pre-programmed path is performed by the operator in real time based on voltage and current values, arc length estimation from the camera image, and experience. It is obvious that although satisfactory results can be achieved the risk of human error in real operations, when the welding runs will last for days, is significantly increased. Although, as it will be explained. However it is not impossible to implement a sensor for CTWD in the RPRS. The solution can be found by using the Dip Resistance as explained below.

1.3.1 Dip Resistance and Reasoning of Use in RPRS

All the types of sensors mentioned in Sensors for CTWD Control [pp. 27] could be utilised but each one has limitations. For the RPRS program, what is needed is a reliable method to measure the CTWD as this change with pipe ovality variations or geometrical variations of the sleeve-on-pipe system on the seabed. When the welding process that is used is dip transfer, and the filler wire is one of the high electrical resistance types [52], it is possible that the filler wire can act as the sensor's transducer. This is effectively the same like the wire touch sensor with the difference that it can operate in real time with welding. Since the changes in CTWD, especially from reasons caused by the pipe ovality variations, are not expected to be sudden and the developed hyperbaric process causes the situation to vary very slowly makes it a very attractive idea that fits the RPRS program very well. This is due to elimination of the need for additional sensing hardware and it will be applicable to the majority of the weld since the developed welding process is performed using dip transfer and the welding wire is mostly made of steel which exhibits relatively high electrical resistance which means that the electrical resistance characteristics of it suit the method of dip resistance.

2 Background Theory

2.1 Underwater Welding Categories

Underwater welding is applied in an increasingly wide range of applications [21, 75] including erection and construction of oil, gas and mineral resources sea rigs [21], lifting and repairing ships [21], salvage and rescue operations [21], laying down [21] and repairing underwater pipelines, periodic tasks like servicing of port structures and bridges [21]. This increase can also be seen by the increase in number of offshore operations including drilling [75], offshore mooring facilities [75], underwater habitats [75] and the wide variety of specialised workboats and oceanographic crafts that have become available [75]. The increase in size justifies the reasonable assumption that onshore prefabrication followed by at-sea assembly has the potential to become an acceptable practise [75]. Therefore, underwater welding will become the logical choice for joining of various segments [75].

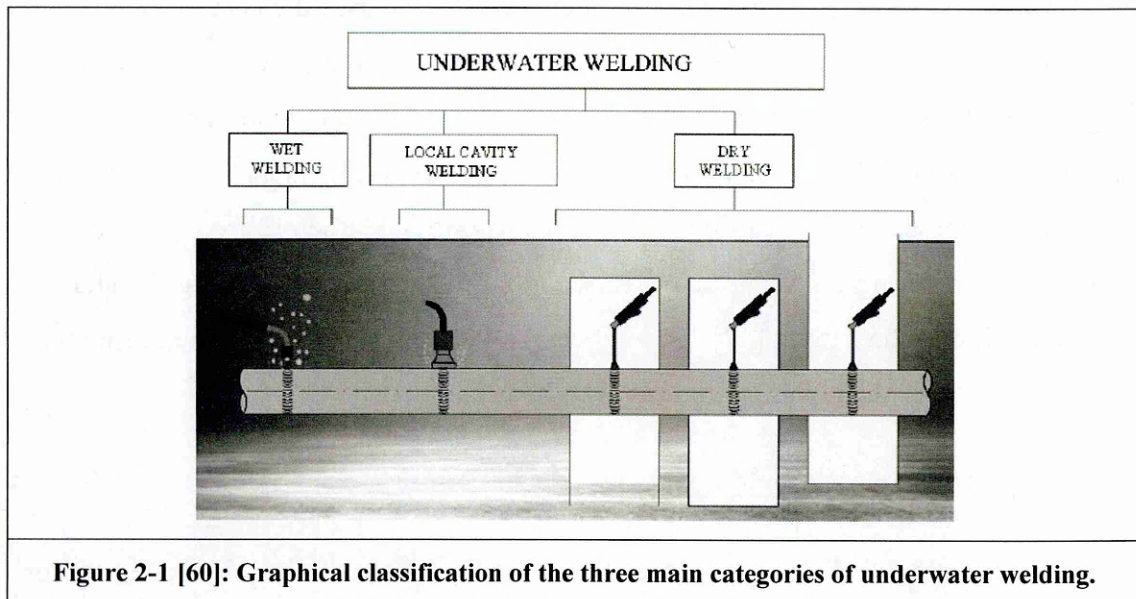


Figure 2-1 [60]: Graphical classification of the three main categories of underwater welding.

Although the demand exists that underwater welds will be at least as good as the ones made on-shore [21], the environmental conditions pose significant challenges. The underwater conditions induce intensive heat removal, hydrogen and oxygen saturation of the molten weld metal and increased ambient pressure [21]. Excellent joint quality can be achieved using dry chamber underwater welding methods [75]; however, this approach imposes size limitations which restrict its use for underwater construction

work [75]. There are three main underwater welding categories [34], shown graphically in Figure 2-1, the coffer dam welding [34], wet underwater welding [21, 34] and hyperbaric [dry] welding [21, 34].

2.1.1 Cofferdam Welding

It is most probable this type of welding to be employed in harbour works or ship repairs [34]. A rigid steel structure, the Cofferdam, is sealed against the side of the structure that needs to be welded [34]. It is a type of 1 Atm chamber access into which is provided via a ladder connected to the production platform making it applicable only in special circumstances [48]. The welders are accommodated in the same structure which is open to the atmosphere [34]. The advantage of the cofferdam welding is that since the process operates in 1 Atm, the welding process is similar to any 1 Atm welding operations. As a result welding quality can be as good as a non-underwater procedure [34]. The limitation of the system comes mainly from the restriction to depth to which a dam can be built [34], usually not more than 10 msw depth [34]. In addition, sealing a cofferdam against complex geometries can be difficult and most of them are custom built which increases the cost of the method even more [34]. Although the cost is very high in some cases [like repairs in high-strengths steel structures in the North Sea] it is the only proven method for acceptable results [47]. An additional disadvantage is that the habitats are quite large themselves and can be the cause of further damage to the structure from the wave or current forces acting on them, or, by mishandling of components during installation and operation of the habitat [47]. Several cases of cracking occurred in adjacent areas and reported after the repair operations have been completed [47].

2.1.2 Wet Underwater Welding

Wet underwater welding is performed without isolation of the electrode, arc or workpiece from water [21, 48, 57, 60]. Touch welding employing coated or wrapped electrodes has been the standard method for producing underwater welds [75]. The most commonly used methods are the Shielded Metal Arc Welding [SMAW] and the Flux Cored Arc Welding [FCAW] which includes the self shielded Flux Cored Arc Welding [60]. Wet underwater welding was first used in the First World War to perform minor emergency repairs in ships [4]. A major advantage of wet welding is

the –relative- simplicity and ability to be used in many different positions allowing complex and unusual joints to be produced [57, 60]. It is generally considered to give joints of low integrity and prone to porosity which makes wet welding useful only for temporary repairs [34]. The problem of poor mechanical properties [45] with increased brittleness and hydrogen embrittlement remain a problem [57]. Heat Affected Zone [HAZ] cracking in wet welding of high strength steels occurs because of the hydrogen in the weld pool [45, 47], the fast cooling rates [45] [which in the temperature range from 800 °C to 500 °C can change from 415 °C/sec to 56 °C/sec [60]], the steel microstructures that develop in the HAZ [47] and the stress levels occurring in the weld joint [45, 47] leading to cold cracking [45].

The operating depth was just a few meters below the surface [4], so there was no significant influence from the water pressure, but from the actual presence of water since the process was performed in direct contact with it. Wet welding with Manual Metal Arc [MMA] using specially developed coated stick electrodes in a water environment is mostly used [34, 45] although Fluxed Cored Arc Welding [FCAW] has been widely used [34, 60] especially in Russia and Ukraine in applications which include repairing the hulls of sunken ships before refloating to the surface [34].

Manual or Shielded Metal Arc Underwater Wet Welding

When FCAW [60], MMA, SMAW or “stick” [9] welding is used in the wet, the weld joint [48, 60] and the arc are in direct contact with the water [9, 48, 60]. SMAW lacks the size limitations of utilising a dry chamber underwater [75] and consequently the manoeuvrability limitations during work. Nonetheless, SMAW suffers from poor weld properties [75] compared to other dry techniques [75]. Figure 2-2 shows such an example. The arc is struck between the workpiece and an electrode and the gases generated in the process [34] from the melting flux covering [57] act as the shielding gas [57] to protect it from the water [34], to protect the hot electrode [6] and molten droplet [6, 57] from oxidation by the gaseous atmosphere [6] and stabilise the arc column [6, 57] by providing easily ionisable material [6]. Nonetheless, the increased water pressure influences significantly the chemical reactions making flux formulations pressure sensitive [6]; below 300 msw it is difficult to achieve acceptable metallurgical properties and metal transfer stability decreases as the

short-circuit frequency increases [6]. The advantage is the simplicity of the process as no sophisticated equipment is used [41, 45, 48], other than suitable insulation to prevent current leakage as the arc is struck and maintained in an electrically and thermally contacting media [48] and waterproof covering of the electrodes [48] to prevent the flux covering from disintegrating in the water [57]. Versatility is also an advantage since the operations are only limited by access to the welder [41].

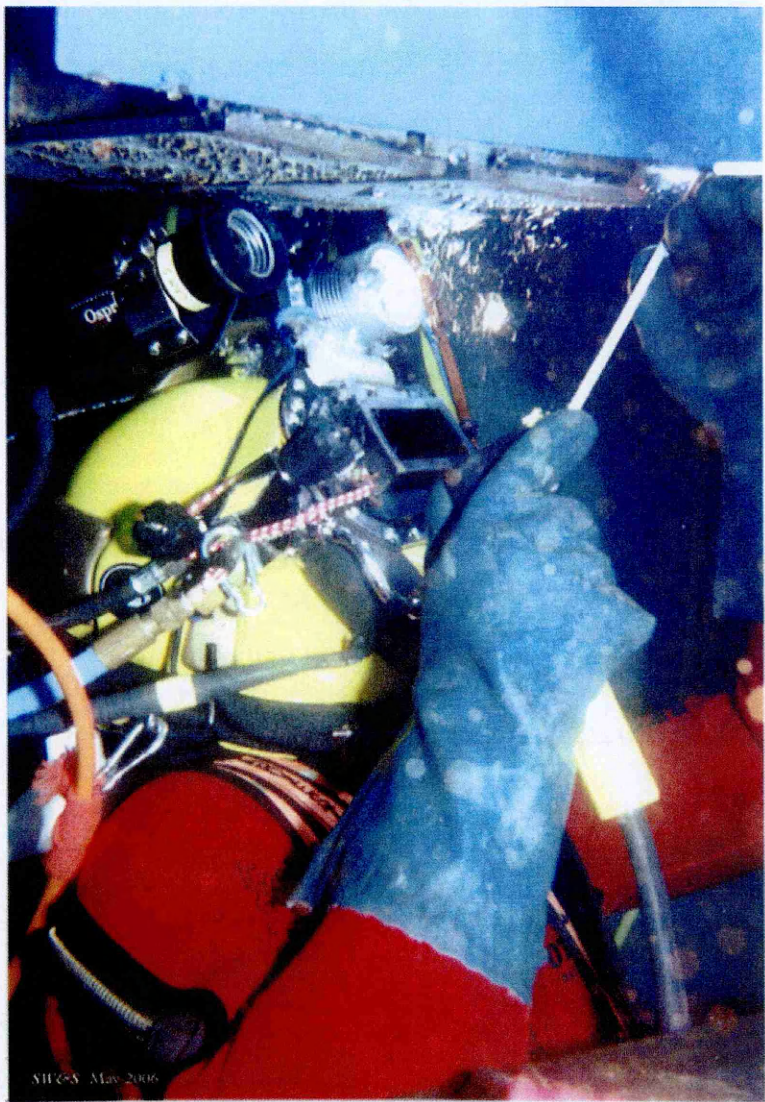
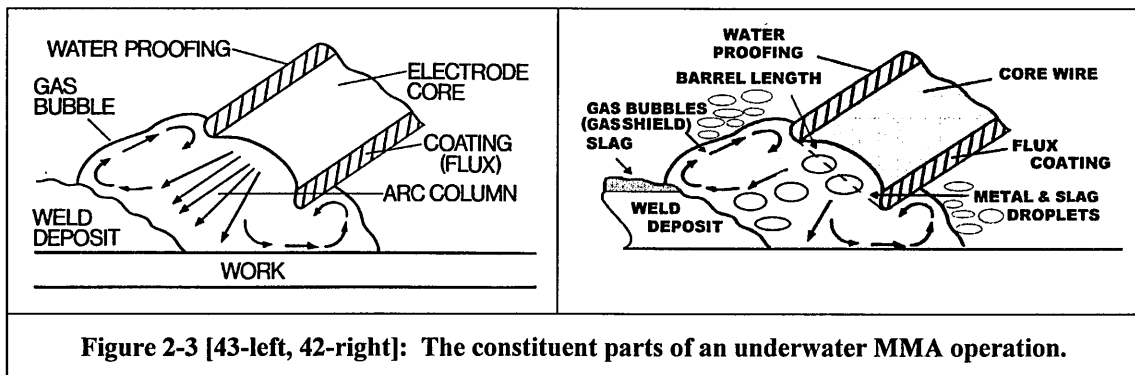


Figure 2-2 [34]: A wet MMA welding operation in the over-head position.

Although wet welding has many benefits to offer, especially in shallow waters, the influence of the pressure on the weld quality prohibits its use in deep waters [6]; the technique is restricted to 50 msw as saturation diving is regarded to be more economically viable below this depth [48] but MMA or FCAW welding is feasible in depths down to 100 m [60]. The MMA method is best suited to temporary repairs and only using fillet welding and is still in use today [4, 45] as the preferred repair method

[41, 45]. The material for the arc formation has to be provided by the specially developed [45] flux constituents [9] covering the surface of the electrode, which have to perform the same functions as in air welding in addition to the requirements the wet environment imposes [57] as shown in Figure 2-3. The arc burns enclosed in a cavity which is formed by the flux covering of the electrode which is designed to burn in a slower rate than the metal barrel of the electrode [57]. This allows maintaining the arc even in poor visibility conditions [57]. During welding, the flux breaks down [9] and melts [57] with the presence of the arc and a number of vital functions are performed [9] as it deposits itself on top of the weld metal as a slag [57].



Decomposition of the flux provides shielding of the molten weld pool [9], shielding of the metal droplets in transfer through the arc [9, 57] and provides additional material which can easily be converted to an ionised gas stream by the arc [9, 57] which influences the energy balance behaviour [9] stabilising the arc by helping carrying the current [57]. Also, the final composition of the molten metal droplets is enhanced by addition of the necessary alloys and scavenging of oxides and impurities which plays a role on the contour of the weld bead and slows its cooling [57]. A further limitation of MMA is the requirement for intermittent welding due to the finite length of the rods which decreases the production rates [41]. The poor visibility which is often encountered necessitates the need to use some sort of a guide for the electrode [57]; thus, tee and lap joints are preferred over butt joints for stick electrode welding [57].

GMA Underwater Welding

A wide belief exist that GMA welding practise is advantageous compared to the use of coated electrodes [44]. These include continuous supply of filler wire [44, 57] [this however makes the process more complex [57]]; continuous supply of filler wire results in automatically maintaining a constant arc length [57], easier shield of the welding area [44] which restricts access of hydrogen resulting in crack-free welds

[46]. Additionally, better vision due to lower levels of fume production [44], higher weight of deposited metal [44] and good opportunities for process automation [44] and ability to use advanced fluxed core wires [44, 46] make wet underwater GMA to be favourable.

Sealing the Welding Area in Wet Underwater Welding

There are two main options available to create a shielded water-free area localised to the welding area. One option is to use a water curtain and the other option is to use a shroud. These options are presented next.

Water Shielded Gas Metal Arc Welding [WSGMAW]

Sealing the welding area can be done in various ways [46], like utilising increased shielding gas flow [46], which works even better when heated [46], using a high velocity conical water jet [46], or combination of shielding gas [for example argon [57], mixture of argon and oxygen [46], CO₂ [46, 70]] and water jet [46, 57] to create a water curtain [46]. This technique is called Water Shielded Gas Metal Arc [WSGMA] and has been reported to improve quality [57]. Increased control over operating conditions and process performance can be achieved if the weld is fully surrounded with a gaseous atmosphere which results in significant improvements in weld quality in comparison to wet welding operations [6]. Figure 2-4 compares the effectiveness between the two techniques as studied by Tamura *et al.* [70] and Figure 2-5 shows the system used by Tamura *et al.* [70] combining the two techniques and an example of its operation [70]. Underwater welding inside a local cavity has been made possible by utilising standard equipment used in semi-automated or fully-automated Gas Metal Arc Welding [GMAW] [60]. Figure 2-6 and Figure 2-8 show the parameters involved in the calculation of the geometry of such a system and how this technique can be applied. Figure 2-7 shows an example of the critical conditions of applying the water shield technique in various underwater welding conditions [70]. *"This method utilises the effects of shutting off the water invasion by the momentum of fluid jet and smooth exhausting of cavity gases by flow entrainment."*[58]. A conical nozzle with a specific angle is employed [57]. The water jet flows out annularly from this nozzle [57], thus shielding the inner gas providing a stable gaseous zone around the arc improving the gas shielding effect in underwater operations [57].

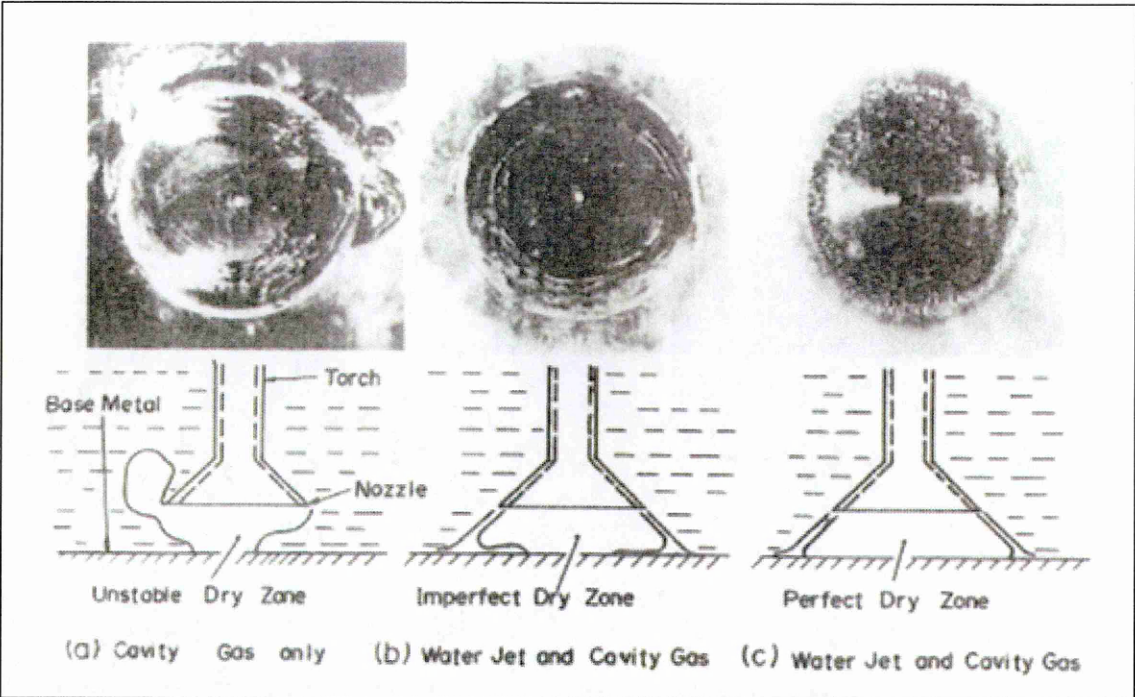


Figure 2-4 [70]: The effectiveness in cavity formation as modelled in three dimensions by Tamura *et al.* [70].

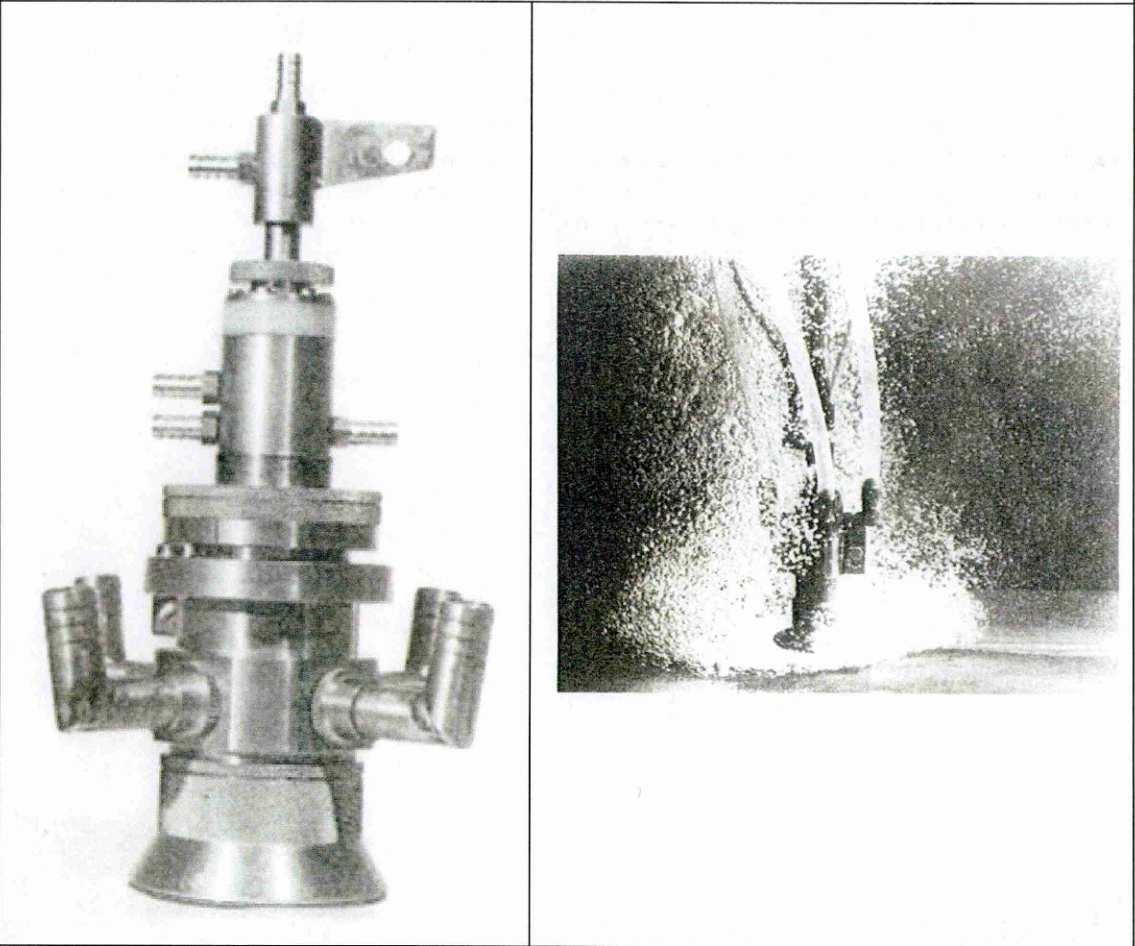
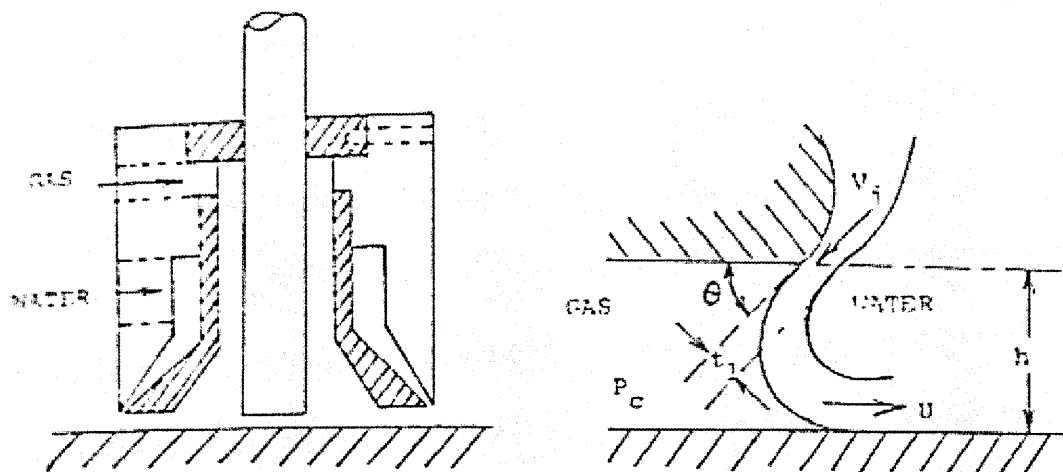


Figure 2-5 [70]: An example of a MIG CO₂ underwater welding torch using water jet and cavity gas [left] and the apparatus under executing conditions [right].



SIMPLE JET THEORY

$$\frac{P_c}{H_j} = \frac{2x}{1+x} ; x = \frac{t_j}{h} \left(\frac{U}{V_j} + \cos \theta \right)$$

$$\psi = \left[\frac{P_c X}{\rho} \right]^{1/2} \frac{h C}{U/V_j + \cos \theta}$$

$$R = D \left[\frac{P_c D}{4} + R_j \right] ; R_j = H_j \left(\frac{2+x}{1+x} \right) \left(\frac{x h}{U/V_j + \cos \theta} \right)$$

OPTIMUM DESIGN - $P_{c,min} > 0$ and $90^\circ < \theta < 90^\circ + \cos^{-1} \frac{U}{V_j}$

Figure 2-6 [57]: An example of a Water Shield Gas Metal Arc [WSGMA] apparatus and formulas for optimum design. Although further analysis is besides the scope of this document, the formulas are illustrated to emphasise the complexity of such systems.

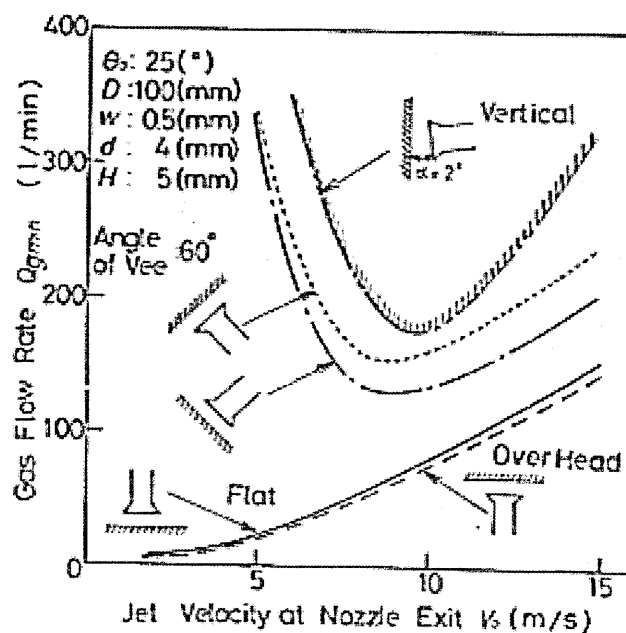


Figure 2-7 [70]: Example of the critical conditions of cavity formation in various underwater welding positions.

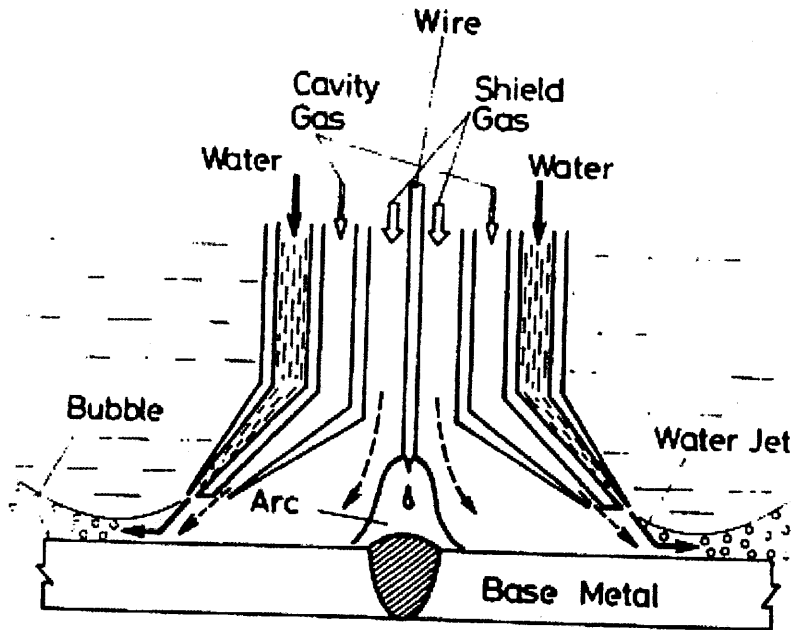
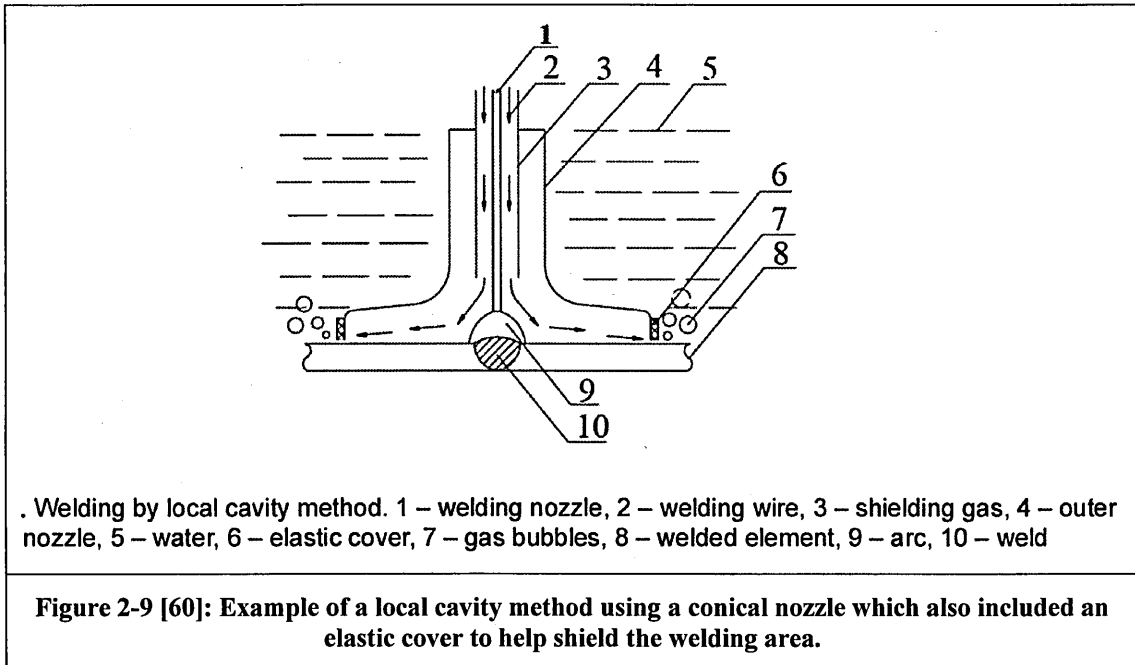


Figure 2-8 [58, 70]: An example of a Water Shield Gas Metal Arc [WSGMA] apparatus which shows the nozzle's design so as to allow a different shield gas to be used for welding reducing the cost of the cavity gas [a less expensive gas can be used for cavity formation].

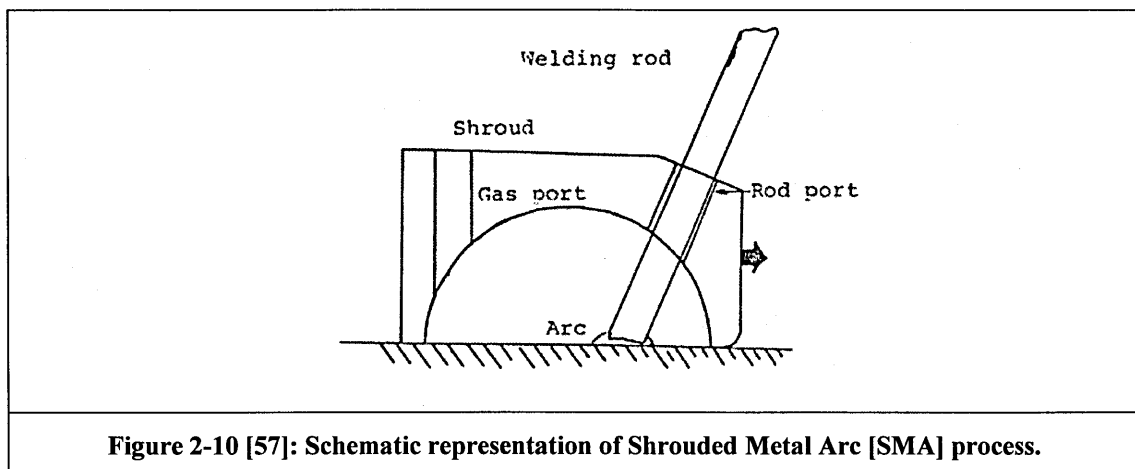
The nozzle shown in Figure 2-9 includes an elastic cover to help seal the welding area [60]. In local cavity methods the cooling rates can be close to the ones in the air [60], especially [as mentioned earlier] if the shielding gas is heated as reported in [46]. Diffusible hydrogen determination tests indicate that the amount of hydrogen in the weld metal ranges from 5 ml to 21 ml per 100 gr of iron [Fe] [60]. With local cavity methods the properties obtained can be much better than the properties of wet welds [60] can be used in depths down to 200 msW [60].

Wet welding with water curtain nozzle is a useful method because the water curtain assists the stability of the local cavity around the weld pool [73]; however, it does not allow detection of the welding path [73]. The main disadvantage of the method is that it does not allow observability of the process [60]. This is because the flow of the water curtain on the parent metal includes fine bubbles of the shielding gas which disturb the observation of the weld pool [73]. Nonetheless, accurate detection of the welding path and the geometry of the welding area are the most important factors to obtain sound welds [73]. It has been reported that local cavity methods can be used with LASER as the heating source [60].



Shrouded Metal Arc Welding [SMAW]

A small shroud can be used to evacuate the surrounding water from the joint to be welded, as shown in Figure 2-10, thus preventing the arc from coming into contact with the water and this process is called Shrouded Metal Arc [SMA] [57] or Shrouded Metal Arc Welding [SMAW].



The gas atmosphere used for this technique does not solve the problem of hydrogen embrittlement as the hydrogen content in the gas is quite large [57]. However, SMA does offer the advantage of slower cooling rates so the welds become less brittle, less hard and with less martensite observed in their microstructure [57]. This results in welding properties that are in between the ones produced in atmospheric welding above sea level and unshrouded underwater welding [MMA] [57]. As Silva and Hazlett [75] report, the work they performed reported in [75] shows that shrouded

arcs present characteristics intermediate of those in open air [1 Atm] welding and open water [unshrouded] welding [75]. The actual size of the shroud is critical and must be compatible with the amount of gas formation at the arc [57] since excess gas can bounce the shroud off the workpiece and lack of gas will not manage to expel the water from within the shroud [57]. It follows that a shroud design with a controllable venting system to achieve equilibrium between the gas formed at the arc and the gas flowing in the shroud is vital so as to keep the shroud-covered area water-free and stuck on to the welding area [57]. It has been reported that using a 1.5 inches in diameter hemispherical shroud seems to eliminate undercut and produces better bead shape [57].

Silva and Hazlett [75] constructed a device that used the gas formed during welding to displace the water from the vicinity of the arc and puddle [75] shown in Figure 2-11. The device was made of a 2.5² inches acrylic block and 1.5 inches in height. The internal chamber has a hemispherical shape 1 inch deep and 2 inches in diameter. The gas ports are required so as to prevent the shroud from floating off the work surface during welding [75]. Another use for the gas ports is to serve as pumps when exiting gas lifted entering water which helps to clean the chamber formed by the shroud [75].

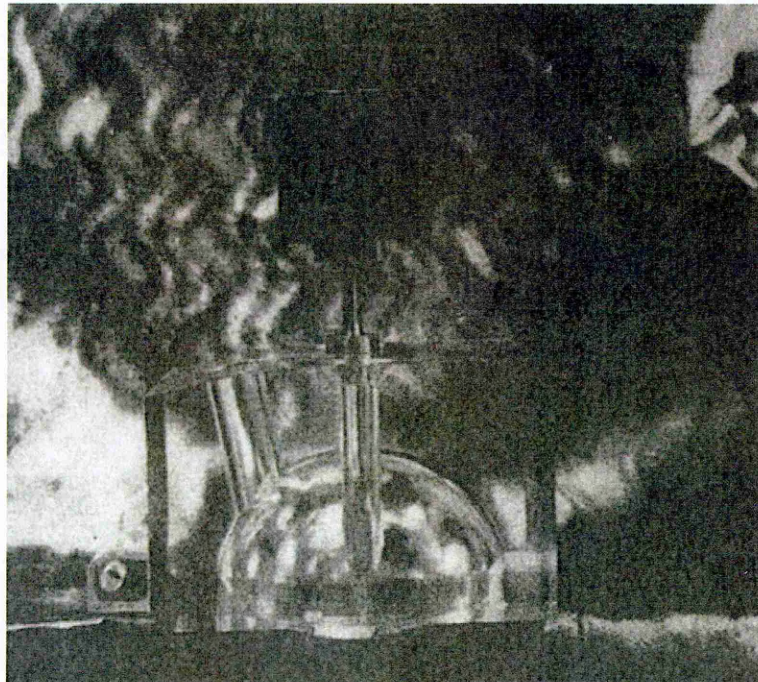


Figure 2-11 [75]: The acrylic shroud used by Silva and Hazlett [75] for their study on utilising a gas trapping shroud to improve bead shape and minimise undercutting in underwater SMAW.

A steel shroud of similar dimensions was also used by Silva and Hazlett [75] to examine the effect of various porting arrangements [75]. For this reason, the device had four ports [75]. The conclusions of the work from Silva and Hazlett [75] was that the need for an inexpensive way of producing sound underwater welds can be satisfied by the use of a SMAW with iron powder electrodes [75]. Silva and Hazlett [75] also concluded that the gas leak rate out of the device influence its beneficial effects, however the degree of porting could not prevent the formation of marensite at the fusion lines [75].

Avoiding Hydrogen Pick-Up

Although the previous can provide a water-free cavity, hydrogen pick-up can occur from the remaining “film” of water on the parent metal [46]. This should be dealt with in two steps, firstly by evaporation utilising the heat input of the arc and subsequent removal through the shielding gas stream [46]. This reliance on the arc’s heat input means that at high welding speeds with low heat input hydrogen might still be present [46], however, assuming that stable cavity conditions can be achieved [46], hydrogen levels low enough can be achieved so as to avoid hydrogen assisted cracking of offshore medium strength steels [46].

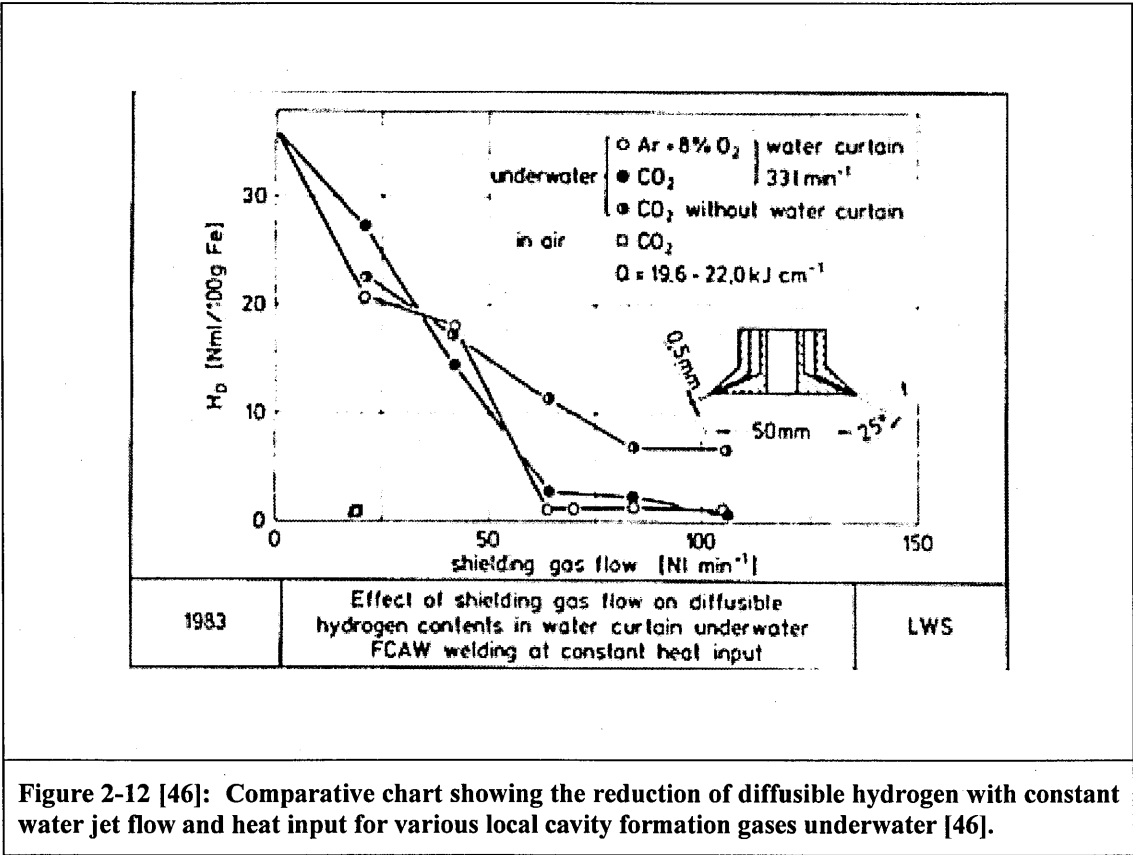


Figure 2-12 [46]: Comparative chart showing the reduction of diffusible hydrogen with constant water jet flow and heat input for various local cavity formation gases underwater [46].

Shielding Gas Vs. Fluxed Cored Wire

The composition of the shielding gas is also important as use of argon and oxygen mixtures reduced the hydrogen content in the weld [46], the danger of explosion especially in great depths is increased [46]. Using a cored wire could offer the advantage of not using a shielding gas [46], instead, by including slag forming constituents in the core of the wire to undertake the protective role a shielding gas might not be required [46] but a stable arc is required [46]. Lucas and Cooper [41] report that the combination of flux formulation and wire composition in Fluxed Core Arc [FCA] wires produce the desired slag-gas forming reactions which reduce hydrogen and oxygen pick-up in the weld metal and improve the weld profile [41].

Limitations of Wet Underwater MMA and GMA

The disadvantage of both, MMA and GMA is the poor mechanical properties that can be obtained due to hydrogen absorption whilst welding is performed in the aquatic environment [44, 45]. The fast cooling rate [44, 45] occurring from the presence of water [44] and presence of local stresses [45] could lead to cold cracking [45] in or next to the weld [33, 44, 45] and hardening [44]. West *et al.* [33] report that hydrogen-induced underbead cracking can be avoided if the carbon equivalent of the base metal is around 0.4 or less; with higher carbon equivalent austenitic wet welding electrodes should be used to avoid such cracking [33]. Nonetheless, water temperature has been shown [33] to contribute to base metal cracking when the carbon equivalent of the carbon steel [ASTM A516 Gr.70] base metal approaches a value of 0.4 [33]. For mechanised wet welding systems it is necessary to position the weld line and select the weaving width accurately, otherwise defects like undercuts and lack of fusion will appear [73].

Semi-Wet Underwater Welding

A variation of the coffer dam and wet underwater welding techniques is to use a system like the one that Bach *et al.* [40] have developed shown in Figure 2-14. Bach *et al.* [40] describe it as a system that is between the coffer dam and the wet underwater welding thus creating a mixture of the two, a fourth category, to be so-called the semi-wet underwater welding [40]. When semi-wet underwater welding is used the resulting weld's quality has been shown to be better than the ones obtained

with the wet welding techniques at water depths up to 50 m [40]. It should be mentioned that the methods reported earlier in Sealing the Welding Area in Wet Underwater Welding [pp. 34] can be clustered under the semi-wet subcategory presented here; however, the following two techniques offer a much better isolation/protection of the welding area from the water environment.

Portable Dry-spot

This technique allows welding in a dry environment by putting a small chamber, usually referred as the portable dry spot, over the welding area by the welder diver [48, 57]. A flexible gland allows the torch to enter the chamber and inert gas supplied through a one way valve system expels the water [48, 57] as Figure 2-13 shows.

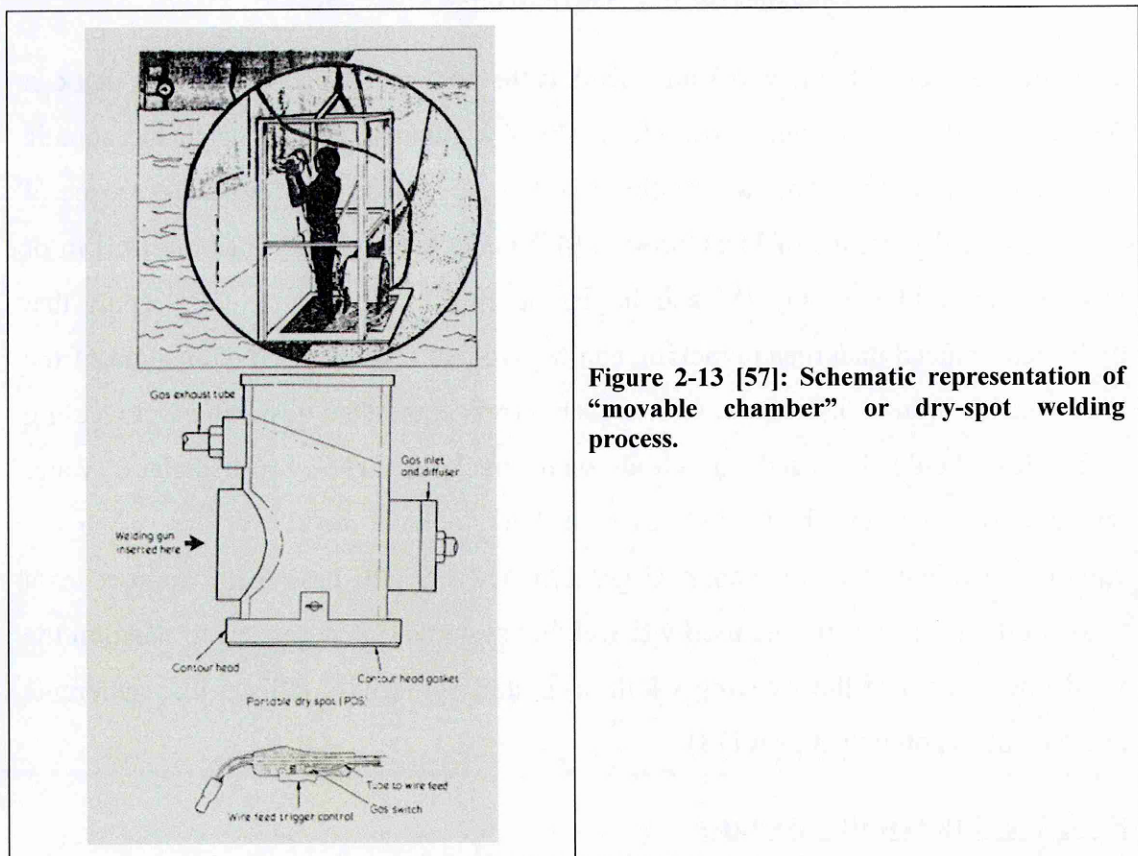


Figure 2-13 [57]: Schematic representation of “movable chamber” or dry-spot welding process.

The most practicable welding processes are MMA and MIG [48, 57]. A drawn-arc stud welding can be used and a way on achieving this by performing underwater welding using the welding gun shown in Figure 2-14 [40]. Features of the stud welding technique are its simplicity and restricted application to local joints [57]. As Bach *et al.* report in [40] work from other authors, where coating of the ceramic ferrules with specially formulated protective paste originally developed for

underwater MMA and GSAW is the ideal solution for reducing water absorption during welding operation [40]. Using this system the coffer dam is extremely reduced in size since only the minimum welding apparatus needs to be hermetically sealed from the underwater environment. The hand-held chamber can be guided by the diver along the desired welding trajectory [57]. Removable contour heads and gaskets can be attached to the open end of the chamber to allow adaptation for odd-shaped joint contours [57]. An adjustable exhaust tube allows excess gas to escape without disrupting a tight contact of the chamber with the welding surface [57]. The use of the movable chamber offers the advantage of preventing contact of the welding area with water until is sufficiently cooled preventing significant hardening of the Heat Affected Zone [HAZ] offering better mechanical properties [57]. Inevitable though, this technique will require the welders to dive and remain exposed to the underwater environment [48] which has its own requirement for safety and can cause other implications. Operation requires the diver to use both hands which means that firm footing and support are required during welding [57]. Finally, the technique offers limited manoeuvrability and flexibility in addition to poor visibility [57]. Lythall and Gibson [69] concluded that although the MIG process is relatively stable for the depth they investigated [69] [≈ 50 msw], after this depth the process suffers from a number of inherent problems [mentioned in 2.2.1] which would make it difficult to be used as a manual process in local dry environments.

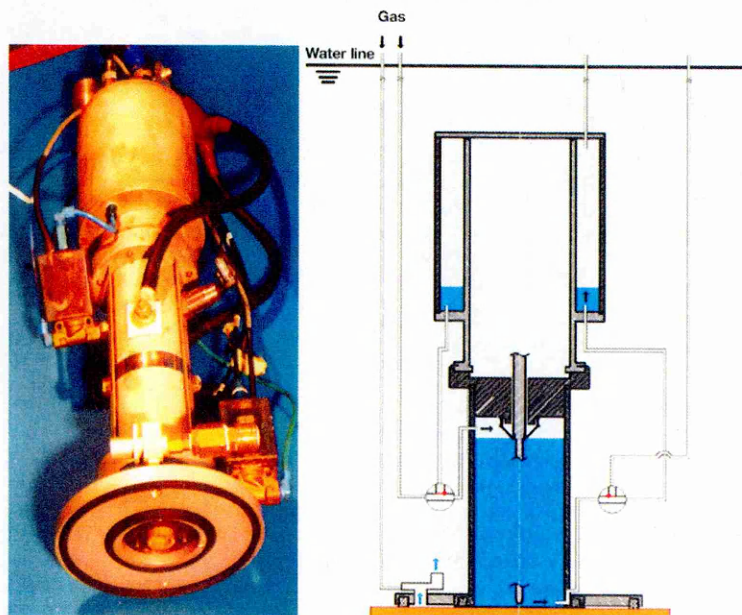
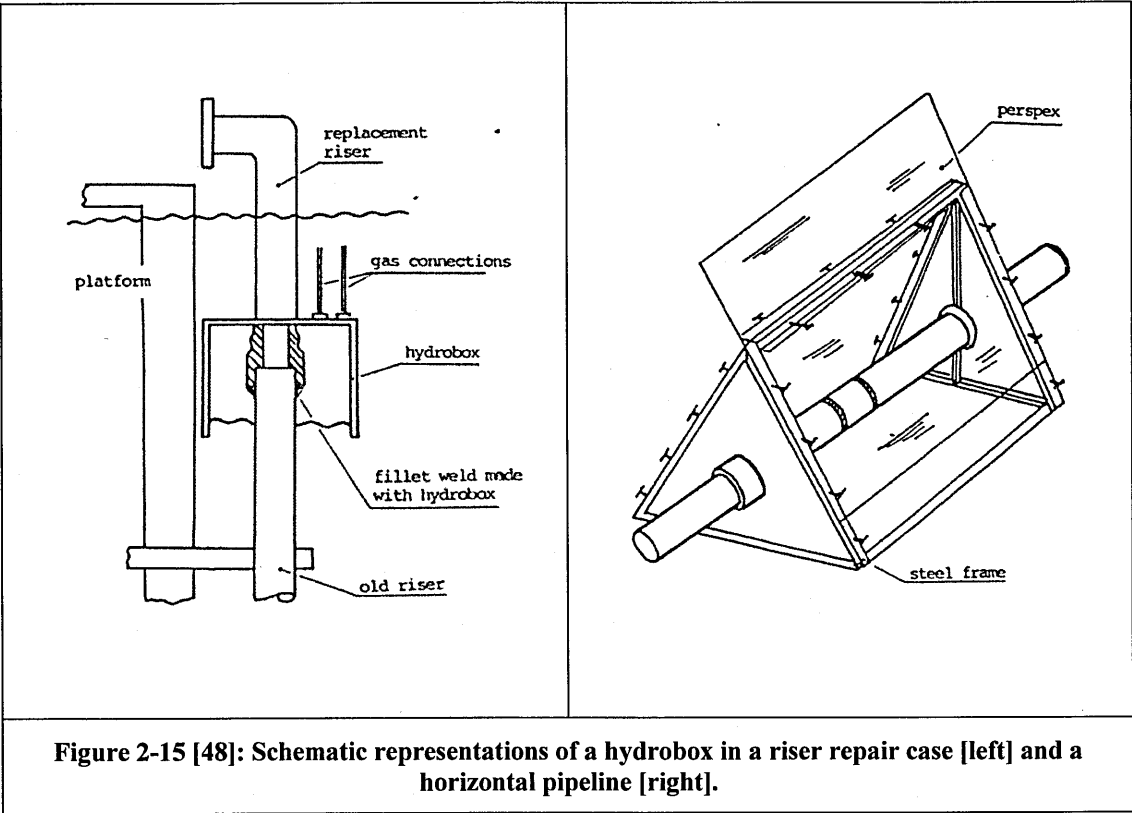


Figure 2-14 [40]: A welding gun developed for drown arc stud welding in semi-wet welding operations by Bach *et al.* [40].

Hydrobox

The hydrobox is a further adaptation of the portable dry-spot [48] system and is closer to the coffer dam system. A hydrobox can be made out of steel, Perspex or rubber [48]. It is a much larger [usually] version of the portable dry-spot system allowing for greater freedom of movement during operation as it fully encapsulates the welding area [48]. Once more, inert gas is used to expel the water via the open bottom of the chamber and it is possible for the diver welder to be only partially exposed to the water [48].

Typical hydrobox system applications are schematically shown in Figure 2-15. The Hydrobox approach allows surface code quality welds to be achieved even though the diver is partially exposed to the water [69]. The Hydrobox based technique, known as ‘Hydroweld’ [69], is centred on the semi-automated GMA process and has been used extensively for offshore construction and repairs [69].



2.1.3 Dry Hyperbaric Welding

Dry welding is said to be performed when the welding zone [welding arc, weld metal and resultant weld bead [48]] is fully isolated from the water [21] by gas coverage using either improvised or specially designed equipment [48, 57]. However, the meaning of the word “Hyperbaric” literally means *an increased pressure environment* and the term really refers to any such welding operation [wet or dry, underwater or not]. Nonetheless, the use of the term “Hyperbaric Welding” is associated with the use of a dry habitat [4, 8, 34, 37, 45, 57], sealed around the structure to be welded and large enough to accommodate the fully equipped diver/welder [34, 45] and is pressure equalised with the ambient water pressure [4, 8, 34, 37, 45, 46, 60]. The pressure equalisation expels the water and produces a habitat suitable for welding [4, 37, 57, 60]. For manual hyperbaric welding the maximum depth is reported to be 300 m [60].

The use of air or gas mixtures depends on the depth [60] but does not mean that hydrogen can be completely removed because of the humidity that exists inside the chamber [57]. The gas mixture must be chosen so as not to be explosive [57] and, if a diver assisted system is used it should be able to provide short-term life support if a malfunction of the life-support systems occurs [57]. Usually a mixture of Helium and Oxygen [Heliox [4]] is used, with partial oxygen pressure of 6 psi to 8 psi [57] although changes are made depending on the specific process requirements [57]. Additional problems, in the diver assisted systems, include the elevated temperatures which in combination with the humidity worsens the working conditions [57], although the visibility and positional stability problems are solved [57].

Dry hyperbaric welding is performed when the depth is increased, for the construction of a new structure, or, for installation of a new pipeline [4, 57]. It is also used for tie-ins [34], or in the case of a permanent repair, like the ones needed for pipeline repairs [34, 57] and risers in the oil and gas industry [34].

Together with GMAW various other fusion welding processes can be used to perform dry hyperbaric welding [6, 60] and it is a possibility to be able to use almost all the

standard welding processes [60]. Processes used are the Shielded Metal Arc Welding [SMAW] [6, 60], Gas Tungsten Arc Welding [GTAW] [6], MMA [34], Tungsten Inert Gas [TIG] [34, 60] and FCAW [34, 60]. Fully surrounding the weld with gaseous atmosphere leads in significant improvements in weld quality when compared with a wet operation [6]. Furthermore, employment of a dry chamber for performing welding repair operations provides weld properties that are better than the ones produced with wet welding [4, 60], in most cases as good as the ones produced in 1 Atm [4, 57, 60] and in many cases superior to those obtained during initial fabrication [6]. Nonetheless, since the gas-filled chamber is in contact with the surrounding water, the gas pressure must be equal to the outside pressure so as to expel the water [45]. Its application is limited by the increased costs [57, 60] the relative immobility of the hyperbaric chambers and their inflexibility [57]. The increased pressure inevitably affects the properties of the weld by affecting the behaviour of the arc [45, 60] and the weld pool [45], an effect that will be analysed below in detail for the GMAW process.

2.1.4 Other Underwater Welding Techniques

Friction underwater welding offers the advantage of being relatively insensitive to water depth and can also be easily used in robotic operations [34], thus is attractive for use on deep water repairs [34], however, it hasn't become a commercial reality yet [34].

The idea with *thermit welding* is to use a deep submersible and remote control of the welding process [57]. Thermit welding does not require power sources hence a complete watertight package could be developed able to be ignited remotely and virtually no welding skill is required for ignition as long as the device is properly designed [57]. An example of thermit welding equipment arrangement for underwater operations is shown in Figure 2-16. Coalescence is produced by heating with superheated liquid metal and slag which is the result of a chemical reaction between a metal oxide and reducing agent with or without application of pressure [57]. This makes this technology attractive for environments as diverse as deep-sea and outer-space [57]. The basic chemical reaction is described by $3Fe_3O_4 + 8Al \rightarrow 9Fe + 4Al_2O_3 + 719.3 \text{ kcal}$ [57] and can achieve a theoretical temperature of 5,590 °F. However, the process is influenced by the increased pressure and the presence of water [57]. The water pressure will affect the properties of the weld and the reaction characteristics and the pressure balance between the reaction vessel and the environment at the moment of tapping the molten metal [57]. Corrosion can be caused by surface contamination and the fast cooling rates can also influence the process.

Underwater plasma arc welding [which achieves best results using water-glass [$Na_2O \cdot 2SiO_2$] shielding] as shown in Figure 2-17 and *electron beam welding* have also been studied [57]. When materials sensitive to heat, like tantalum, are to be welded *resistance welding* has been used but only on land under a few inches of water [57].

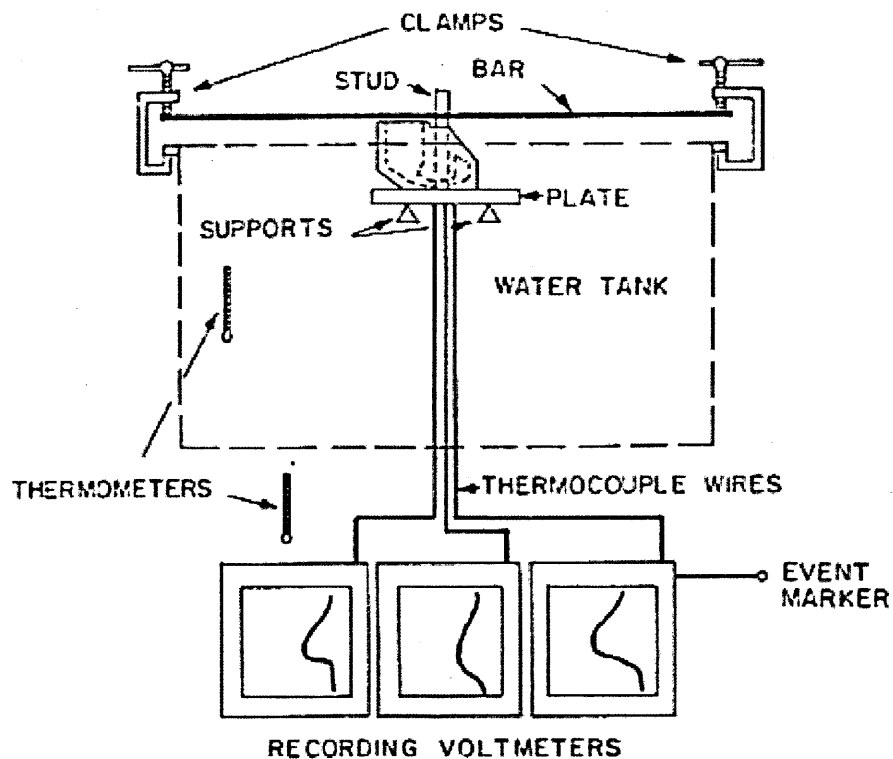


Figure 2-16 [57]: Equipment arrangement for underwater thermit welding.

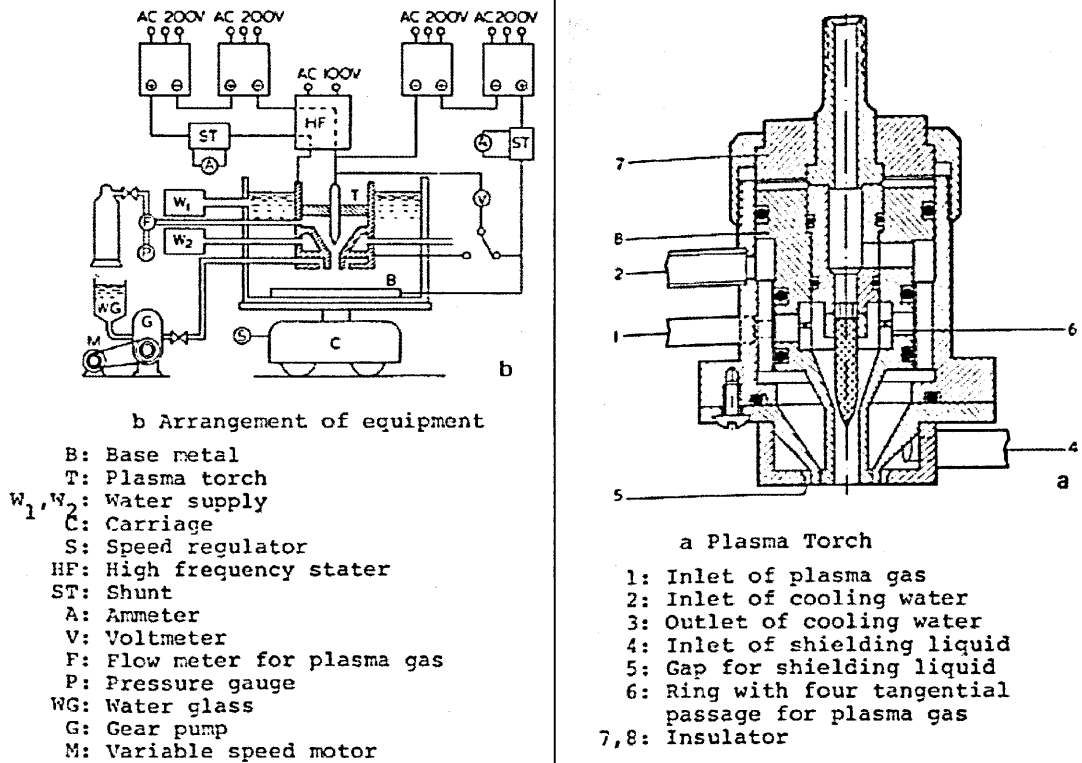


Figure 2-17 [57]: Equipment arrangement for underwater plasma welding on land [left] and detailed description of the plasma torch [right].

2.2 Hyperbaric Welding Process – A Brief Overview

Under hyperbaric conditions the welding process and arc characteristics are different from those at 1 Atm. It has to be noted that trends and characteristics vary between different processes [for example GTAW and GMAW], as well as when the same process technology is performed under different operating parameters and ambient conditions. Hence, the following are to be used only as a guidance note as future data might introduce important changes; therefore, it is advisable that a review of most recent literature is performed anytime accurate process behaviour is desired to be known. The arc behaviour has been studied and the results of some of these studies [1, 4, 5, 6, 7, 8, 9, 10, 38, 69, 71] are summarized below with primary focus on hyperbaric MIG welding process for the RPRS program.

In order to perform arc welding it is necessary to have an electrically conducting gaseous plasma that in general should be self-sustained and able to provide the process with a stabilized source of heat [9]. There are three factors that influence the arc structure:

- 1) Plasma material properties [4, 9]
- 2) Environmental conditions [4, 9]
- 3) Current flowing through the arc [4, 9]

The process reaches the equilibrium when the energy supplied equals the energy that is lost at the electrode, the work piece and the surrounding environment [9]. In such a case, for a given current, arc voltage can be regarded to be an indicator of the energy loss [9].

2.2.1 Generalised Welding Arc behaviour under Hyperbaric Conditions

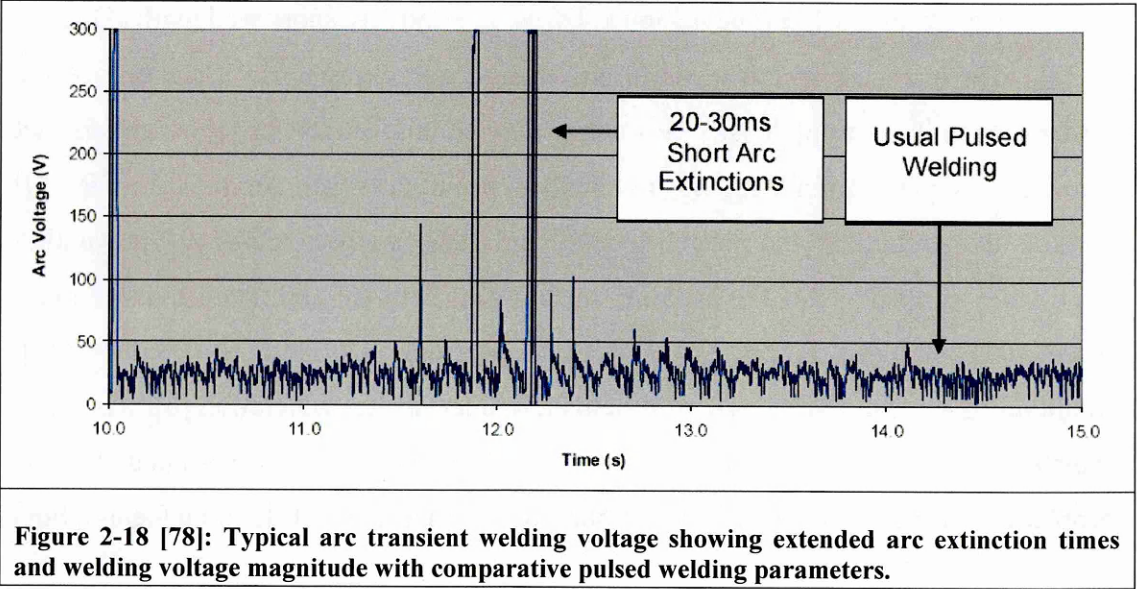
All arc processes involve the generation of electrically conductive gaseous plasma [9]. Gaseous conductors are highly susceptible to the influence of ambient pressure [71]. ambient pressure influences significantly the performance of the welding process and the resultant weld properties [1, 5, 38] and in general it is found that the major influences are on arc stability and power dissipation in the arc column [71]. For

successful welding a stable arc with suitable heating input characteristics must be maintained [9, 71] and the influence of ambient pressure on these properties is of great importance [71].

As the ambient pressure increases, particle densities increase proportionally [9]. At elevated pressures cooling rates are of the order of 4-to-5 times greater than for welds made at one atmosphere with equal heat input conditions [6]. This is evident in the shape of the deposited weld beads which show a steeper wetting angle and rough surface finish which also shows evidence of the pool disturbance [6]. The fully turbulent conditions governing the welding arc's behaviour are at least partly responsible for the weld pool's disturbance [6]. As a result of the increased cooling rates, the cooling effect on the arc increases [7] [at high ambient pressures [71]] and the energy/heat loss from the outer arc region increases [7, 9, 57] and as a result the arc voltage increases [9, 57, 69] as the ambient pressure increases for both pulsed and non-pulsed MIG welding process [69]. Nonetheless, the higher fall voltages for consumable processes [compared to TIG] give an indication that the heat transfer efficiency of the process should not be greatly influenced by the increased ambient pressure [71]. The cross-sectional area of the arc is reduced as ambient pressure increases [57, 71] and its brightness increases extremely [10]. This happens as the arc tries to counteract the increased losses it 'experiences' and reduces its cross-sectional area [7] of the central current carrying core [9], whilst the outer regions of the arc expand [6]. Because of that, destabilisation of the arc plasma occurs [1, 5, 38] and the gas entrained by the arc [6, 7, 9], hence the arc column [1, 5, 38], becomes increasingly turbulent [1, 5, 6, 7, 9, 38] because of the cooler outer regions of the arc [9] resulting in a decrease in the plasma velocity [1, 5, 6, 9, 38].

The reduced plasma velocity makes the arc susceptible to external sources of force like gas currents [7, 9], stray magnetic fields [6, 9] residing in the workpiece [9], and interactions resulting from self-induced fields in the welding arc and the workpiece [9] [associated with the current path through the workpiece [9]] causing arc blow [9] [mainly for TIG process] and electromagnetic forces [7], significant voltage disturbances and oscillation amplitudes which increase rapidly with increasing

pressure [9]. The arc roots tend to contract [6, 7, 9] because of the increased heat loss from the arc's outer regions [7] and follow an increasingly random path [6, 7]. The different current densities between the arc column and the arc roots [1, 5, 38] and the ones on the electrode surfaces [7] [on the droplet [7] which whilst under development/growth is not enveloped by the arc plasma [9] and the weld pool [7]] resulting from the localisation of the arc roots on the surface of the molten pool and wire tip [9] creates electromagnetic plasma jets [7] the strength of which increases with ambient pressure increase [7]. As a result, formation of opposing jets [5, 38] [which inevitably form at pressures of more than a few atmospheres [5, 38]] takes place which develop rapidly to become of more or less equal force as the environmental pressure increases [7]. High speed cine-films show that the small current arc carrying core invariably acts to repel the metal droplet as a result of the reaction forces of the plasma jets [9]. This causes the generation of repelled metal transfer with increased spatter [1, 5, 6, 7, 38, 69], which is enhanced from excessive stubbing of the welding wire [69] and possibly through the mechanism of torque transfer [69], especially if the welding power sources cannot cope with the process' requirements [69], and instantaneous [41] or extended periods of extinction of the welding arc [69]. In the RPRS hyperbaric process it is common to have arc extinction periods 20 ms to 30 ms long [78] as shown in Figure 2-18. Elevated levels of fume generation [6, 7, 69] due to superheating of the wire and weld pool due to constricted arc roots [7], which could become a serious problem for visibility [69], and process instability [1, 5, 38, 69].



It is thought [7] that at high ambient pressures the fume production rates may decrease because the anode and cathode root contraction can lead to a corresponding reduction of the area in which superheating occurs [7]; however, no quantitative analysis has been performed at high ambient pressures [7]. In addition, as the pressure increases [10] and the welding arc contracts [9], the energy of the welding arc redistributes itself [9] [due to columnar shape [9]] and the occurring energy loss due to radiation [brightness] from the welding arc increases [9].

The characteristics presented above [most of them] are common to all welding arcs used offshore, however, the exact change in arc behaviour is dependent on the environmental conditions under which the operation takes place, in other words, each case is different [9].

2.2.2 Arc's Length Role

In general, under high ambient pressure environments long arcs require stabilisation [71]. Various ways of stabilising a welding arc can be employed as reported in [71], depending on the application. As an example, free-arcs [like the welding arcs] might be possible to be stabilised by self-induced gas flows [71]; other situations might require wall stabilisation, applied gas flow or magnetic fields [71]. In general it is a large number of factors that will combine in order to determine the stability of a given system [71]. When the process takes place at higher pressures, some control over the effects reported in 2.2.1 can be achieved by using relatively short arc lengths [1, 5, 7, 9, 38]. The short arc length tends to prevent arc root expansion [7] and reduce the differences in the current density between the arc column and the arc roots and the net forces reduce [7]. Minimising the arc length [typically less than 1 mm [1, 5, 6, 9, 38]] controls the strength of the plasma jets [1, 5, 38], hence their action [9], preventing large scale movements of the arc root on the weld pool [6] and metal transfer takes place either through a dip process [9] or by droplet motion around the arc column [9]. Maintaining the short arc length also helps to reduce spatter generation [6]. As metal transfer occurs in the downhand and overhead position [9] it is assumed that the droplet it is driven by the gas flow surrounding the plasma jets [9]. Nonetheless, high

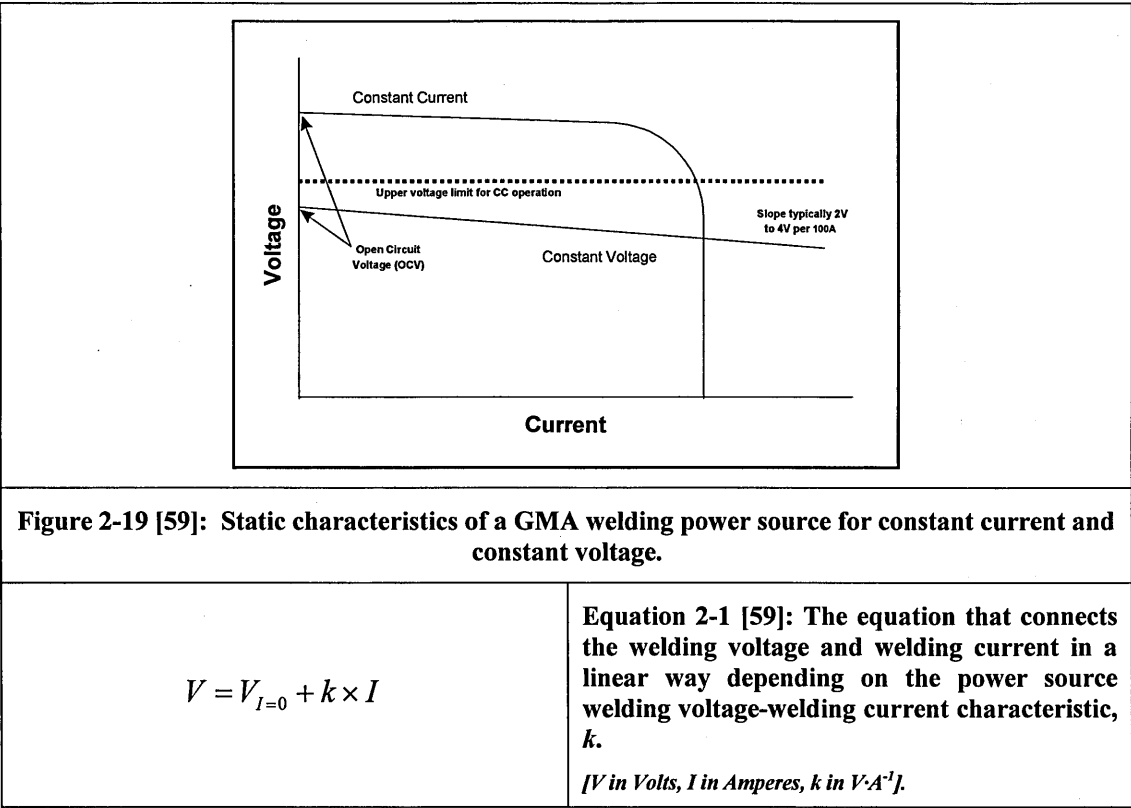
speed video monitoring [9] show that the small current carrying core of the arc invariably acts to repeal the droplet as a result of the plasma jets' reaction forces [9].

2.2.3 Wire Diameter

In order for short arc lengths to be maintained, it is necessary that accurate control over the power delivered to the process is achievable [6]. Successful process control in consumable systems [71] is achievable only with small diameter filler wires [9, 71], for both SMAW and MIG under hyperbaric conditions, which are generally smaller compared to the ones used for the equivalent 1 Atm process [71]. Maximum stability is obtained using either solid wires with diameter 0.8 mm or 0.9 mm, or cored wires of 1.0 mm in diameter [9]. This could be due to the resistivity of the welding wire and the area of contact of the molten droplet with the unmelted welding wire [9] since significant force is required to overcome the surface tension and detach the droplet [9]. The surface tension depends on the area of contact between the solid welding wire and the molten droplet [9]. The resistivity of the consumables influences the heat generation due to power dissipation on the solid wire [9]. By varying the CTWD, the electrical extension of the wire can be altered [9] which can be used to control the current flow as the operating point moves along the power source characteristic [9]. This can be done because the voltage drop on the wire extension has a relatively high value [9]. If a larger diameter consumable is used, the voltage difference per unit change in the wire's electrical extension is small and excessive deviation of the welding torch is required for current control [9]. This results result in gas shielding alterations to the molten weld pool and surrounding regions which are unacceptable [9].

2.2.4 Power Source's Characteristics

The hyperbaric GMAW process operation is closely related to the dynamic and static characteristics of the power source used [59]. Constant welding current operation provides close control of the metal transfer behaviour [59] and a constant welding voltage characteristic provides a measure of self adjustment as shown in Figure 2-19. The slope, or degree, of self adjustment can be given by Equation 2-1.



In consumable arc systems it has been reported by Allum [71] that as it has been observed by other researchers the preferred polarity might need to change with ambient pressure other than 1 Atm [71]. It appears that self adjusting power source characteristic is required for control over the arc root behaviour [9] by maintaining the short arc lengths [5, 6, 38]. The reason is unclear [9] but experimental trials indicate that constant current operation leads in excessive spatter levels as a result of the very strong plasma jets [9]. The assumption that the size of the cathode root will depend on the welding current flow is reasonable [9]. In a constant current operation, the power source will force the amount of welding current flowing to remain the same [9]. If the availability of electron emission sites on the metal surface is low, excessive heating of a localised area occurs [9] as more electrons have to flow through a smaller surface area [in constant-current mode of operation [9]] which create strong plasma jets [9]. A self adjusting characteristic reduces the welding current flow which increases the welding voltage [9] when insufficient emission sites are available [9] allowing some control over the plasma jet formation to be maintained [9]. The degree of self-adjustment must be chosen to be such so as the level of current change for unit change in arc length is optimum and independent of the ambient pressure [1, 5, 38]. Therefore, the static slope characteristic of the power source is pressure dependent to reflect the pressure dependence of the arc voltage [1, 5, 38].

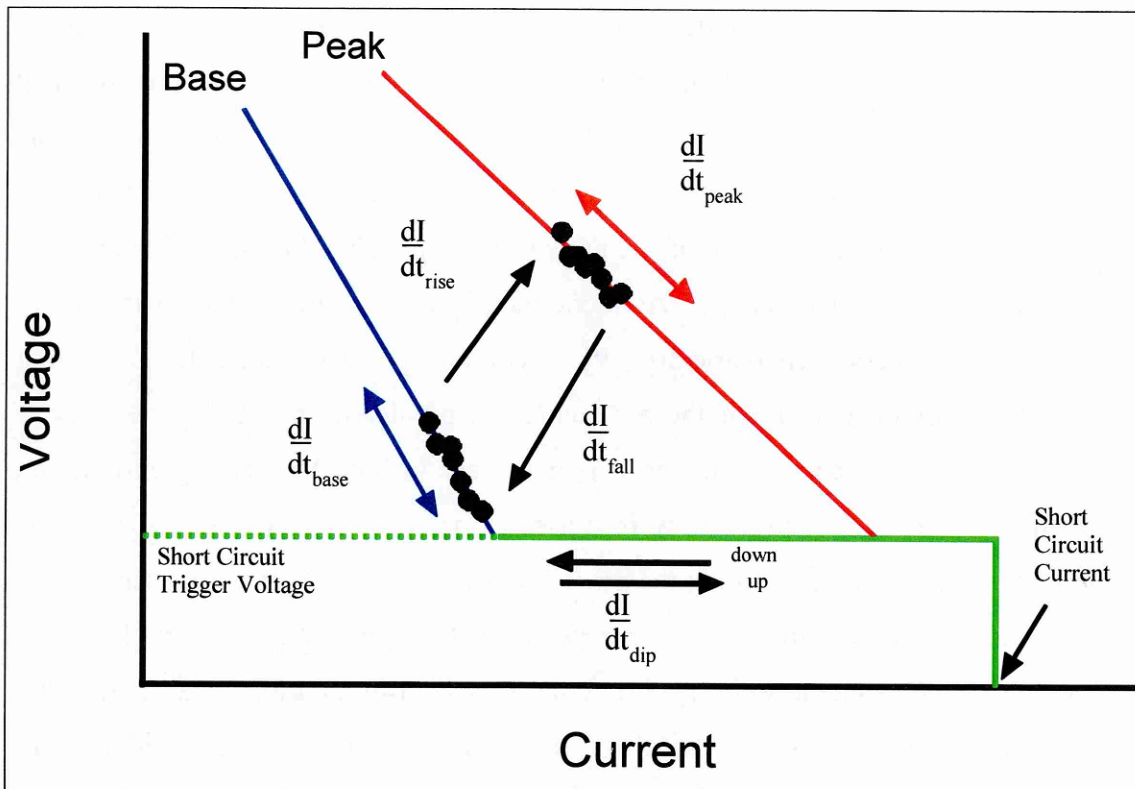


Figure 2-20 [7, 9]: Illustration of the output characteristics trend and the dynamic response conditions of a GMA hyperbaric welding power source.

$$\kappa = \frac{E_1 \times \sqrt{P}}{C}$$

Equation 2-2 [9]: Equation used to determine the required change in current for a 1 mm change in arc's length; in this case, based on the numbers given here, a 42 A change is required for correct a change of 1 mm in arc length regardless of the ambient pressure.

[E_1 : Electric field strength at 1 Atm in V/mm [in the order of 0.8 for argon, 1.8 for helium], K is the slope in $V \cdot A^{-1}$, 'C' is a constant which depends on the composition of diameter of the consumable [of the order of 42 for 0.8 mm diameter A18 grade wire].

It is important to note that as the ambient pressure rise the differences between the pulsed current operating mode and dip transfer mode based on similar static and dynamic power source characteristics are diminishing [9]. In pulsed hyperbaric GMAW arc's control is achieved based on the self-adjustment principle using the same technique as for 1 Atm GMAW [9]. With increasing pressure the power source's slope must be adjusted so that a unit change in the arc length results in a measured change in arc current regardless of the ambient pressure [9]. Figure 2-20 shows an example of the power source characteristics for hyperbaric GMAW [9]. To define the position of a characteristic, a set point and a slope must be specified [9].

The optimum slope is pressure dependent as the strength of the arc's column electric field is approximately proportional to the square root of the ambient pressure [9]; Equation 2-2 is found to hold true [9]. The operating point's position represents the intersection point of the arc's and power source's characteristics and is dependable on many factors including the type of the parent metal, the shielding gas, the wire feed rate and the wire's stick-out [9]. As mentioned in 2.2.2 short arc length is used to control the process hyperbarically [9]. Unlike the one atmosphere welding conditions, current delivery of the arc cannot be pre-determined before welding is initiated [6]. In a practical situation it is necessary to link the welding current and welding voltage so as current flow increases as arc resistance is reduced [and the opposite] resulting in maintaining the arc without its roots to contract excessively [6], otherwise process instability and excessive spatter production occurs [6]. The development of a suitable welding current delivery control algorithms has shown that GMA process is suitable for welding operations over a wide range of ambient pressures [5]. This is due to the mismatch between the relatively high frequency range of welding arc's instabilities and the lower frequency response of the weld's pool [1, 5, 6, 38]. The change in the balance of power [by controlling delivery of the welding current] also results in increased heat transfer to the parent metal resulting in reduced susceptibility to lack of fusion defects [1, 5, 6, 38].

Finally, Lythall and Gibson [69] reported that the limited capabilities of their power sources which could not supply sufficient voltage to overcome the Ohmic losses to sufficiently emulate realistic hyperbaric conditions; the power sources' limited performance could not maintain neither pulsed nor non-pulsed stable MIG conditions resulted in shorter arc lengths where the electrode was stubbing in the weld-pool with a frequency that it was increasing as the ambient pressure was increasing producing an audible effect as well [69]. It is thus concluded that for hyperbaric operations the power sources have either to be close to the area of the welding operation or to have 'extreme' performance capabilities, the second being a much more costly route. Nonetheless, at this point, Lythall and Gibson [69] mention that their experimental apparatus was not due to Ohmic losses on the welding cables and the limited capabilities of their power sources [69].

2.2.5 Shielding Gas Composition

Lythall and Gibson [69] reported that the shielding gas did not appear to have a significant effect on fume generation, spatter levels, or, arc stability [69] and that the welding arc was more unstable in the nitrogen environment [69] but they investigated the pulsed and non-pulsed MIG processes for a shallow depth range [≈ 50 msw] [69]. Therefore, the work from Richardson *et al.* [7] is considered to reflect better the hyperbaric MIG process [especially for the operating depths of the RPRS program] and as they report in [7] shielding gas composition does play an important role as presented next. In parallel with optimising pulsing characteristics, shielding gas composition can help as well [7]. A consequence of the short arc length is the reduction in voltage [7]. In general, the arc voltage increases approximately in accordance with the square root of ambient pressure [7]. Short arc lengths result in an electrode dominated voltage drop with a small arc column component [7]. This reduces the overall process power which results in weld beads with steep wetting angles [7] owe to increased heat extraction from the high pressure environment [7].

Introduction of helium rich shielding gas increases the voltage without increasing the arc length which increases the process power and helps to spread the weld bead and reduces the wetting angle [7]. The shielding gas composition has a significant effect on the surface tension and consequently on the metal transfer and spatter formation [7]. At pressures above 20 Atm, equivalent to 190 msw there is a little difference between the weld results produced with gas mixtures containing active components and the ones made with inert components based gases [7]. This, in addition to the increased spatter and reduced stability caused by excessive active additions [7] makes the operation in an inert environment more desirable [7]. Also, the operation in an inert environment [like argon [4]] is further substantiated since helium or helium based mixtures [like Heliox [4]] can increase the cooling rate, therefore can affect the mechanical properties achieved [4].

2.2.6 The Restraining Influence of Other Factors

Except from the direct influence of the ambient pressure as described above, other factors in the hyperbaric environment make the process difficult. Below is a short description of these factors as they have been reported from Håbrekke *et al.* [8].

Influence of Ambient Pressure and Magnetic Fields

Firstly, the increased ambient pressure has a fundamental effect on the arc and the voltage which is required to sustain it [8] further analysis of which has been presented already in various parts of this section [2.2]. Although introduction of suitable magnetic fields can aid arc's stabilisation [71] as reported earlier in 2.2.1, the strength of the magnetic fields can be a major problem that can cause the arc to be considerably deflected from its pre-planned trajectory [9], something that is supported from the previous theoretical approach [6, 7, 9]. Reports from operational examples attribute operational instabilities to pipe magnetism [71] and as Allum [71] reports, laboratory tests from other researchers indicate that for given arcing conditions under increased ambient pressure the welding process can become increasingly susceptible to a given magnetic field which is thought to be a result of changes in arc column and current distributions associated with the ambient pressure [71]. In order to counteract that factor, the TIG systems have been designed to have degaussing coils, which will reduce the residual magnetism of the pipes in order to allow for correct operation [8] and this approach will be implemented in the MIG RPRS. The process is also carefully monitored using cameras and the torch and wireguide is adjusted to offset any deflections that occur from remaining magnetic fields not neutralised by the degaussing coils [8]. In addition, recent MIG experimental work in Cranfield has shown that with a magnetic field up to 1,000 Gauss and pressure up to 18 Atm, the arc deflection is severe, but the arc is not extinguished, using the parameters developed for the RPRS program.

Burn of rate

A detailed description of the principles of hyperbaric GMAW process operation is outlined by Nixon *et al.* [59] from the wire burn-off rate behaviour and arc voltage perspective. The welding wire's burn-off rate must be matched to the metal transfer rate to maintain process stability [59]. In free-flight transfer, the welding wire's

burn-off rate and the consumable's feed rate match at all times and as a result a fixed arc length is achieved [59]. In dip-transfer mode of welding, the burn-off rate varies with time and results in arc length's oscillations and repetitive short-circuit events [59]. For ensuring stable operation, the mean burn-off rate and wire feed rate must match so as to ensure stable operation [59]. In the hyperbaric welding process, the electrode burn-off rate behaves in a complex manner [71]. During pulsed hyperbaric GMAW the burn-off rate can be as much as 40 % higher than the expected level based on the average welding current [59]. For electrode-positive FCAW and solid-wire MIG ambient pressure seems to have no effect on the burn-off rate [71]. For an electrode-negative MIG process, the burn-off rate increases peaking at 2 Atms to 3 Atms increase above 1 Atm [71] and then falls in such a degree so its value at 7 Atms to be less than 50 % of the value in 1 Atm [71]. As Allum [71] reports, researches have found that with SMAW process in electrode positive mode, the burn-off rate increases by 30 % for the first 4 Atms of ambient pressure increase, a behaviour that is associated with the redistribution in arc heating such that more power appears at the rod and less at the plate [71].

Influence of Reduced Visibility and Diver's Performance

Another restraining influencing factor is the reduced visibility inside the habitat [8], caused by the refraction which occurs in the vicinity of the arc by the turbulent motion of the cool gas that surrounds the plasma column [9]. Filtering the image can help [9] but this increases the complexity of the instrumentation, hence increases the cost and makes reliability an issue as it will be discussed later in optical sensors 2.4.2. The operators view is restricted to what the cameras can see. Even in the case of the PRS where the operation is diver assisted, the communication with the surface is difficult because the helium and oxygen humid atmosphere has a different density than normal atmosphere and causes the voice box of the divers to produce distorted sounds making the communication with the surface difficult [8]. On top of that, the increased ambient pressure and the limited space inside the habitat have a negative effect on diver's performance [8]. Also, due to the hyperbaric environment, there is a certain amount of time that the divers can operate and as a result, many divers are needed in different shifts in order to complete large welds [8]. This should not be an issue for RPRS since no divers will be involved and the use of two cameras should provide sufficient visual information for the operators.

2.3 MIG Hyperbaric Welding for the RPRS Program

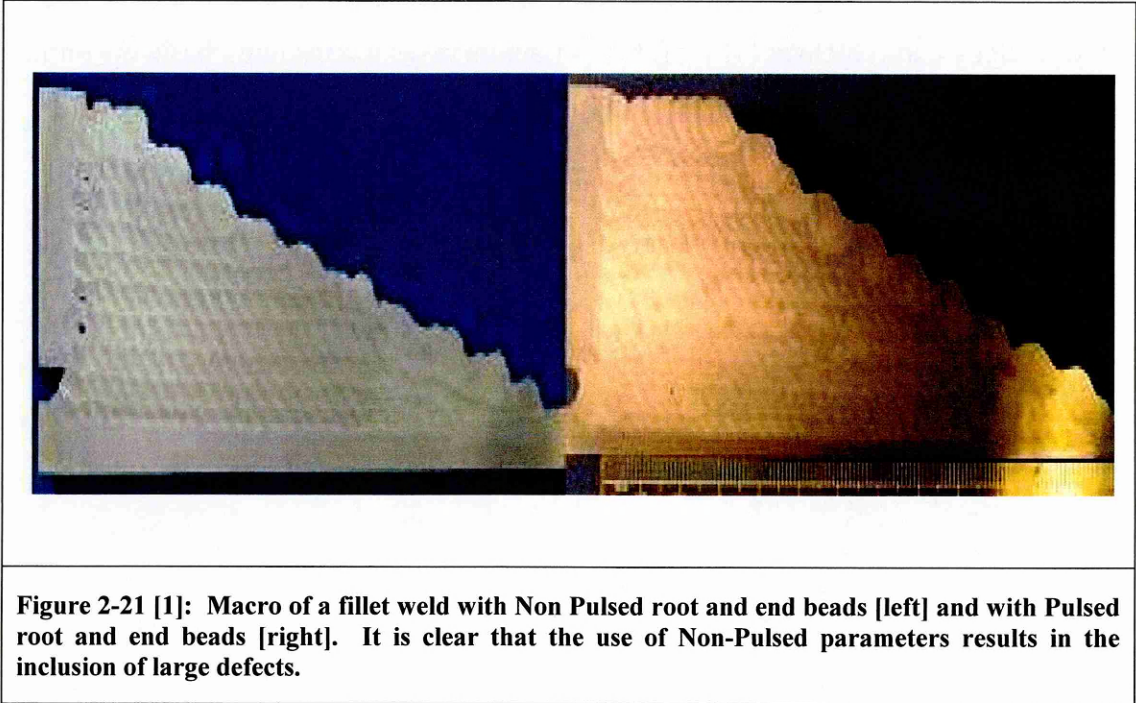
The RPRS system is designed to be used in depths of 180 msw to 370 msw in the first instance, so parameter development had to develop acceptable welds for that depth. The results of this development are summarized below.

In increased hyperbaric conditions, the arc behaviour can be stabilized by keeping the arc length constantly short and using small diameter welding consumables as mentioned earlier in 2.2.2 and 2.2.3 respectively. Key to success is the accurate and precise control of the current delivery to the arc.

It was found that the best results for the fillet welds of the RPRS program were produced by using pulsed welding [without weaving] for the first and the last pass of each layer [11, 39] and non-pulsed [with weaving] welding for the rest of the layer's passes [11, 39]. The reason for use of the pulsed stringer beads [no weaving] is that they offer improved penetration to the parent metal/sleeve interface area [1, 11] with no serious defects [11]. As a result, the voltage is kept at a higher level and subsequently the current is kept at a lower level [11] [average 24 V, 220 A [1] – 229 A [39]] and the process is virtually free of short circuits [11] operating mostly in spray mode [1]. The use of a pulsed stringer bead at the last pass gives an improved profile to the layer with smoother appearance [11, 39]. During the rest of the passes for each layer, the power source settings are set to non-pulsed behaviour [1, 11, 39] [18 V, 220 A setting [39]]. This makes the power source controller and the power sources to try and keep the process to a lower voltage and the current to a higher level [11]. This is helped by increasing the wire feed speed [1, 11] compared to the non-pulsed [11], which as a result has that the process behaves like conventional dip transfer [1, 11].

One reason to use the dip transfer mode of operation is that it reduces the spatter produced from the process [1, 11, 39] with good bead stability in the over-head position [1, 39]. This is very important considering the fact that the operation will be completely automated and that reduced spatter will prevent its accumulation on the tip

that could influence the process by altering the effective standoff, hence the voltage feedback to the power source controller and the current delivery from the power sources. However this way of transfer means that the beads tend to have steeper sides which may create defects [11], generally of the order of [0.3 mm – 0.8 mm [1]] due to lack of fusion since it is more difficult for the beads to blend with previous ones [11]. Figure 2-21 shows two macros, one with non-pulsed [left half] and one with pulsed root and end beads [right half]. It is clear that the use of non-pulsed conditions in these areas can create large defects.



Wire and Wire Feed Rate	1) mm Metal-Cored ESAB HBX Wire 7.5 m/min for 1 st Pass Stringer – Pulsed Welding 8.0 m/min for Weaved Fill Passes – Non-Pulsed Welding
Travel Speed	6.0 mm/s for 1 st Pass Stringer 6.5 mm/s for Weaved Fill Passes – 6 mm Weave Width
Build-Up Strategy	3.5 mm Over between Passes 3.5 mm Up between Layers
Power Source Control	Dedicated Controller for flexible waveform control and 3 of Fronius TPS 450 Power Source Units giving 200 V, 450 A Capable for Operating in Electrode Negative mode
Table 2-1 [1]: Basic operating parameters for 12, 3 and 6 o’clock.	

The increased travel speed during the non-pulsed weaves also influences the short-circuiting frequency and the spatter produced as well as the bead shape [11]. During parameter development, the best combination of the travel speed and the wire feed speed was selected that gave the best compromise between them to achieve the optimum metal transfer [11].

It is also important that the welds are always made vertically down starting from 12 o'clock and finishing at 6 o'clock and in such a manner so as to overlap the beads at 12 o'clock and 6 o'clock [11]. Table 2-1 summarises the resulting basic operating welding parameters.

2.4 Sensors for Arc Welding Process Monitoring and Control

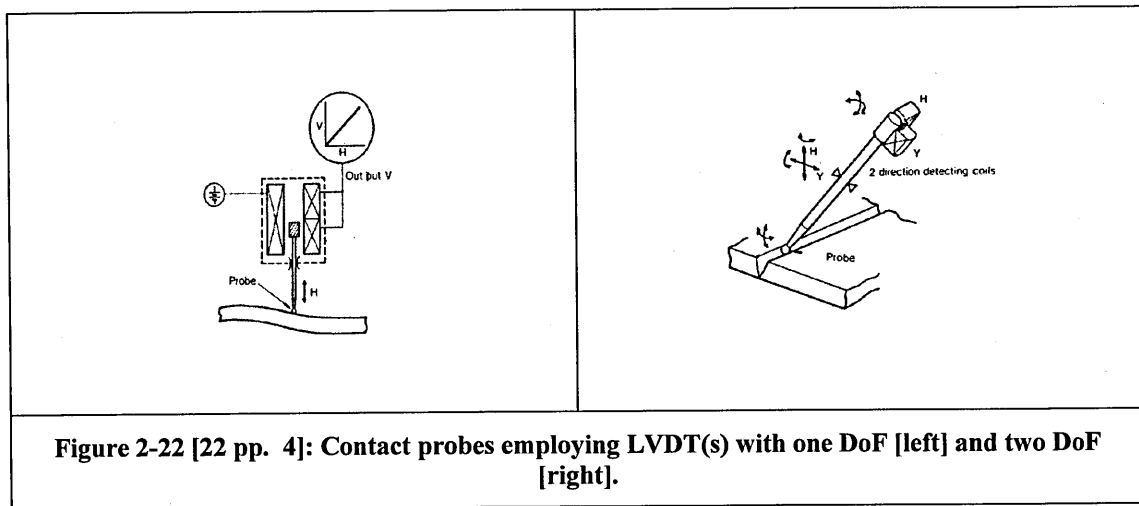
Like every process, a crucial factor for successful welding is to be able to maintain the process parameters inside their limits. Maintaining the geometry between the welding torch and the parent metal is one of the main priorities either in automatic or in manual welding. Below is a description of the various types of sensors used to detect deviation from the optimum geometrical configuration in automatic welding enabling the system or the operator to take corrective action. This description will aid the understanding of the reasons behind the selection of the dip resistance method as the sensory technique.

2.4.1 Tactile sensors

The category of tactile sensors employs some sort of a mechanical probe in contact with the parent metal [22 pp. 4] mounted in a known location relative to the welding torch forming a single system giving the ability for real time torch position feedback and control. The sensor outputs an electric signal which corresponds to the height alterations of the parent metal [22 pp. 4]. As the system moves in a known trajectory through space the parent metal variations can be mapped into a computer. Then the computer by knowing the geometry of the sensor/torch system and by knowing the rest of the parameters like the torch speed and direction can manipulate the torch height accordingly to keep the CTWD constant. Contact sensors are used in seam tracking, welding torch angle control and in detecting the width of the groove [22 pp. 18-22].

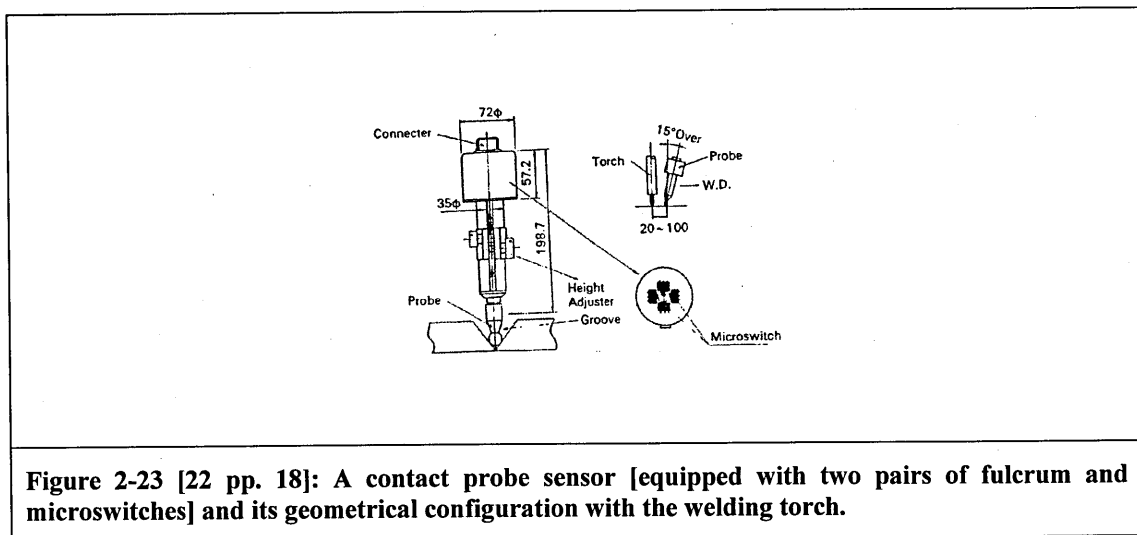
Tactile Probe's Design

The probe is designed with one or two Degrees of Freedom [DoF], as shown in Figure 2-22 [22 pp. 4]. The sensing part can output either an On/Off value based on threshold limits or a continuously variable output [22 pp. 4], as shown in Figure 2-22. The On/Off types employ limit switches which flip their output between On/Off values when the predetermined limits are exceeded [22 pp. 4]. A potentiometer or a Linear Variable Differential Transformer [LVDT] can be used to construct a sensor with continuously variable output [22 pp. 4].



Seam Tracking Using a Tactile Sensor

For seam tracking a contact probe can be used in a geometrical configuration as the one shown in Figure 2-23.

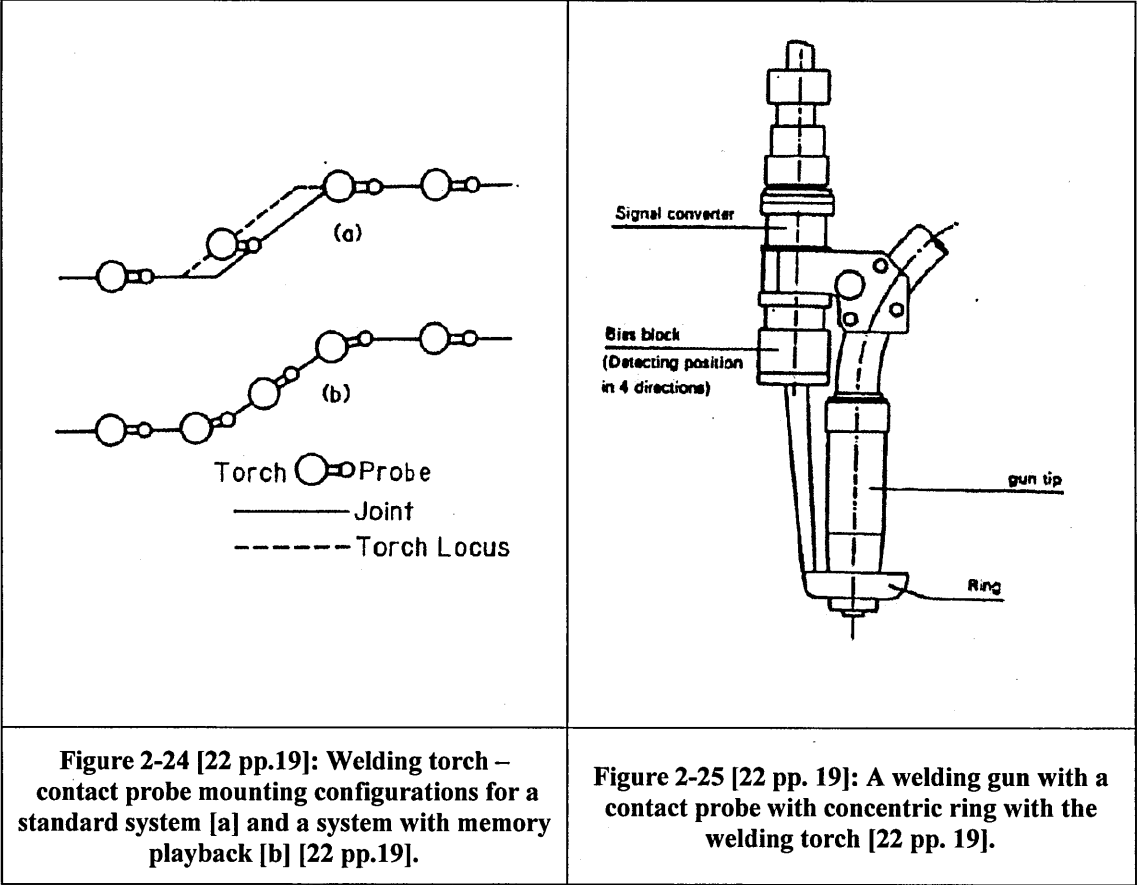


As the system moves inside the groove, the probe operates the microswitches located in its base when the displacement of the probe's tip exceeds the predetermined limits of the dead zone in which case an actuator moves the torch-probe system back to the central point [dead zone for the microswitches] [22 pp. 18-19].

Memory Playback and Sensor Preceding Types

Another way for seam tracking with a contact probe is to use a memory playback type [sensor preceding type] [22 pp. 19]. This has an advantage compared to the previous case with the sensor mounted in the front of the welding torch in a complementary system. The probe and the welding torch are mounted in different driving units with known geometry between them [22 pp. 19]. This gives the ability to trace and follow

the weld seam in every shape [22 pp. 19]; in Figure 2-24 the difference during the operation of a memory playback type, [b], and a standard system, [a], is shown. With the memory playback type, the weld seam geometrical information is stored in memory and the welding torch is moved accordingly so as to follow the trace. As shown in Figure 2-24, with a standard system if the seam has steep changes the welding torch will be out of tracking.

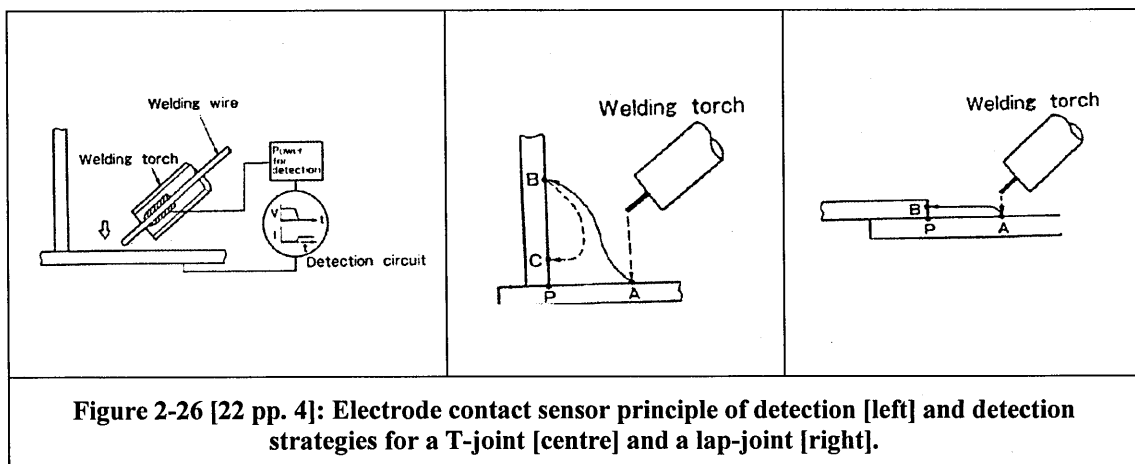


Teaching Playback Type

A parallax of the memory playback system is the teaching playback system with same principle of operation but the seam tracking is done prior to welding and the torch is driven from the pre-stored trajectory values. For more complex welding geometries a contact sensor aligned with the centre of the torch is used like the one in Figure 2-25; here, a ring with contact section concentric with the welding torch is used [22 pp. 19]. The electromechanical operation remains the same but this geometrical configuration allows the sensor to be pushed into contact with both members of the joint in fillet and V-groove butt welding [22 pp. 19].

Wire-Touch Type

Finally, for seam tracking, it is possible to avoid the use of a mechanical probe by using the filler wire itself to detect the geometry of the welding area as illustrated in Figure 2-26. This type of sensor is called [22 pp. 4] wire touch, wire earth or touch sensor; the method has been developed for welding robots and effectively detects the deviation between a taught point in the robot path and the actual location of the joint at that point [22 pp. 20]. This allows either to find the start of the weld line and then to track the seam using another sensor during welding, or, to find both ends of the weld line and then to adjust the pre-programmed robot trajectory to match the actual geometry. The tactic of detection is to extend the filler wire by a known length and to move the torch accordingly until the wire touches at least one spot in each surface [22]. Contact with the parent metal is confirmed by detecting the small current flowing through the filler wire when applying a driving signal of 300 V to 600 V at 50 Hz to 600 Hz [22 pp. 4]. Since the electrical resistance of the filler wire influences the value of current flowing, its extension may be controlled automatically by cutting before sensing commences, or by detecting the length of the extension by comparing it with a reference point [22 pp. 4-5]; for added accuracy of the estimated coordinates a wire lock mechanism is installed [22 pp. 5]. For the case of a right angle seam, two contact points are required [one on each surface] and the tip of the filler wire is positioned so as to bisect the right angle [22 pp. 20]. A four-point method can be employed to detect surface intersection angles other than 90° or for the detection of the end of the components [22 pp. 20].



Torch Angle Control Using A Tactile Sensor

Contact sensors can also be used for torch angle control. Figure 2-27 shows such a configuration where two styluses control the position of the wipers for the two potentiometers inside the sensor casing [22 pp. 21]. The styluses are positioned slightly separated from each other in the welding direction [22 pp. 21]. The sensor is mounted with the welding torch in a single system [22 pp. 21]. In a flat surface, the styluses maintain the wipers at the same level hence no difference appears in the output of the two potentiometers [22 pp. 21]. When inclination occurs the output of the two potentiometers changes and a suitable actuator can be used so as to maintain the torch vertical [22 pp. 21], or, at any other desired angle.

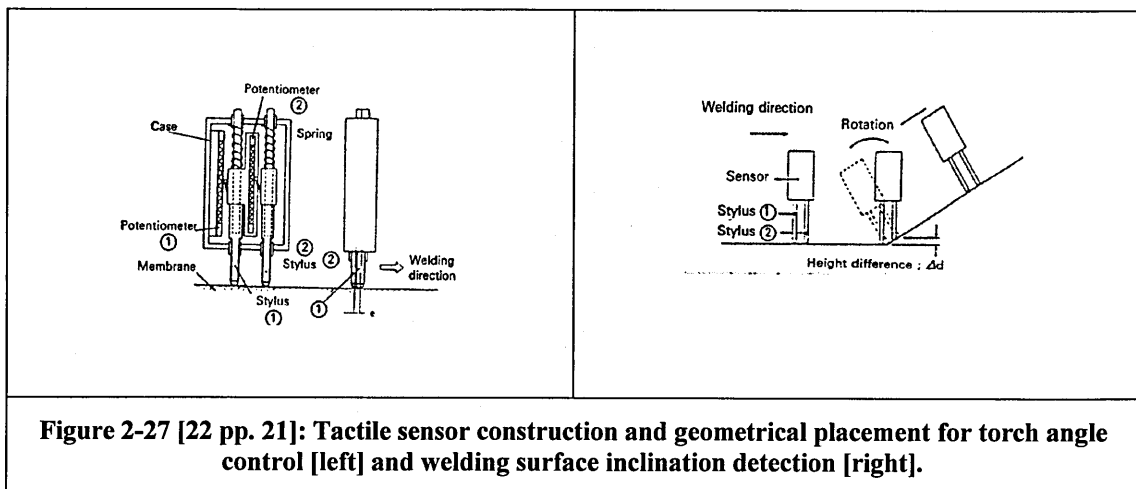
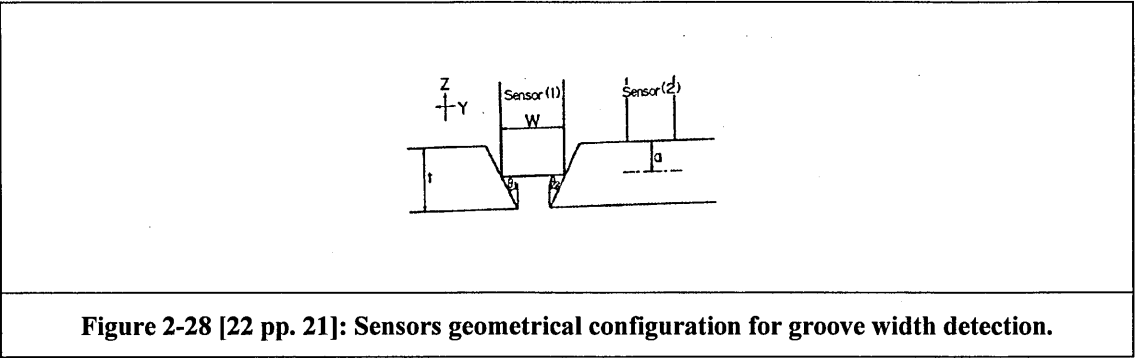


Figure 2-27 [22 pp. 21]: Tactile sensor construction and geometrical placement for torch angle control [left] and welding surface inclination detection [right].

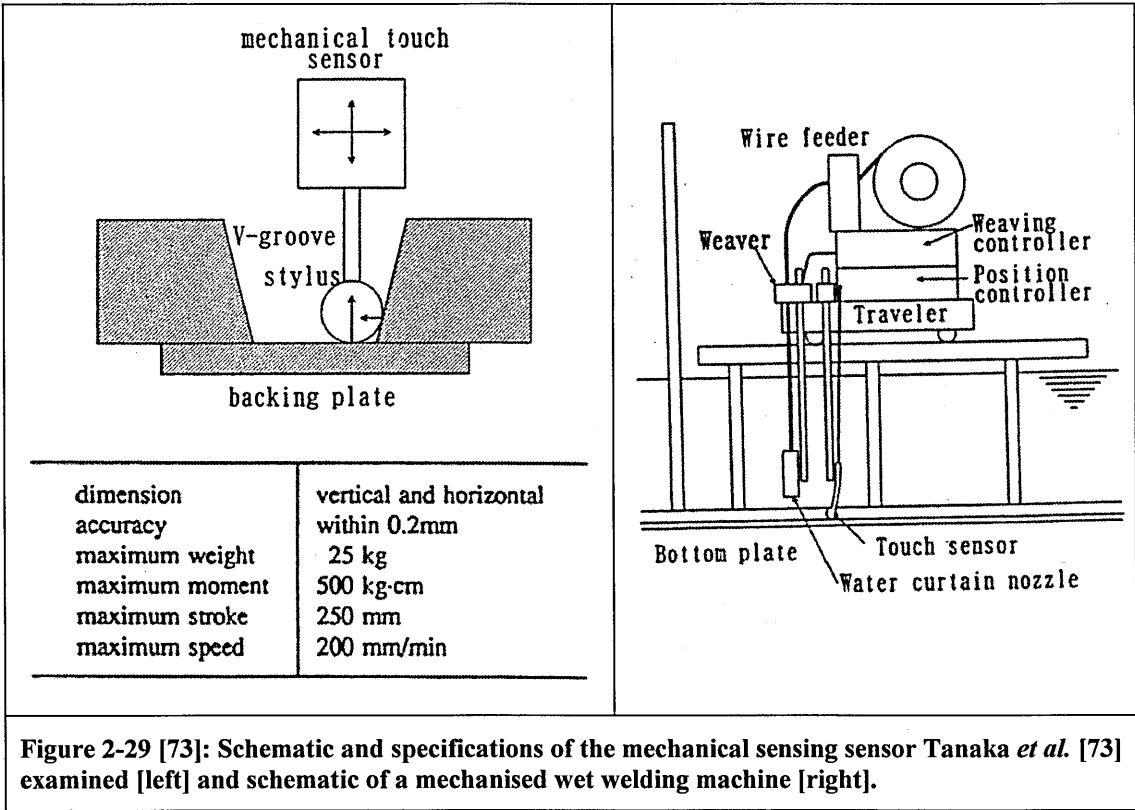
Groove Width Detection Using a Tactile Sensor

For groove width detection a similar type of sensor configuration is used as shown in Figure 2-28 [22 pp. 22]. In this case sensor 1 is the groove tracing sensor and its roller is inserted in the groove whilst sensor 2 is used to compensate for material deformation [22 pp. 22]. From the differential depth information obtained from the sensors and the groove angles θ_1 and θ_2 the groove width and its cross-sectional area can be calculated [22 pp. 22].

Tanaka *et al.* [73] examined the mechanical sensing technique for use in the Mega-Float structure [73] in wet conditions [73]. The mechanical sensing system's schematic and its selected specifications are shown in the left part of Figure 2-29 [73]. The system shown is an established method for mechanised welding in 1 Atm [73]. The probe touches the root and the sidewall of the groove [73].



The system controls the position of the stylus so as the vertical and horizontal touching pressures to be within the design specifications at all times [73]. The specifications shown in the left part of Figure 2-29 are for used tactile sensors [73]. The probe's radius is an important factor for accurate seam tracking and Tanaka *et al.* [73] have chosen this value based on their experience [73]. In general, sensing ability on root gap width is required for fully mechanised process [73]. The right part of Figure 2-29 shows a mechanised wet welding machine with mechanical touch sensor [73]. As shown, a water curtain method has been chosen.



Tanaka *et al.* [73] determined the weaving width and the relative torch position before the welding process [73]. The weld line was straight and the root gap was almost constant and no tacked weld bead existed in the groove [73]; this allowed successful welds to be achieved for all trials [73]. As Tanaka *et al.* [73] report, “a flexible

shelter against spattering was attached behind the sensor to avoid miss-operation of seam tracking by adhered sputters on the groove surface [73]”.

Summary of Tactile Sensor's Features

Tactile sensing is a simple and inexpensive technique and the added complexity for a real time system is not significant. Nonetheless it has the disadvantage of added hardware which requires that the geometry of the torch and the probe(s) must be extremely precise, something that in practise, hyperbarically, might be difficult to maintain. Reasons are changes of the geometry due to gravity, water currents, movement of the system around the pipe which changes the centre of gravity or misalignment of the torch during welding due to an error which might even require the system to be recalibrated whilst submerged or even salvaged for repair. Use of the filler wire as the probe is very attractive as an idea but the need for sensing prior to welding cannot take into account disturbances occurring during welding and it does require additional hardware to cut and lock the position of the wire before sensing. It should be noted that in the RPRS's case, spatter accumulated over many welding passes on the probe or the parent metal and sleeve itself can influence the detection causing errors. This was addressed by Tanaka *et al.* [73] using a flexible shelter which leads to the conclusion that, indeed, spatter can influence the accuracy of detection, especially when spatter levels accumulate over a number of weld passes like in the case of a fillet weld for the RPRS. The addition of a flexible shelter for use in RPRS constitutes extra hardware, one more possible area that something might go wrong, and it could make visual observation even more problematic. In addition to that, Tanaka *et al.* [73] report that the mechanical touch sensor is an established method for a well-prepared groove face and offers reliability and durability when the groove line is well prepared, otherwise exact observation of the weld groove geometry if required before welding [73]. This can be a problem for RPRS since after each pass the geometry could be slightly altered due to the weld bead appearance and accumulated spatter, therefore the geometry should be re-examined and mapped for each pass.

2.4.2 Optical Sensors

These sensors can be active or passive. Active are the sensors that emit a light signal and a light detector senses the reflection. Passive are the sensors that use the process' visual information and the ambient light' reflection as input signals to be detected from light detectors. An example of an active sensor is the LASER stripe sensor. An example of a passive sensor is the use of a camera without active luminance of some sort on the welding area. The advantage of active sensors is that they can be quite accurate and do not depend on external stimuli. The advantage of passive sensors is simplicity and lower cost in comparison with the active ones and in some cases, as with the use of cameras, the same sensor can be used to detect more than one parameter. A disadvantage for both, active and passive optical sensors is the need for proper alignment of the sensing system with the rest of the welding material and apparatus so as to aid correct detection. Coupled with the increased cost and performance susceptibility from smoke, spatter and arc radiation forcing to preview the joint before welding [32] and not in real time is also a significant drawback.

The use of optical sensors allows various control systems to be constructed for detection and control of tacking beads, welding start and end points, wire tip position, seam tracking and torch height control as well as in adaptive control of welding conditions [22 pp. 11].

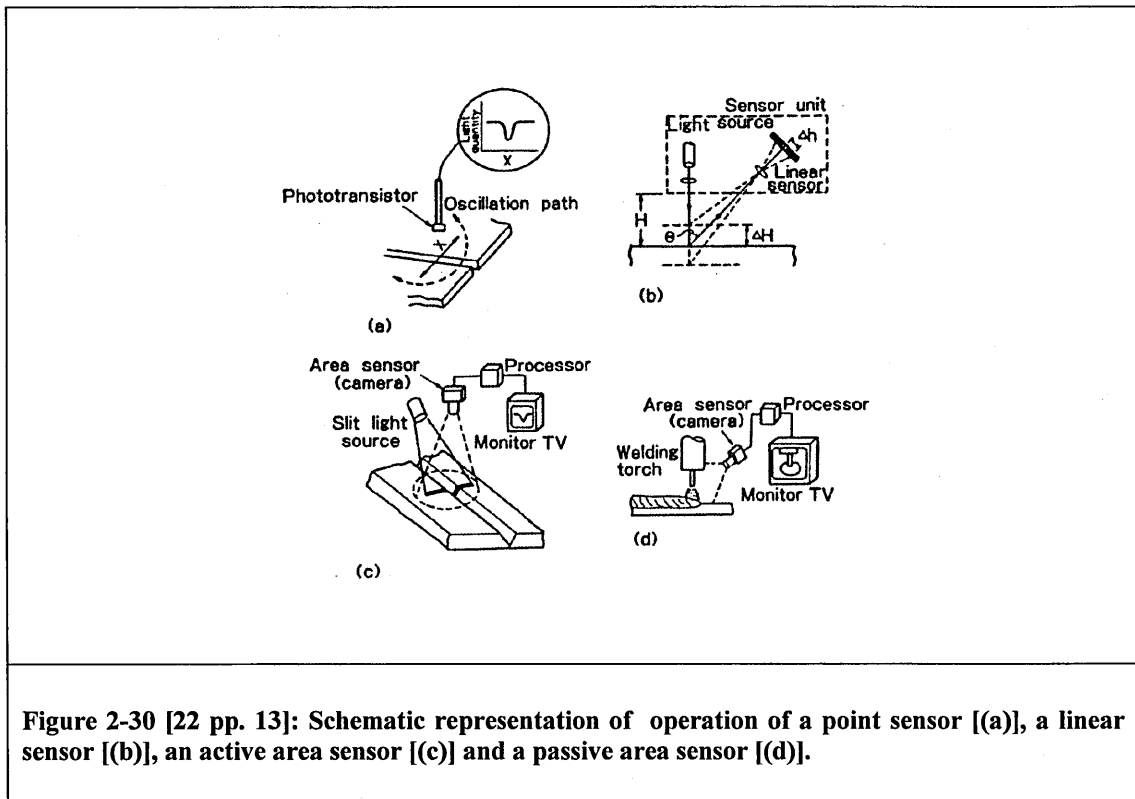
Optical Sensors Categories

Optical sensors capable of detecting light in the visible spectrum or LASER radiation are classified by the shape of their light-receiving surfaces into three main categories [22 pp. 6, 26]. The first category is Point Sensors which uses a photosensitive device like a photodiode or a phototransistor and detect a point light source which is detected or emitted from a material providing a discrete On/Off or continuously variable [analogue] output [22 pp. 7]. The second category is Linear Sensors [also known as light cutting [73]] designed to detect a line of light reflected or emitted from a surface in one dimension [22 pp. 7]; they can be constructed by several point sensors assembled as a linear array [22 pp. 7]. Depending on their type a discrete On/Off output [22 pp. 7] or an analogue output [22 pp. 7] can be provided. The third category

includes the Area [Image] Sensors designed to detect reflected or emitted light from a surface in two dimensions assembled in two dimensions [22 pp. 7]; again, depending on the sensors' type a discrete On/Off or analogue output can be obtained. However, according to Satoru [26], in practice optical sensors are divided into LASER [Light Amplification by Stimulated Emission of Radiation] sensors used to detect reflected LASER beam(s) and visual sensors which observe directly using Charged Coupled Device [CCD] based cameras [26].

Principles of Operation of Optical Sensor's Categories

In the top left [part (a)] of Figure 2-30 a point sensor is shown [also known as spot beam sensor [26] or, more commonly, the LASER displacement gauge [26]], which operates by oscillating or rotating a point sensor [22 pp. 11]; as the sensor moves the amount of light received by it changes depending on the geometry of the surface [22 pp. 11] [assuming homogenous surface reflectivity] which allows the position of the sensor at each given point in time in relation to the parent metal to be detected by processing the amount of light received [22 pp. 11]. The top right of Figure 2-30 [part (b)] shows a linear sensor. In such a sensor a point source of light [transmitter] illuminates the parent metal surface with a stripe of light and its reflection is picked up by a linear sensor [receiver] arranged at a fixed angle ' θ ' [22 pp. 11]. The stripe of light can be obtained via a cylindrical lens or by oscillation of a mirror in a light channel [22 pp. 34]. Both the transmitter and receiver are installed in the same housing [22 pp. 11]. The principle of operation is based on the principle of the linear displacement by Δh of the reflected light on the receiver's surface for a displacement of ΔH of the reflection surface [parent metal] from the transmitter [22 pp. 11]. By controlling the height of the torch whilst detecting the height of the sensor from the parent metal as the sensor is oscillated or rotated the geometry of the parent metal can be detected [22 pp. 11] [again, assuming homogenous light reflectivity]. Finally, an area sensor is constructed by replacing the detector of a line sensor with a camera which feeds information to a processor which then analyses the picture to detect the morphology as shown in Figure 2-30 [part (c)] [22 pp. 13]. Alternatively a passive area sensor with no transmitter can be used where the camera monitors the welding process and the processor analyses the information [22 pp. 13] as shown in Figure 2-30 [part (d)].



Active Optical Sensors

Active optical sensors have quite significant practical limitations. The point sensor produces errors because the surface condition can easily affect the reflective light [26] which can be compensated with the use of a camera as the light receptor but scanning an area has also limits in the speed of detection and precision [26] and high speed scanning using a mirror is preferred. Additionally, the surface condition also influences the measurement thus extra care must be taken [26]. Finally, measuring near the welding arc is impossible [26]. The use of a CCD camera and a slit sensor is a much better option but requires image processing making the task even more complex and costly [26].

Passive Optical Sensors

Passive optical sensors enable detection of features such as dimensions of the work pieces, defects and temperature directly from the brightness and colour information taking advantage of filtering and image processing techniques [26]. In order to enable the use of a passive visual sensor in welding it is necessary to acquire clear images of the features wished to be measured under the presence of arc light [26]. This requires

the use of optical filters, timing control of the shutter or using a wide dynamic range sensor [26].

Requirements for Camera Application

Depending on the welding method, various methods have been employed to enable use of a camera. Accurate control of the shutter timing might be required so as image acquisition to occur when arc light is at its minimum and its influence is minimised as well as optical filters [26]. Other methods use momentarily reduction of the welding current during shutter opening or measuring different features during the peak and base periods of the welding current cycle [26], such as groove detection during peak period and molten pool during the base period [26]. Figure 2-31 shows a timing diagram of the events taking place when the technique of momentarily reduction of the welding current is employed [26]. In this case the shutter opens only for 1 ms at which point the welding current drops below the base value of 60 A down to 20 A.

As different welding parameters produce optical information at different areas of the electromagnetic spectrum [wavelength] the filters are selected based on the parameter desired to be measured [26]. Figure 2-32 shows the different spectral characteristics of the arc light and the molten pool light require the use of specialised band pass and band stop filters in combination so as to “bring” the parameter wished to be measured in the dynamic range of the sensor.

Physical factors, like spatter and camera fixing location, also pose difficulties [26]. As shown in Figure 2-33 where a spatter sticking preventive mechanism is employed [26], the size of the sensor assembly becomes significantly larger than the original size of the camera itself making the situation even worst for most cases since the assembly needs to be moved along the welding path [26].

Visual sensing is an essential feature of an intelligent robot [73]; however, for underwater wet welding it might be difficult to keep the welding area clean [73]. The use of a water curtain also disturbs the visibility of the welding area since it is completely covered by the high-speed water curtain and the fine bubbles of the

shielding gas which are released at the out-skirt of the water curtain, on the work plate [73]. A suitable way would be to use a fiber-scope technique, inlaid inside the nozzle which requires sophisticated techniques but makes accurate detection of the groove face possible together with allowing observation of the welding conditions [73].

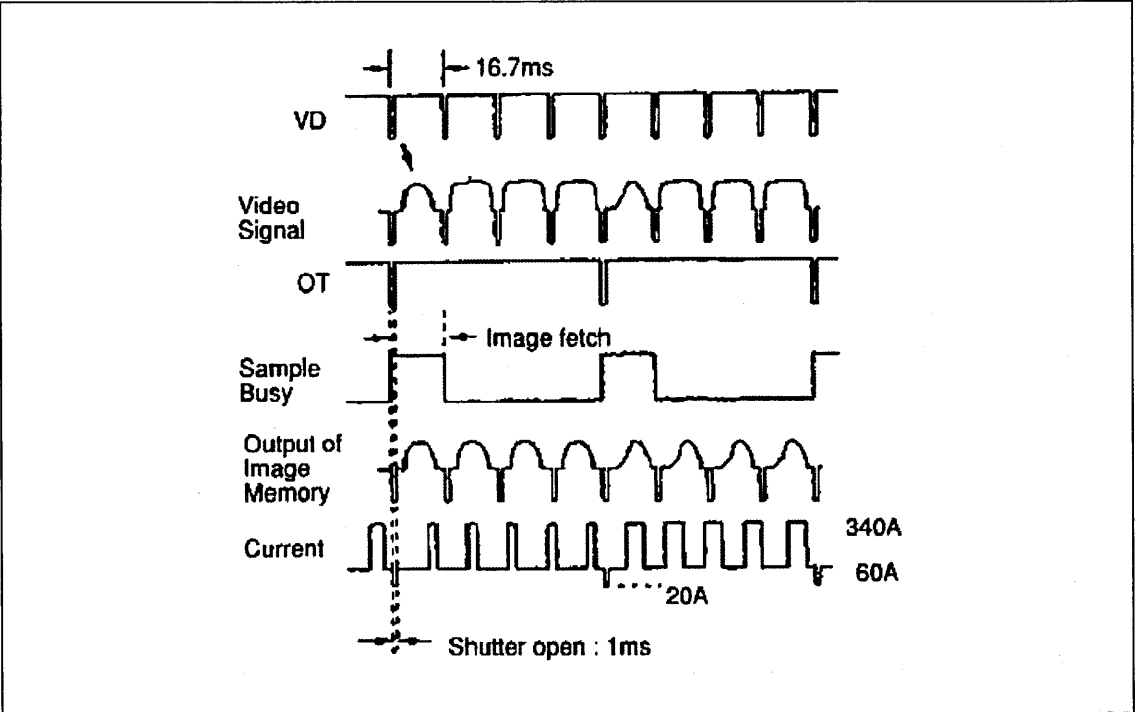


Figure 2-31 [26]: A timing diagram for a system utilising momentarily reduction of the welding current below its base value during shutter opening.

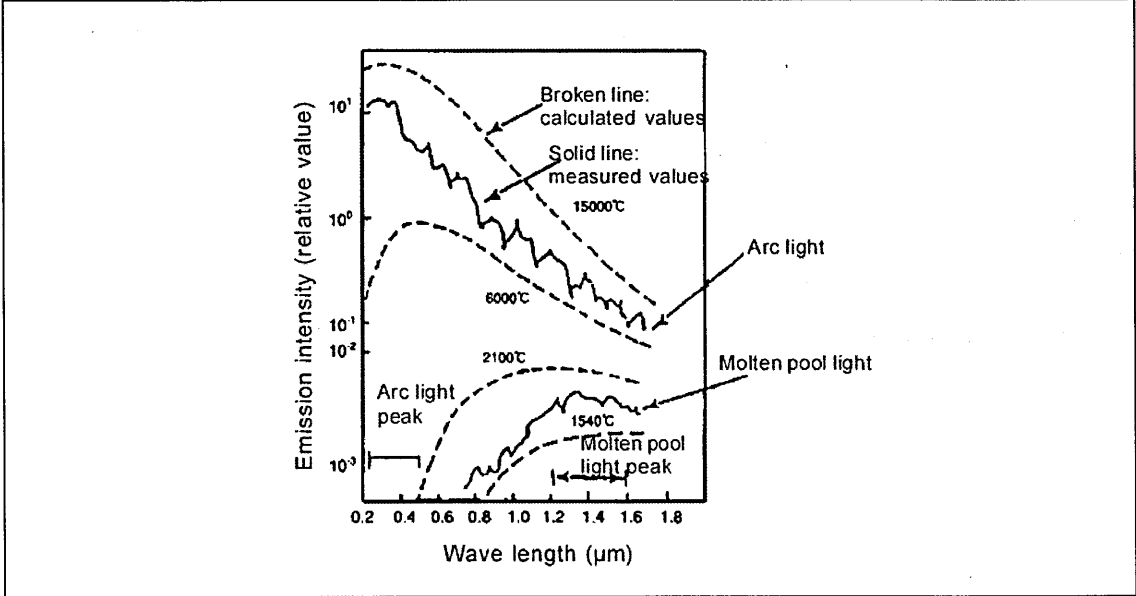


Figure 2-32 [26]: The spectral characteristics of the arc light and the molten pool light.

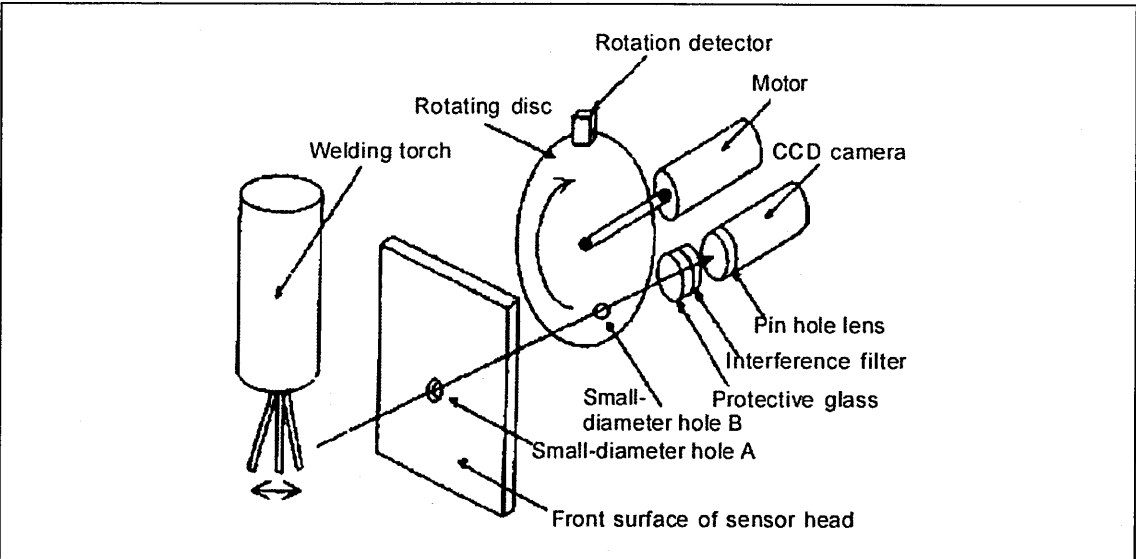


Figure 2-33 [26]: The various accessories required to enable the use of a camera in welding applications make its physical implementation and control operation a complex task.

Tanaka *et al.* [73] used a fiber-scope system in wet welding conditions, shown in the left part of Figure 2-34 [73] where additional water flow along the axis of the video camera was employed to avoid disturbance of observation from muddy water, high-speed flow of curtain water and fine bubbles from the shielding gas of the welding nozzle [73]. Another way of installing the fiber-scope is shown in the right part of Figure 2-34 [73]. Here, the fibre-scope is installed inside the welding nozzle which eliminates the problems of influence from the water curtain and the fine bubbles of shielding gas [73]. However, there are still many structural difficulties [73], as an active system such as the linear sensor is difficult to be installed and a passive system is the only available option [73]. The proximity of the sensor to the welding area makes possible to damage the sensing system due to the increased temperature of the welding arc and spatter from the welding process [73].

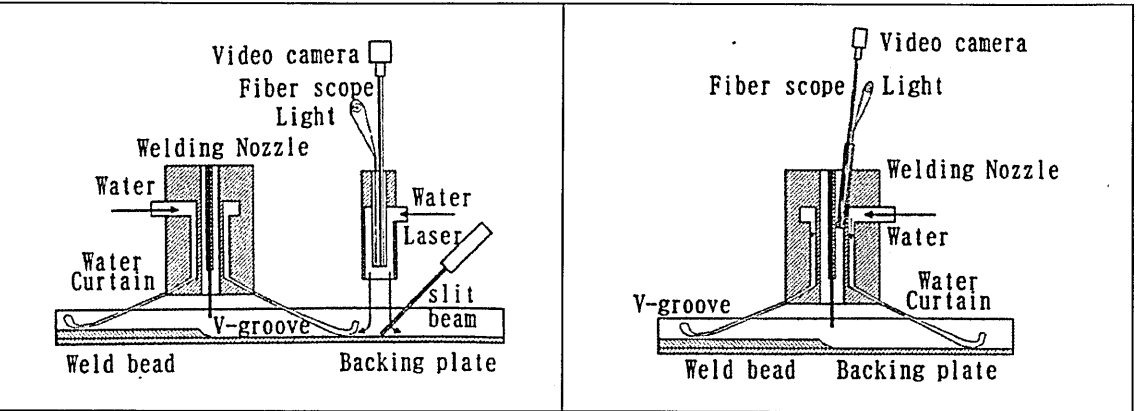


Figure 2-34 [73]: The visual sensing method used by Tanaka *et al.* [73] where the fiber-scope was installed outside of the welding nozzle [left] and the method by Tanaka *et al.* [73] where the fiber-based system was located inside the welding nozzle [right].

For deepwater the requirements of a vision systems are very specific due to the operating pressure and housing requirements [6], the welding environment and the flexibility in design for general set-up and arc viewing [6]. For optimising design it is necessary to consider designing and implementing the camera, filter and housing components directly attached onto the weld-head [6].

Summary of Optical Sensor's Features

An optical sensor, especially the use of a camera, is probably the most flexible sensor since it can satisfy various measuring needs even in real time. The hyperbaric system already includes two viewing cameras, however, the development of a suitable processing algorithm coupled with the need for vibration-free positioning of the camera during orbital welding and the need for additional optical filters reduces the attractiveness of this approach for purposes other than arc viewing and process monitoring and verification.

2.4.3 Temperature Sensors

These sensors are used in adaptive control of the welding conditions aiming to optimise the welding bead shape or penetration bead shape [22 pp. 5]. They can be of contact type, like thermocouples and thermistors or of non contact type such as pyrometers [also known as radiation thermometers [20], or light thermometers [22 pp. 5]] and infrared thermometers [22 pp. 5, 26] which are a sub-category of the pyrometers [20] and explained further in the Visual Temperature sensors section. The use of these sensors allows the temperature in or near the weld to be measured [22 pp. 5]. These types of sensors do not allow easy and accurate detection of the torch position except for the case of the visual temperature sensor presented next.

Visual Temperature sensors

These sensors use Infrared Radiation [IR] to detect the heat from the arc and the welding surfaces in order to extract the information and recreate an image in the IR spectrum. Processing of these images allows detection of the position of the torch and wire insertion and changes in the bead width [26]. Their operation is based on the principle that the arc should be used under conditions which make it act as a constant and repeatable power [energy/heat] input to the welding surfaces [24, 27]. Therefore,

any deviation from the target arc power would indicate a change in one or more conditions and subsequently the process behaviour and process results [heat intensity of the arc] and counteraction measures could be taken. These systems are designed to monitor the heating and cooling rates of the welded joints and enable the control of them so as to remain within their optimum ranges [26, 27]. Figure 2-35 shows the geometrical configuration used by Chin *et al.* [27], to examine the feasibility of using a thermo-vision system. In Figure 2-36 a thermal image of the welding process is shown when the arc is located in the middle of the seam with its corresponding temperature vs. distance scan [27] and Figure 2-37 shows the alteration in the result when the arc is not located in the middle of the seam [27]. As shown by the thermal images and the temperature vs. distance scans, the error in the arc location can be detected hence corrective action(s) can be taken to compensate.

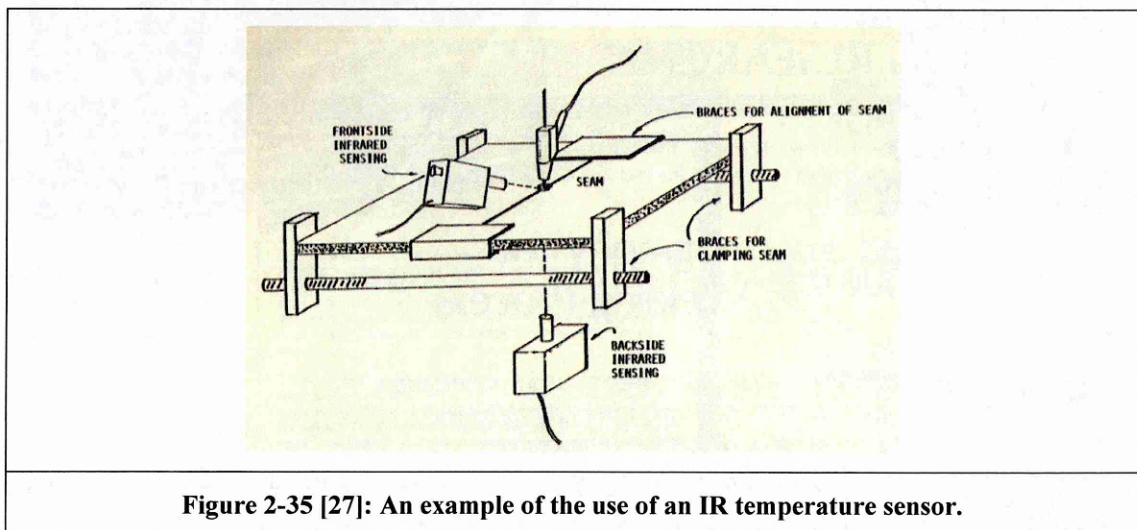
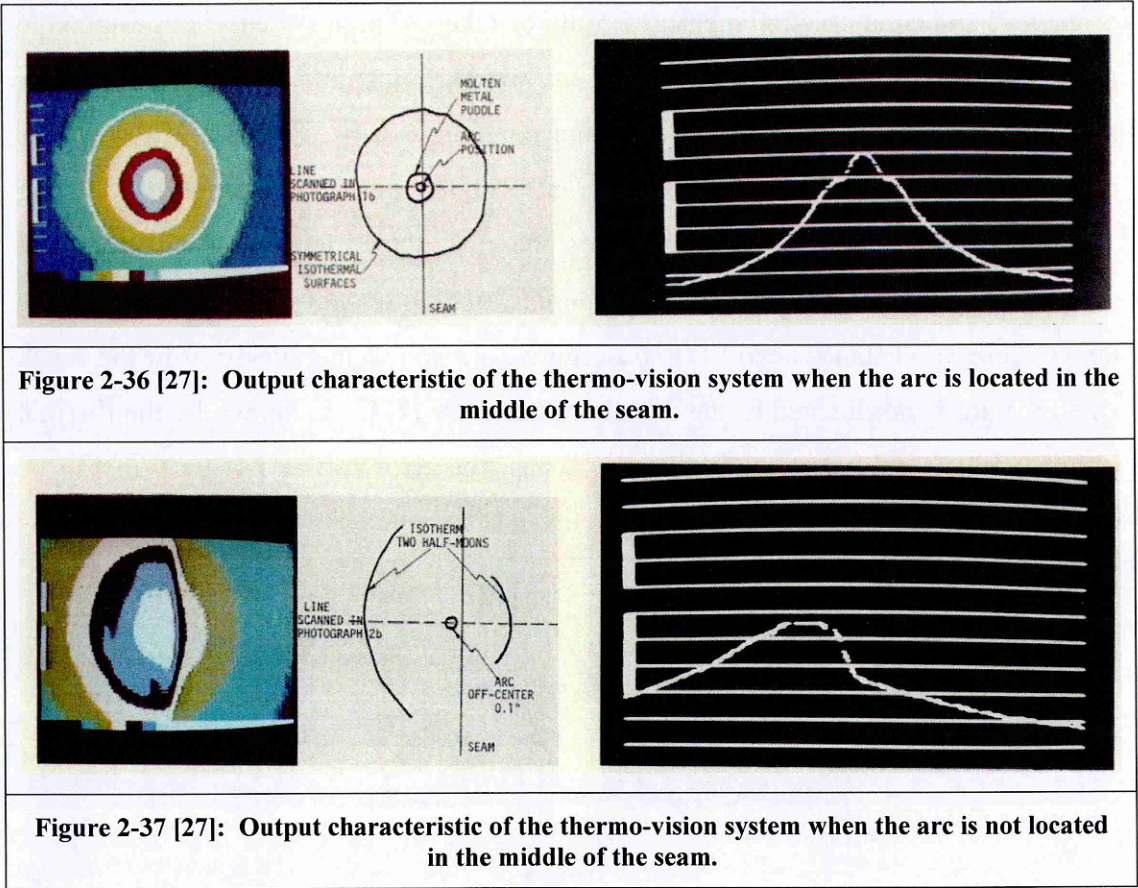


Figure 2-35 [27]: An example of the use of an IR temperature sensor.

Although IR emission measurement in general is influenced by the thermal emissivity of the welded members [26], the effect of varied emissivity on cooling speed is small enough to be considered insignificant for practical reasons [26] but surface condition also influences the measurement [24] as well as arc light which necessitates the use of filters for selective viewing of the spectrum [24]. Ultraviolet Radiation (UVR) has been proposed as an alternative method for temperature measurement since it is generally unaffected by emissivity and is effective for measuring high temperatures [26]. Another limitation of thermo-vision [26] systems is that it is not possible to produce visible information so as to extract characteristic quantitative data as in the case of visual sensors [26]. Finally, like optical sensors, IR optical sensors are big in size making it difficult to be employed [26] as they generally need to be moved along

the path of the heat source [26]. The advantages and disadvantages for thermal visual sensing are the same as in the case of the optical sensors.



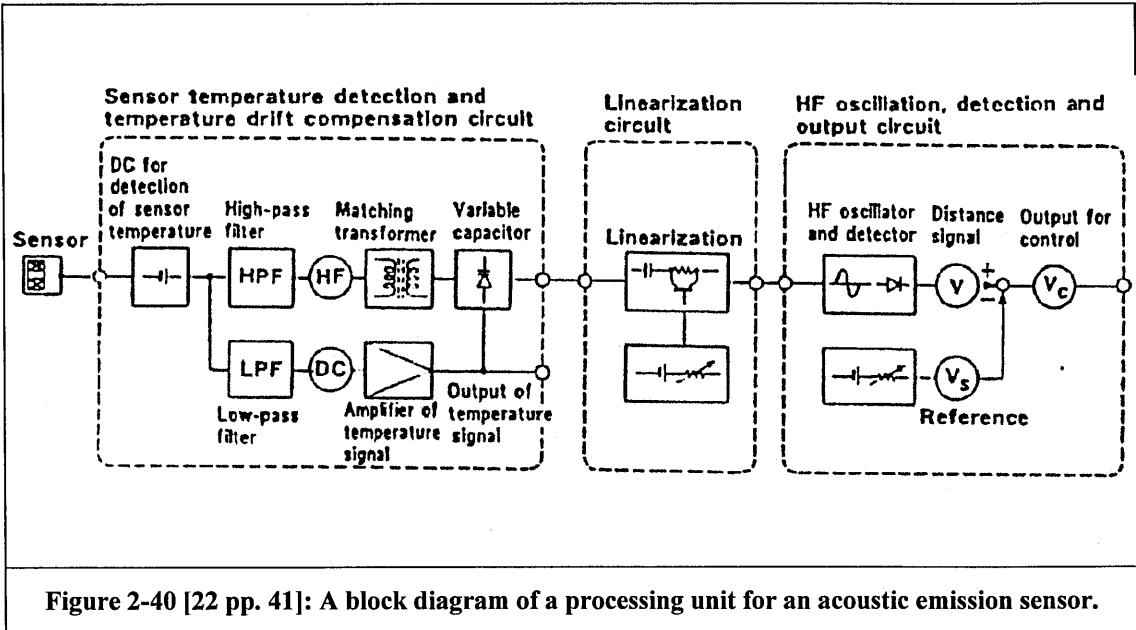
2.4.4 Acoustic emission sensors

It has been reported that the arc welding acoustic “noise” differs according to various welding parameters [23], hence the acoustic signals can be used to assess process stability and detection of welding conditions resulting in weld defects [23] in dry or submerged arc welding [23]. Welding arc’s stability measurements have been shown to be possible by Chawla *et al.* [67]. Experienced skilled welders can evaluate the arc welding process’ performance just by listening to the sounds generated [23, 67, 68]. An instructor should be able to distinguish between an experienced and a novice welder just via the arc sound information [67]. In a GMAW process these signals contain information for the arc column behaviour, the molten pool and the droplet transfer [23]. Most MIG welding processes generate sound in the 70 dB range [67]. The sensors are constructed using microphones as the transducer element to capture the sounds [22 pp. 7] and import them in a processing unit so as to extract the information required. Information generated inside the parent metal owing to the

The diagram illustrates the experimental setup for the proposed system. It features a Power Source connected to a Wire feeder and a Tacho. The Wire feeder is connected to a Torch, which is connected to an Arc. The Arc is connected to a Work Piece, which is connected to a Moving Table. A microphone is connected to a Signal Conditioning & Isolation Interface (Volte Amps WFR CH4). This interface is connected to an A/D Board, which is then connected to a PC. The PC is shown displaying a bar chart on its monitor.

In a typical system a microphone is used which is located 400 mm [22 pp. 41] from the arc point [120 mm for TIG welding] [22 pp. 41]; the distance, which as mentioned varies greatly between different processes, is important as it needs to be optimised so as the amplitude of the sound pressure waves to enable adequate S/N ratio [22 pp. 41].

Typical systems are shown in Figure 2-38 and Figure 2-39. The different indices for detection are the acoustic wave type, the spectrum's width, correlation function [self-correlation and/or mutual correlation] and periodicity [22 pp. 41]. Besides the information contained in the audible spectrum the information on the supersonic spectrum can be explored [22 pp. 41] as well as the information contained in the whole acoustic band and the welding phenomena that generate it [22 pp. 41]. Figure 2-40 shows a block diagram of a processing unit for an acoustic emission sensor.



It is sensible then to use this audible information to detect and control various welding parameters including but not limited to CTWD and welding arc's length. It is a very interesting idea but the disadvantage is that acoustic waves are easily to be influenced from background noise [67], so it might not be suitable for any environment. There are advanced signal processing techniques that could be employed to distinguish and extract the relevant information but this increases the complexity and subsequently the cost of the method.

2.4.5 Proximity Ranging Sensors

These, active sensors emit either an electromagnetic signal [electromagnetic wave] or an Ultrasonic Signal [pressure wave] and detect the reflection of it. In welding the ultrasonic sensors tend to be used avoiding the more complex radio frequency grade instrumentation for handling high-frequency electromagnetic signals. The electromagnetic sensors are classified in two categories, the capacitance type and the Eddy current type [22 pp. 39]. The capacitance type is greatly affected by the flatness or parallelism of the surface to be detected thus there is the tendency to be avoided for welding applications [22 pp. 39].

Ultrasonic Ranging Sensors

The principle of operation of ultrasonic ranging is based on the principle *“that the propagation interval for the ultrasound in air is related to the distance between the ultrasound source and the reflection point and the distance between the reflection point and the receiver”* [32]. In the ultrasonic’s field, work is focused towards measuring distance and azimuth between the torch and the welding location [28]. Researchers have examined the use of ultrasonic sensors in frequencies below 100 kHz and their use for seam tracking in arc welding has been demonstrated [32]. However, in general, the lower the frequency the higher the width and the wavelength of the ultrasonic beam which results in lower resolution [32]. For satisfactory resolution an operating frequency of 700 kHz is required [28] but besides the difficulties imposed by atmospheric conditions [28] which significantly decay the ultrasonic signal [32] the arc welding process produces significant ultrasonic energy [28] as noise mainly concentrated below 1 MHz [32]; as a result, the S/N ratio makes the situation even more complicated. In order to overcome these problems sophisticated systems must be used [28] which complicate the implementation of such systems. Zhang *et al.* [32] developed a seam tracking system using ultrasonic ranging operating at 1.15 MHz resulting in a diameter of the sonic beam below 0.5 mm enabling the use of the system for seam tracking of nearly any type without the need for grooves or wide gaps [32]. The system shown in Figure 2-41 was used by Zhang *et al.* [32] to study and improve an ultrasonic ranging system. As shown, a mechanised system is required so as to scan the whole surface.

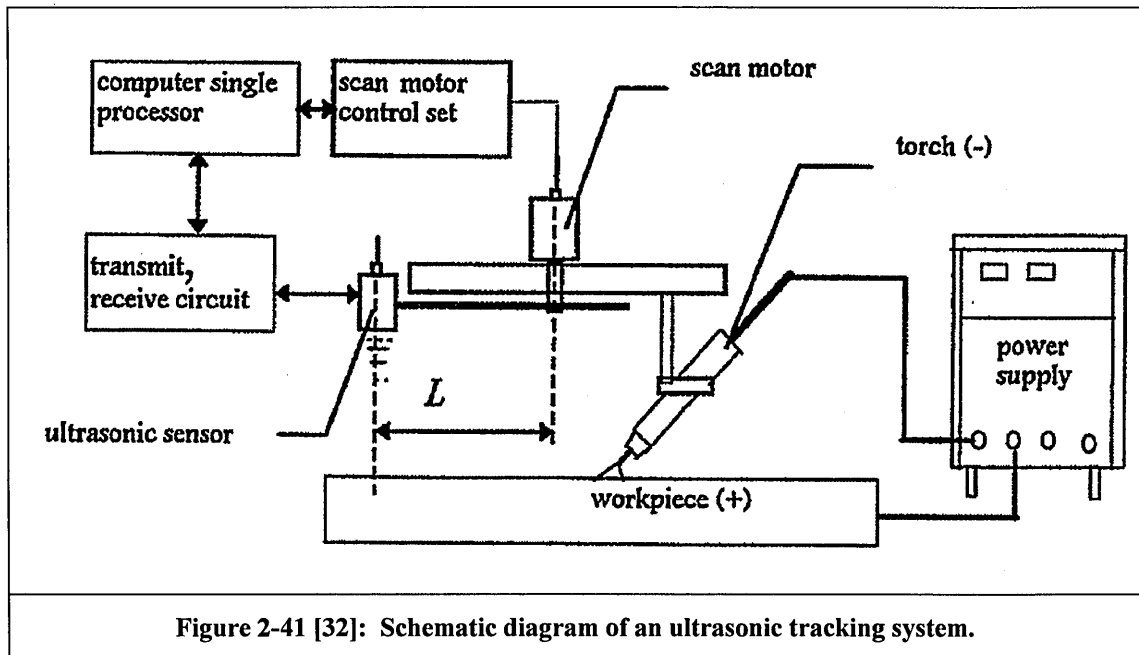
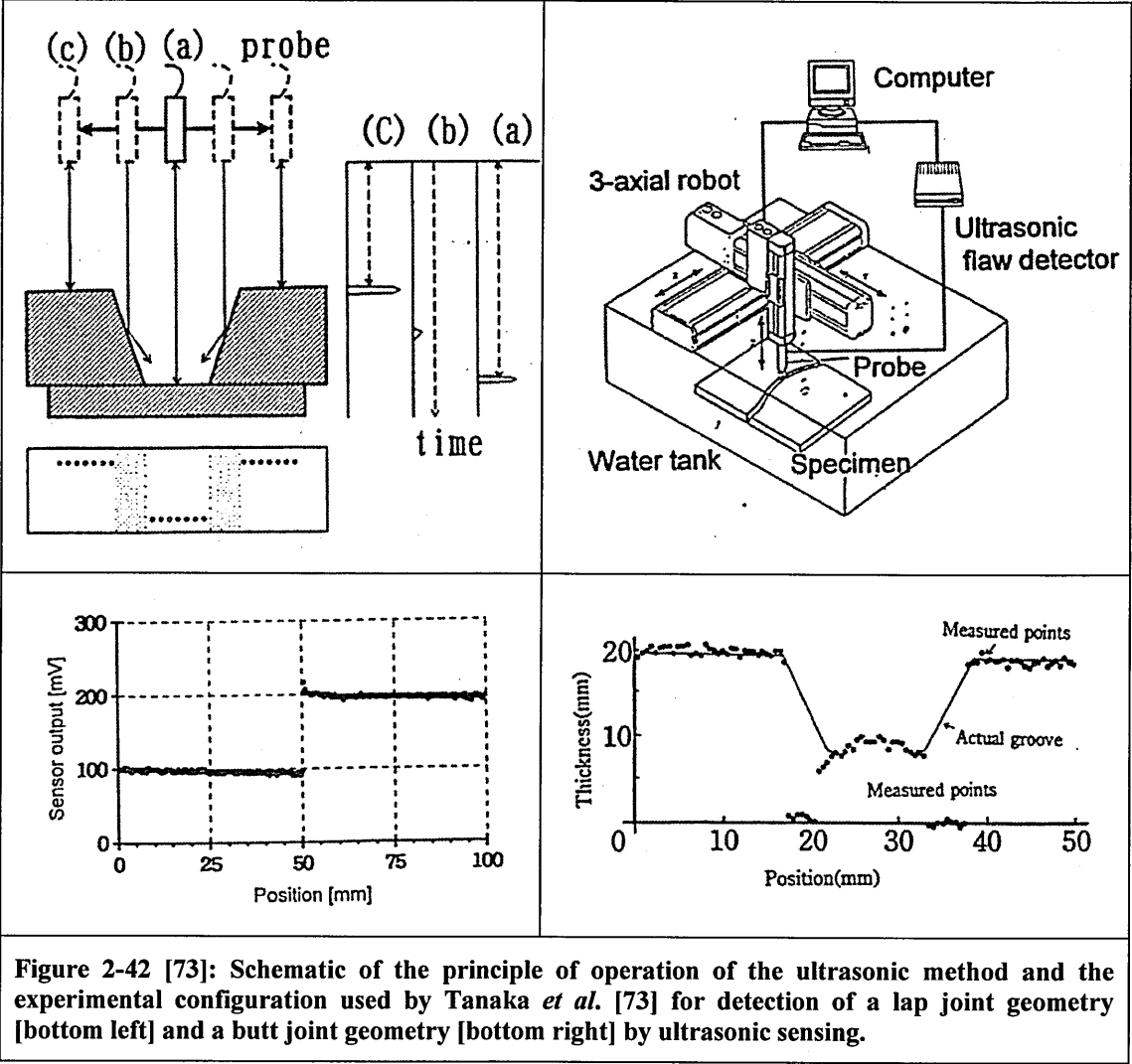


Figure 2-41 [32]: Schematic diagram of an ultrasonic tracking system.

Tanaka *et al.* [73] used two types of ultrasonic sensing systems [73]. The first one shown on the top left part of Figure 2-42 had the purpose of successfully detecting the exact location of root edges. The authors of [73] used a 10 mm diameter transducer with focal length inside the water equal to 32 mm and frequency of operation at 5 MHz [73]. The distance between the transducer and the workpiece could be checked to establish a reference value regarding the time delay of the ultrasonic reflection [73], in other words the time-of-flight. As Tanaka *et al.* [73] report based on other researcher's work, by scanning the area transversely, the groove geometry can be detected [73]. For the system shown in the top left part of Figure 2-42 the reflection of the ultrasonic beam from the sidewall of V-groove is hardly obtained because the surface of the wall is flat and uniform [73]. However, by detecting accurately the levels of the workpiece's surface and the root, the wall surface can be estimated [73]. The top right part of Figure 2-42 shows the schematic of the experimental setup [73].

The bottom left part of Figure 2-42 shows an example of edge detection for lap joint by ultrasonic sensing [73]. As shown, the edge point was clearly detected and the focal point of the transducer was small enough to detect the distance with accuracy [73]. Nonetheless, as Tanaka *et al.* [73] report, if not the time-of-flight but the amplitude of the reflection is used, it is difficult to obtain a correct value [73], due to the fact that the intensity of the reflection is strongly influenced from surface

conditions and geometry factors, like surface roughness and surface angle [73]. The fluctuation of the intensity was found to be especially high near the sharp edge [73]. The bottom right part of Figure 2-42 shows the system's results for detection of a butt joint [73]. The plate's thickness was 20 mm and the groove's angle was 60°. When the bead does not have a rough surface it is possible to detect detected [73]. The measured results for the wall's surface position were inaccurate and correction processes were needed [73].



A linear sensor array which employs electronic scanning [73] [also known as phased array] has been considered as well [73]. The sensor had an array of 90 elements and a valid observation field of 50 mm with a frequency of operation 5 MHz [73]. In a phased array, the scanning beam is stirred by activating the transducers sequentially. The advantage of such a system is that the transducer is not required to be moved [73] since the scanning beam is stirred electronically, and the groove geometry can be measured in a short amount of time [73]. However, because the wavelength is longer

than in the case of a light-based sensor, the possibility to measure in a muddy condition exists [73] since ultrasonic waves are pressure waves capable of penetrating the mud layer.

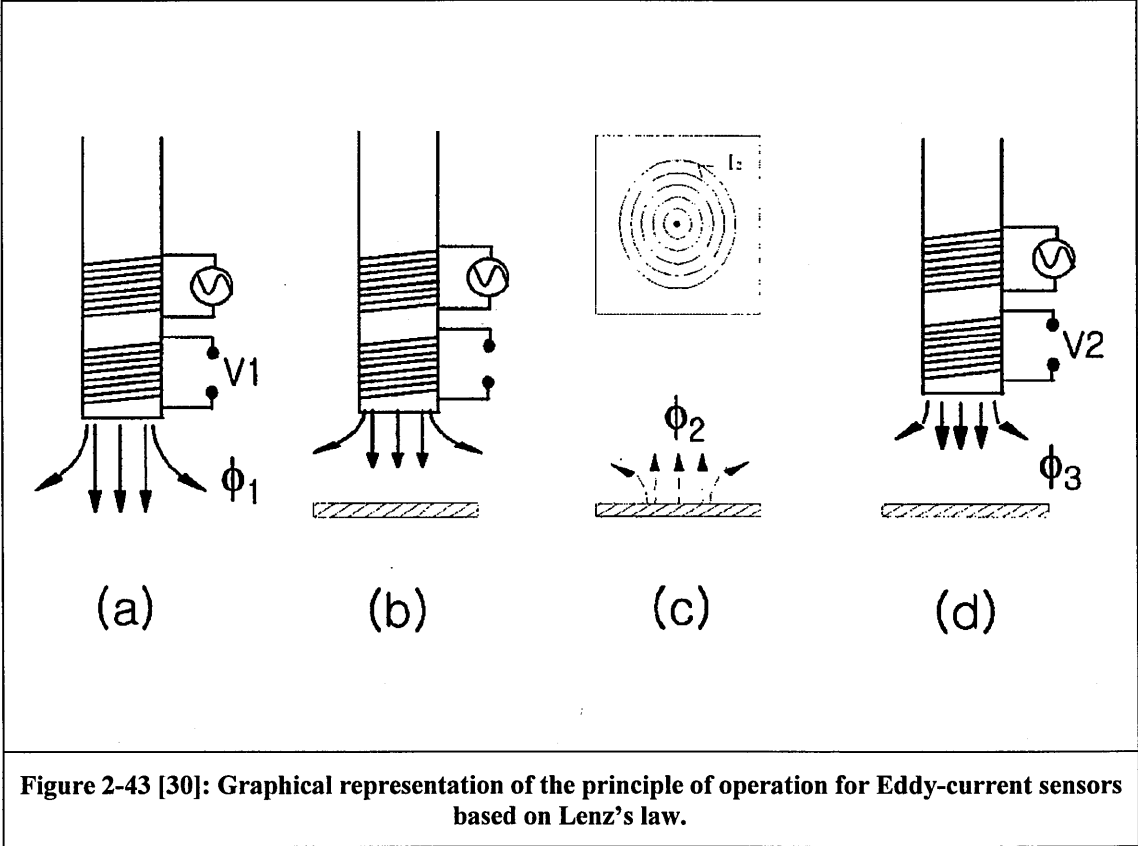
As with the case of tactile and optical sensors, ultrasonic ranging sensors require special installation and maintenance in order for accurate results to be achieved and the difficulties due to the inaccessibility to the system when submerged in case of any emergency repairs makes their use unattractive. Ultrasonic sensing is a good candidate for evaluation of the groove's geometry under-water, especially in low visibility conditions [73]. The use of a water curtain requires careful relative distance of the nozzle and the sensor because the water curtain will disturb the accuracy of the ultrasonic transmission [73].

Eddy Current Type Proximity Ranging Sensors

Eddy Current Type Sensor's Principle of Operation

The principle of operation of an Eddy current sensor is based on a phenomenon known as Lenz's law [29, 30]; Figure 2-43 shows this graphically. A coil, acting as the exciter coil, is wound around a metal core and connected in a sinusoidal [alternating] voltage generator, with a second coil wound beneath it, acting as the sensing element and is placed above a conductive material, as shown in part (a) [30]. An AC current, the result of the sinusoidal voltage, I_1 , is passed through the exciting coil as shown in part (a) which creates a magnetic flux Φ_1 [29, 30] which passes through the sensing coil causing a voltage V_1 to be generated at its ends and then, the magnetic flux passes through the conductive plate [30]. As the sensor system moves onto the plate (b), the magnetic flux Φ_1 induces an Eddy current, I_2 , which in turn induces a magnetic flux Φ_2 with such direction so as to oppose to the magnetic flux Φ_1 (c) [29, 30], a phenomenon which is called Lenz's law [29, 30]. The interaction of the two opposing magnetic fluxes Φ_1 and Φ_2 results in the original magnetic flux Φ_1 to be reduced in value resulting in a new magnetic flux value, Φ_3 , smaller from the original value Φ_1 by a magnitude equal to Φ_2 as shown in (d) [29, 30]. As a result, the induced voltage V_1 on the sensing coil reduced proportionally into a new value V_2 [30]. The value of V_2 depends on the distance between the coil and the plate [29, 31],

the shape/geometry of the surface [29, 31], the continuity [29, 31], conductivity [29, 31] and permeability [29, 31] of the surface, the frequency of the AC current [31], the temperature [22 pp. 40], the flaws inside the surface [31], spatter [22 pp. 40] and the angle between the coil and the surface/ feature to be detected [28].



Non-Differential Eddy Current type Probe Type

A single coil can be used [22 pp. 40], as shown in Figure 2-44, in which case it is the change in impedance for the high-frequency current that passes through the coil that provides the required information [22 pp. 40]. When a single coil is used, the AC current is superimposed on a weak Direct Current [DC] and the voltage drop on the electrical resistance of the coil provides the information to compensate for the thermal effect [22 pp. 40]. Figure 2-45 shows a typical output pattern from a system employing a single coil sensor.

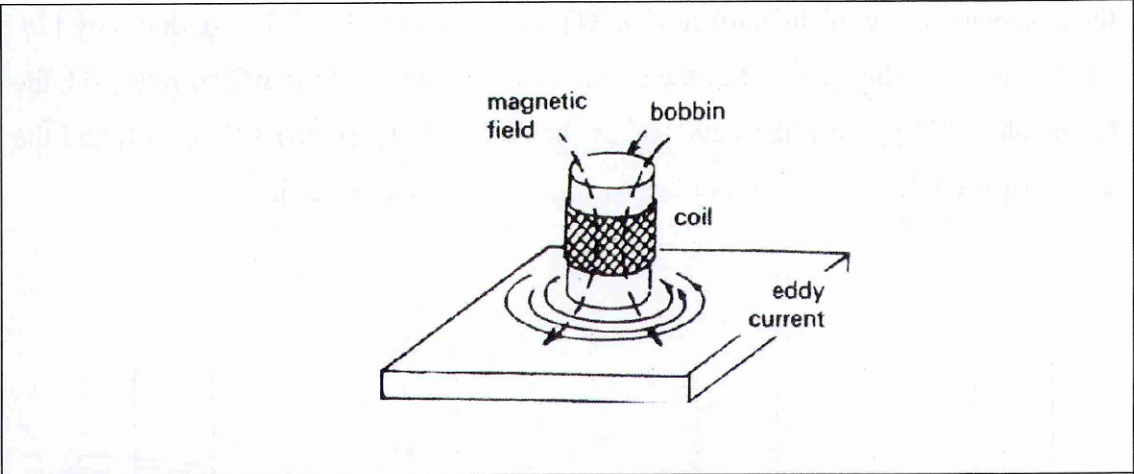


Figure 2-44 [22 pp. 39]: Graphical representation of single coil electromagnetic sensor's operation.

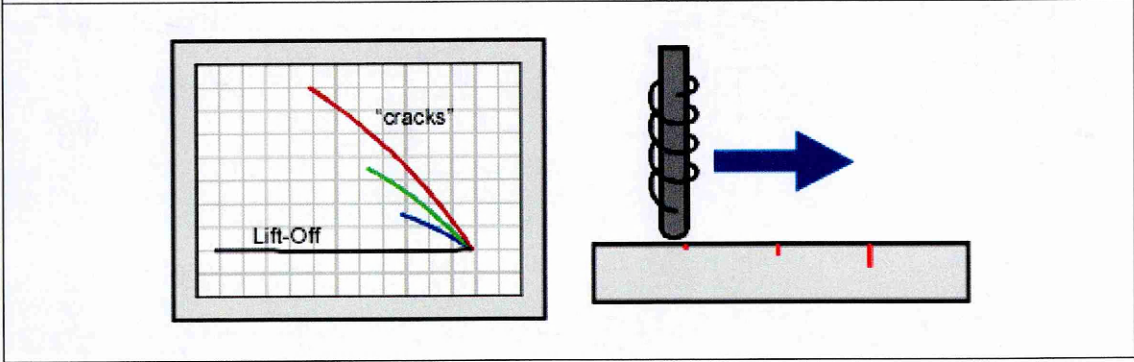


Figure 2-45 [31]: Graphical representation of a typical output of a system employing a single coil electromagnetic sensor.

Differential Eddy Current Type Probe Type

A differential connection and lap winding as shown in Figure 2-46 can be used to prevent welding-induced disturbances from the magnetic field and temperature [22 pp. 6]. In this case the windings are connected in such a way so as lift-off information to be preserved. In Figure 2-47 [31] a typical output of a differential probe is shown in which information about the lift-off has been cancelled due to the differential connection of the windings which effectively cancels-out the common signals on the two windings.

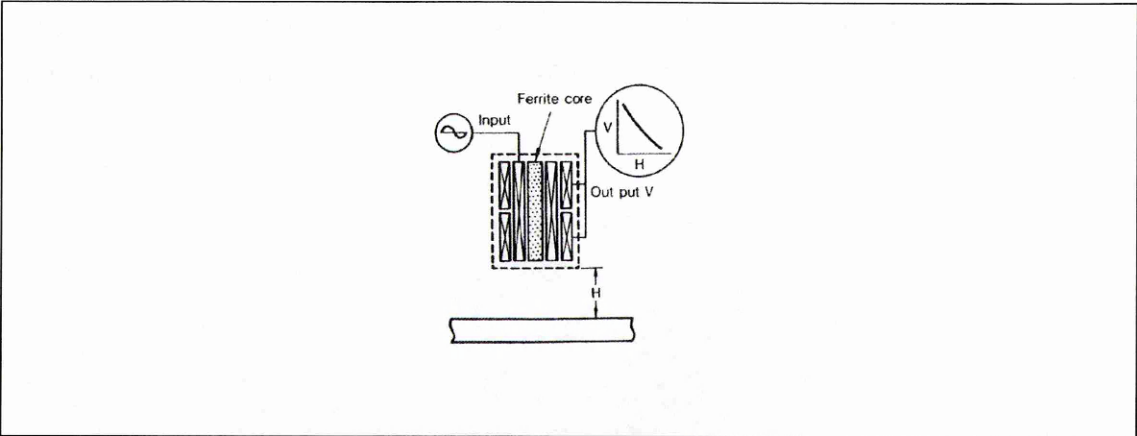


Figure 2-46 [22, pp. 6]: Graphical representation of a differential probe which shows the relationship between lift-off and output voltage level.

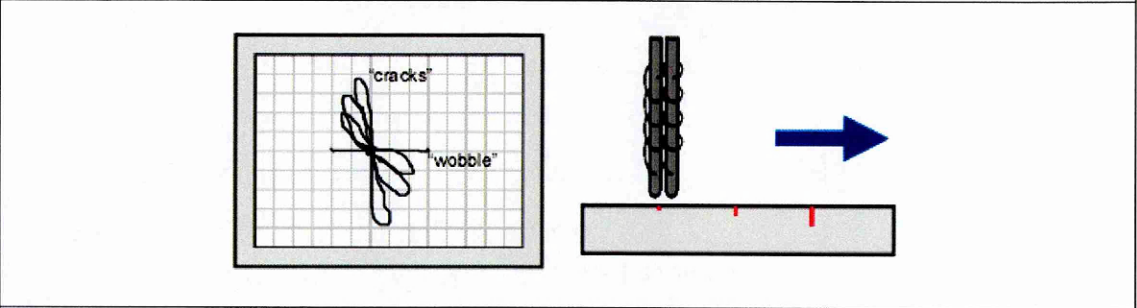


Figure 2-47 [31]: Graphical representation of a differential probe's output when the coils are connected in such a way so as to cancel out disturbances from welding magnetic fields and temperature which results in cancellation of the lift-off information.

Application Examples of Eddy Current Type Proximity Sensors in Seam Tracking

Figure 2-48 shows the diagram of an electromagnetic sensor system developed by You and Kim [29] for automatic seam tracking for sheet metal butt joints. As shown, the system is computer controlled and moves the sensor ahead of the torch from left to right in the direction of travel of the welding torch so as to detect the joint.

Figure 2-49 shows the schematic of a system developed by Kim and Shin [30] for seam tracking of I-butt joints using a dual-electromagnetic sensor [30] in a differential reflection or driver/pickup configuration [31]. More specifically, two sensing coils winded around two cores next to each other with the exciting coils winded around both cores [30, 31], as shown in the right of Figure 2-50 compared to an absolute configuration [31] shown on the left of Figure 2-50. This allows the detection of the seam without weaving the sensor assembly based on the assumption that when the sensor is exactly above the centre of the seam the output from the two sensing coils will be equal [30]. Similar strategy was adopted by Howarth and Guyote [28] which

state that by arranging several sensing coils under the exciter coil and adding or subtracting the voltages from each in various arrangements information about the joint position can be obtained [28].

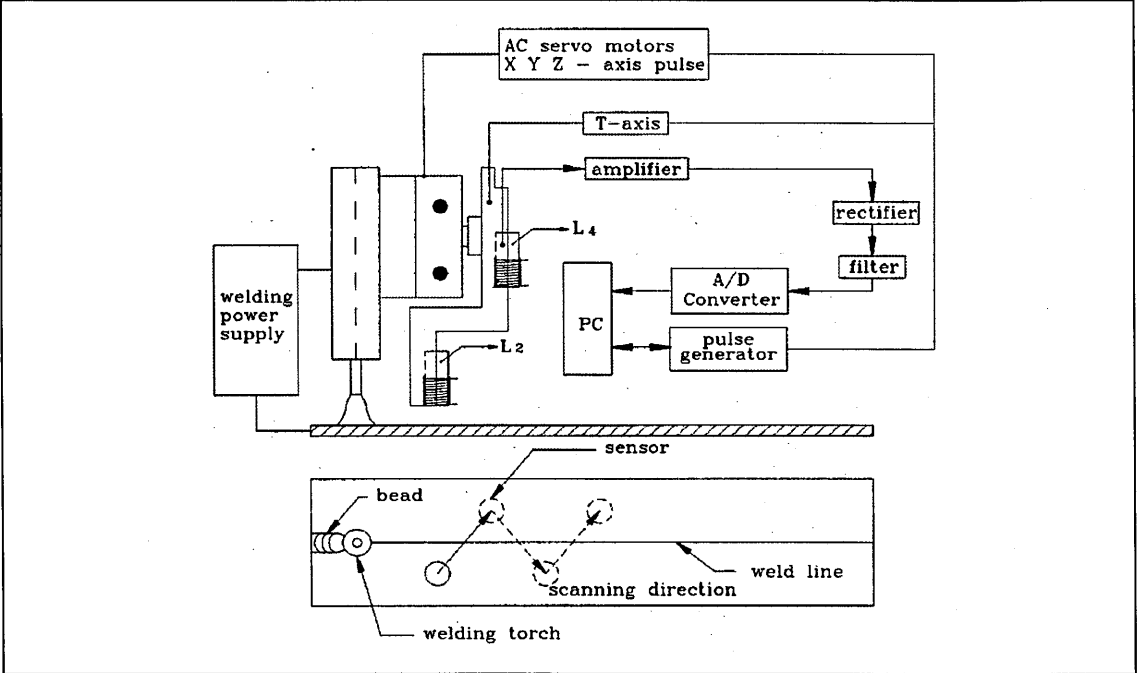


Figure 2-48 [29]: Example of a system for automatic seam tracking for sheet metal butt joints using electromagnetic sensors.

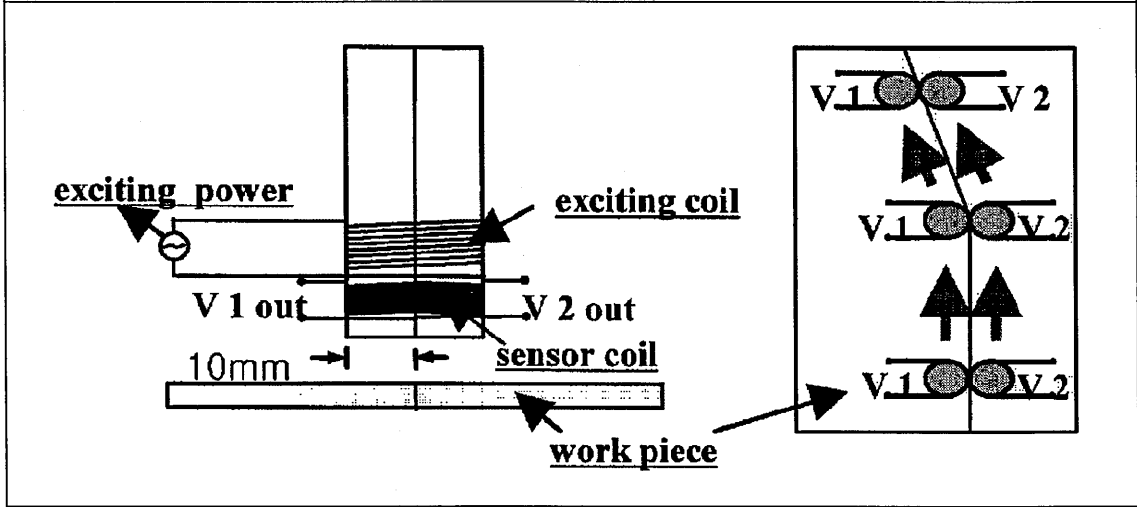


Figure 2-49 [30]: Example of a system for automatic seam tracking of I-butt joints using a dual-electromagnetic sensor in a differential reflection or driver/pickup configuration.

In Figure 2-51 a schematic of a configuration is shown used by Howarth and Guyote [28] in which two sensing coils were connected as a figure of “8” axially aligned with the exciter coil. When each sensing coil is on one side of the joint the net voltage is zero but when the sensor is misaligned to the joint, a voltage is produced, the polarity and value of which is indicative of this misalignment [28]. The authors report that using these different combinations in processing the coil’s voltages “independent

information has been acquired about the lateral distance that the sensor is offset from the joint, the height of the sensor above the metal, and the Euler Angles which define the angular orientation of the sensor relative to the joint” [28]. Based on this information, it is possible to define the required correction in the robot’s path so as to correctly position the torch [28].

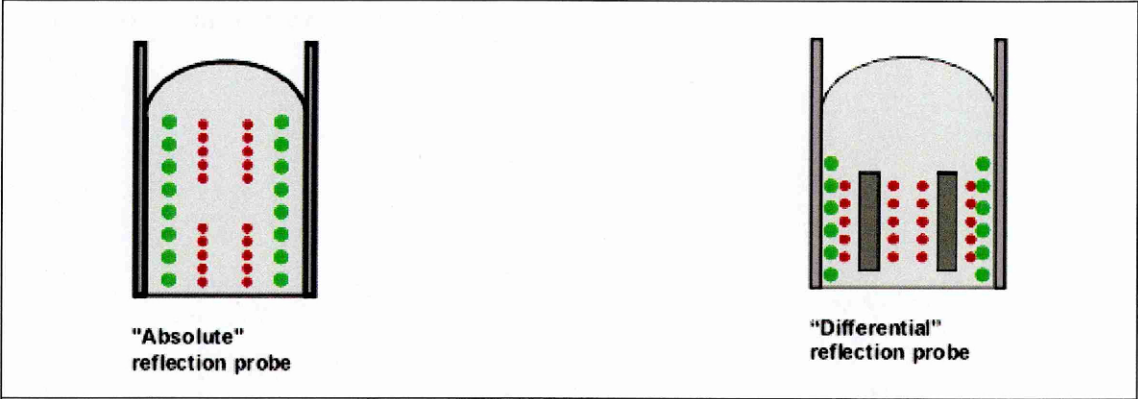


Figure 2-50 [31]: Graphical representation of the physical construction differences between the “Absolute” [left half] and the “Differential” [right half].

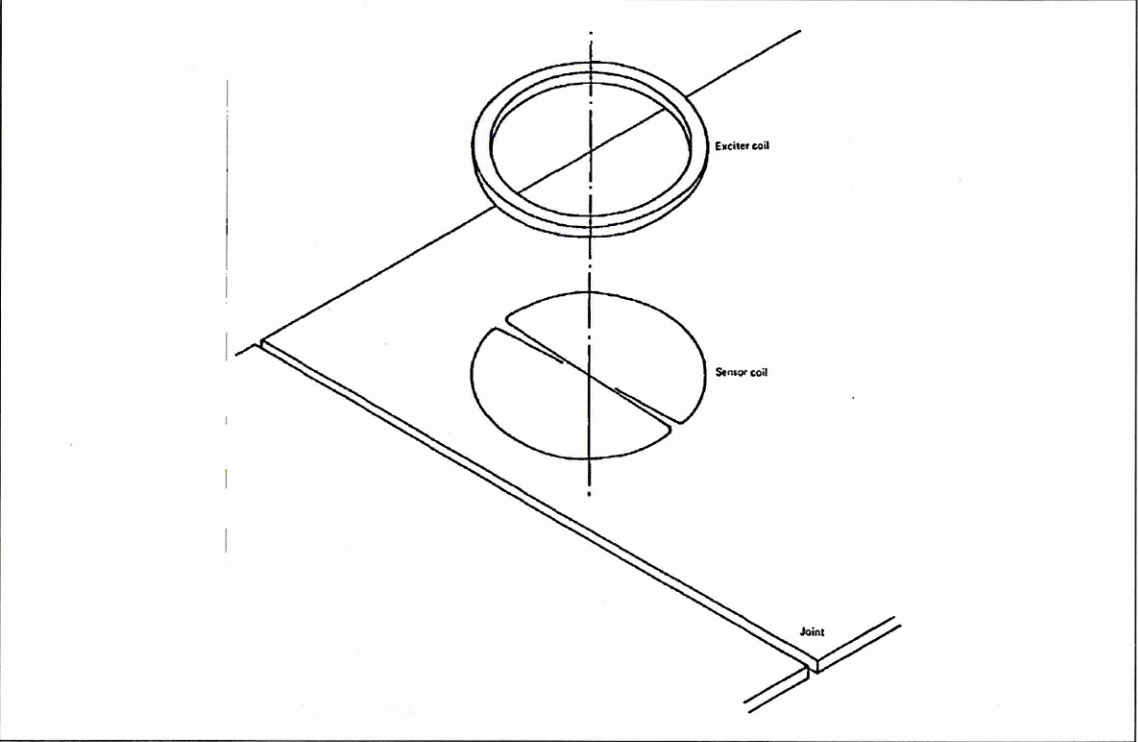
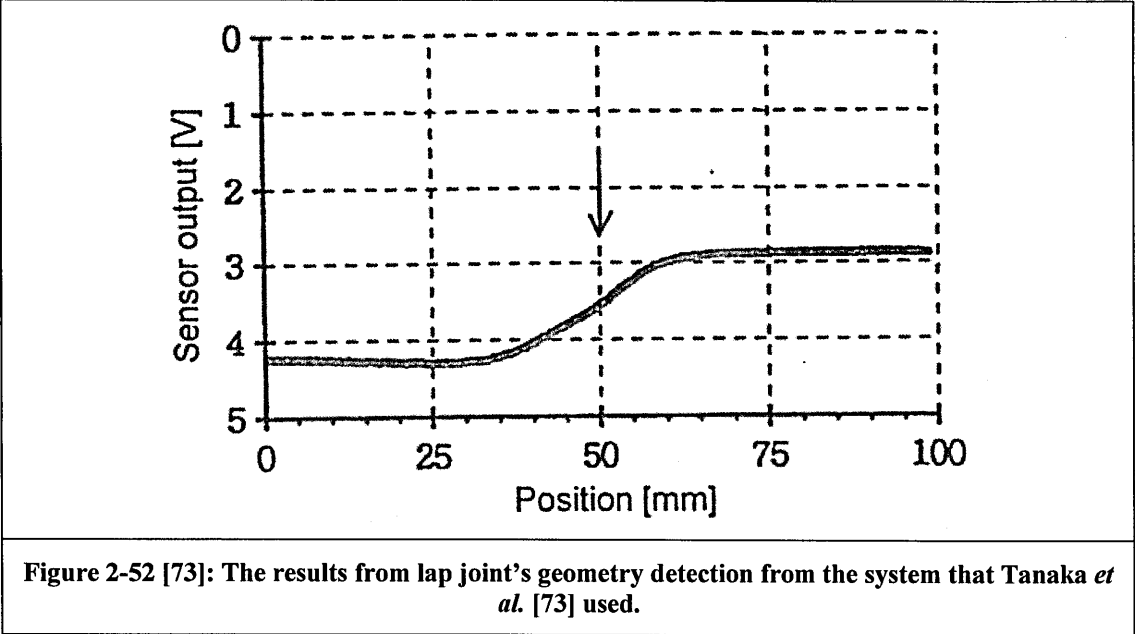


Figure 2-51 [28]: Seam tracking using two sensing coils in a figure of “8” configuration, axially aligned to the exciter coil.

Tanaka *et al.* [73] tested an Eddy current system for mechanised wet welding. The researchers used the same mechanised system shown in Figure 2-42 [73] and adopted for using the Eddy current sensor. The diameter of the transducer was 20 mm and the measurable distance was between 0 mm to 10 mm [73]. Mechanised transverse

scanning was employed to detect groove's geometry [73]. Figure 2-52 shows the results of the system used for edge detection of lap joint [73]. The focal spot diameter was approximately 20 mm [73]; this value is too broad for detecting the sharp edge of the test piece and the results are not too clear [73]. The same tendency prevailed for both, V-shaped and I-shaped grooved specimens [73] which meant that this Eddy current sensing method is not suitable for correct groove geometry detection [73].

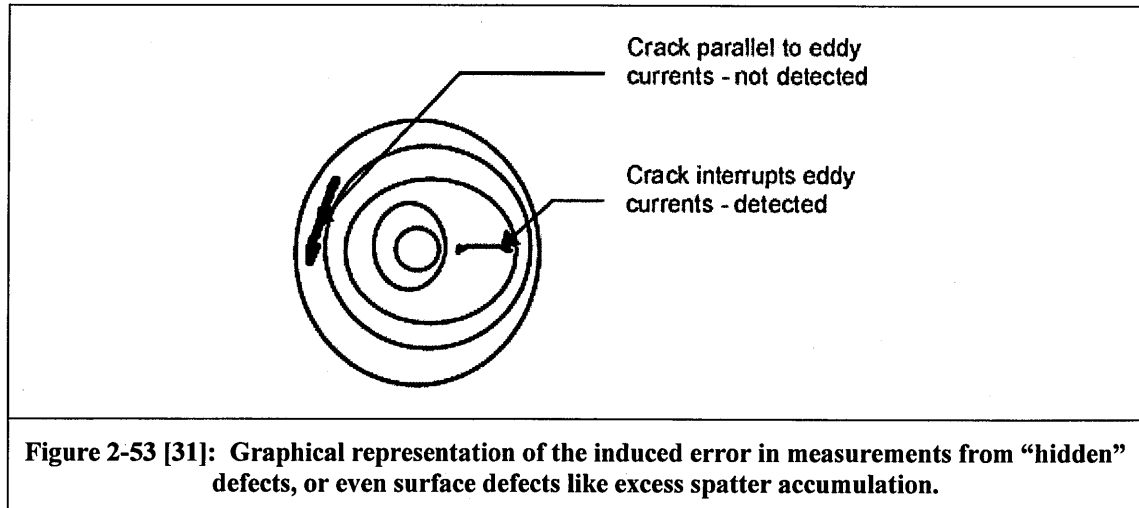


Summary of Eddy Current Type Proximity Sensors

It should be noted that care must be taken in the selection of the probe itself, since probes with one sensing element, absolute probes [31], do give information about the vertical distance or lift-off [31] of the sensor from the surface in contrast with the differential probes which lack this ability. Probes with more than one windings, differential probes [31], might be designed in such a way so as the connections between the windings provide lateral information for seam tracking or presence of defects but no information about the lift-off which they tend to cancel out together with effects from temperature changes [if the measuring instrumentation operates in a balanced configuration [31]] and external interference [31].

The last point to remember is that surface or deep defects vertical in the flow of Eddy current can interrupt it as shown in Figure 2-53 causing weaker or misaligned magnetic flux resulting in errors in the position estimation. For the RPRS, a similar

situation can occur when such defects are generated either during the preparation of the pipe ends. Additionally, alteration of the surface conditions, like accumulation of excess spatter during numerous welding passes, can result in erroneous parameters estimations.



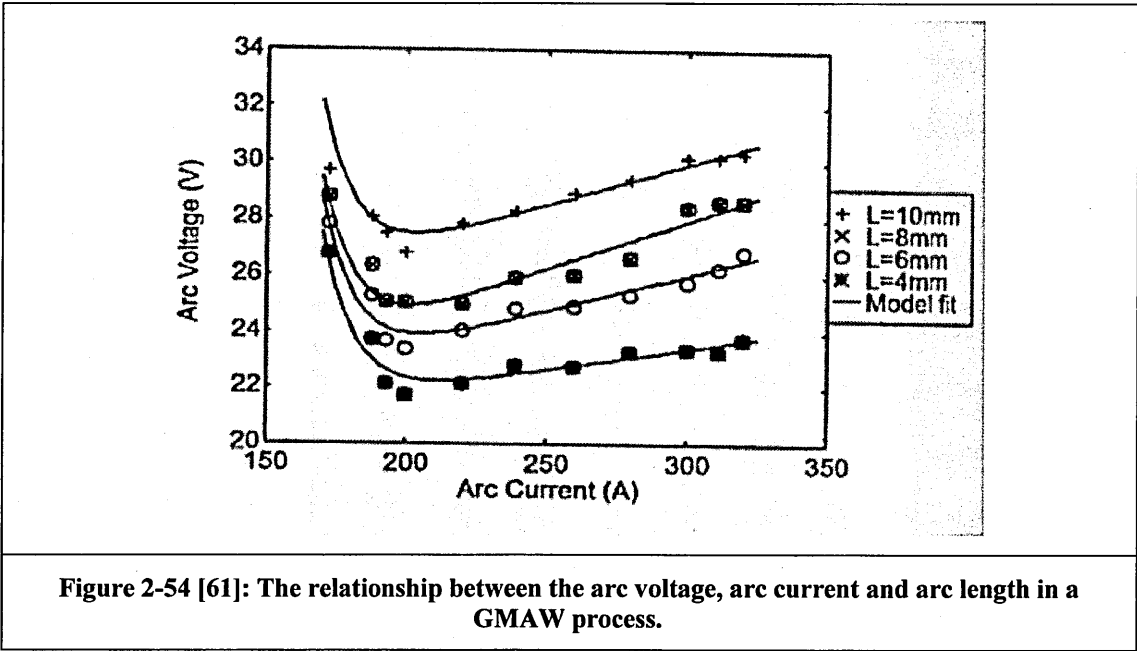
The use of electromagnetic proximity sensors for the hyperbaric program is an attractive idea but what it has to be taken into account is that the magnetic field developed on the submerged pipe can be significantly high. Although degaussing coils will be employed it is best to avoid the use of any electromagnetically dependable sensors. In addition, these sensors constitute extra hardware which needs to be added which is susceptible to the same problems that the tactile sensors are. Finally, like the tactile sensors, spatter accumulated over many welding passes on the probe or the parent metal and sleeve itself can cause errors in detection.

Proximity Ranging Sensors Vs. Vision systems

According to Howarth and Guyote [28] both Eddy current and ultrasonic ranging sensors have potential advantages over the various vision systems. The authors of [28] report that processing of vision systems’ data is more difficult, and the use of a camera-based optical system and supporting equipment imposes a higher cost. Additionally, eddy current sensors offer immunity to fumes from the welding arc; nonetheless, it has been reported from observations in real applications’ that accumulated spatter deposited on the surface of the eddy current sensor gradually alters the sensor’s operation, something that can be a problem in the RPRS’s operation as mentioned earlier in the Summary of Eddy Current Type Proximity Sensors.

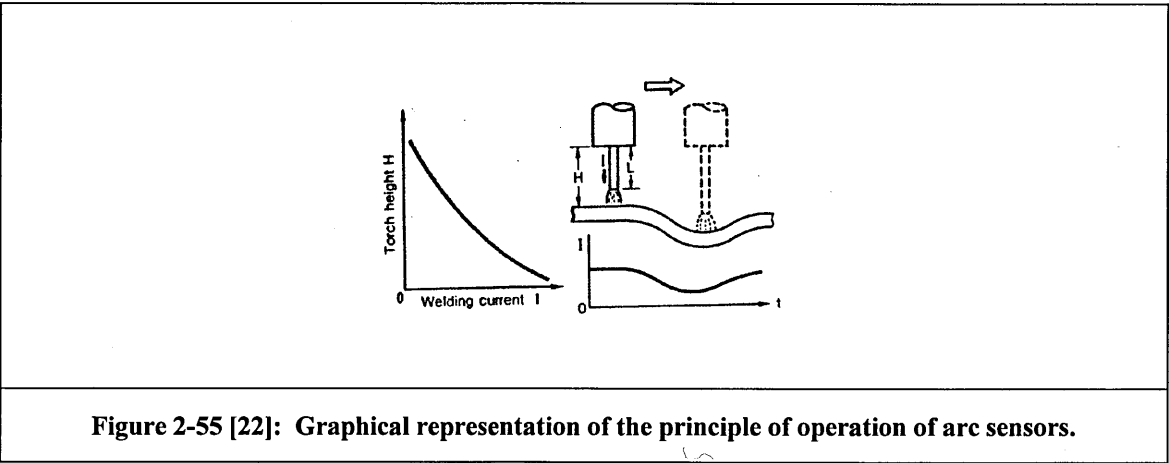
2.4.6 Arc Phenomena Sensors

The sensor that attracts the attention most is the arc phenomena sensor, also called an arc sensor, Automatic Current Control [ACC] sensor, Automatic Voltage Control [AVC] sensor or through-the-arc sensor [22 pp. 5]. This technique uses the arc as the sensor itself and the correlation between the arc voltage [32, 61], the arc current [61] and the arc length [32, 61], more specifically, it utilises the changes in the welding current or welding voltage or even [in some cases] the wire feeding speed in response to changes in torch height [22 pp. 5]. An example of the correlation between the arc voltage, arc current and arc length is shown in Figure 2-54. It is the most prevailing sensor for seam tracking in arc welding processes [32] and the reason is that there is not the need for the extra cost to buy a sensor [22 pp. 25], or the problems associated with installation and maintenance ensuring that any variable is referred to the interaction point and not to a point close to it [22 pp. 25], which could have different behaviour resulting in error in the measurement and estimation of the magnitude of the wanted variable. It is also a robust method against smoke, spatter and arc radiation [32]. The disadvantage is that depending on the information required to be extracted, it might be a quite complex way of sensing which could increase the cost and limits the use of this type of sensor, since in many systems, this is not a very attractive idea and some form of sensor tends to be employed. This happens because of the need in through-the-arc sensing for the joint sidewalls to be well defined or have a groove [32], the undesired coupling between the sensing and the welding process because of the mandatory weaving of the torch [32] and complexity of the arc itself which requires complex mathematical treatment in real time if valuable results are required. The dramatic fluctuations of the welding current and voltage are usually treated using a smoothing filter [22 pp. 5], applying Fourier transformation on the waveforms [22 pp. 5] or utilising information collected only in arcing periods [22 pp. 5]. Adaptive control is applied by utilising the short circuiting frequency of the filler wire and the number of abnormal current peaks [22 pp. 5].



Principle of Operation of Arc Sensors

Figure 2-55 shows graphically the principle of operation of arc sensing utilising the welding current information; assuming a constant stick-out length ‘L’, as the torch height ‘H’ increase, the welding current decreases [due to increase in the filler wire resistance] and vice-versa.

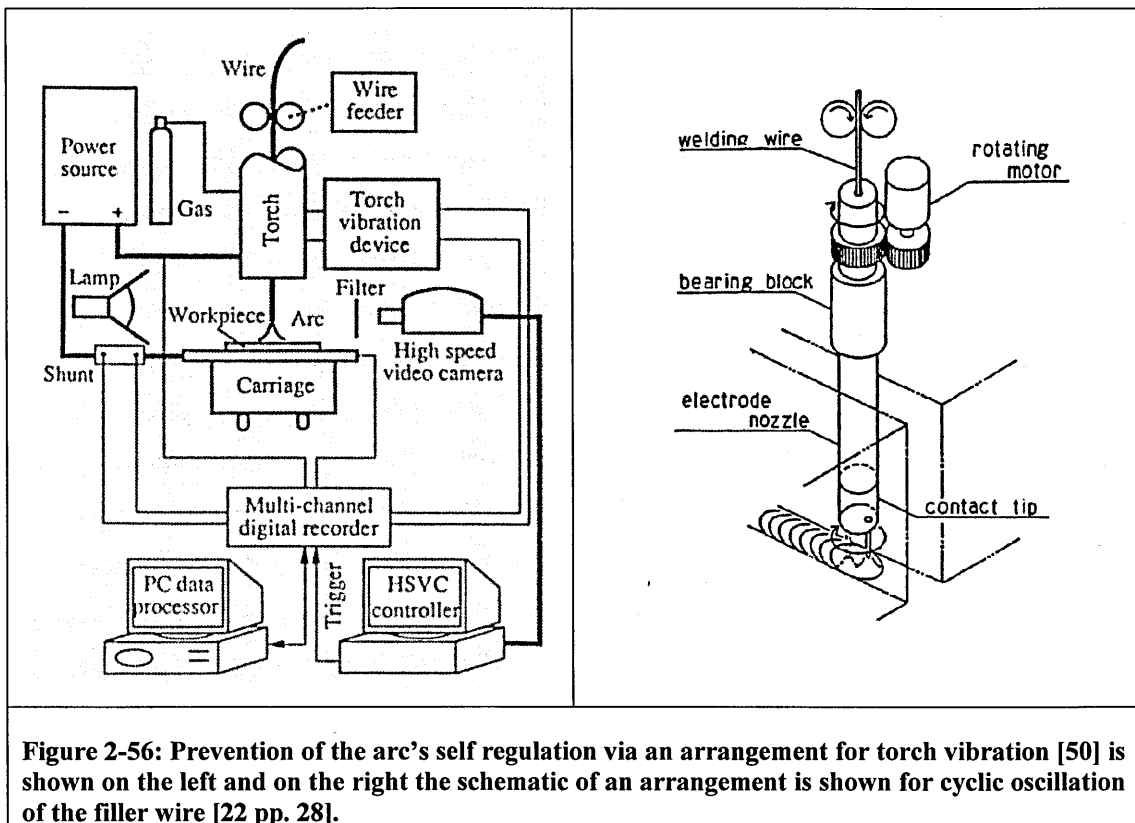


The principle of operation assumes a constant stick-out length which requires the self-regulation of the arc to not operate [22 pp. 27]. In practical applications this will not normally happen unless the change in the torch height is transient and fast which, with the exception of presence of surface defects, is not realistic.

Prevention of the Arc’s Self-Regulation for CTWD and Seam Tracking

As mentioned in Principle of Operation of Arc Sensors above, the self-regulation of the arc must not interfere; this is achieved by weaving the torch in the groove [22 pp.

28, 32] fast enough as shown in Figure 2-56, or, alternatively [22 pp. 28] a filler wire manipulator can be employed as shown in Figure 2-56 which rotates the filler wire around the welding point up to 100 Hz allowing high-speed welding and detection sensitivity [22 pp. 28]. If the rotation speed [or oscillation frequency] is high enough, the welding arc's self-regulation does not operate [22 pp. 27] and the higher the oscillation frequency, the higher the sensitivity of the sensor [22 pp. 26]. By comparing the welding current with a reference value, the difference can be used as the feedback signal which will allow torch height control and seam tracking [22 pp. 28].



Seam Tracking and Deposition Control via Torch Height Control

Oscillation of the entire torch side-to-side inside the seam it is possible to achieve seam tracking together with deposition rate control [22 pp. 29]. When the response of torch height control and the oscillation speed is fast enough and is combined with arc length control [22 pp. 28], the torch will trace a locus parallel to the groove surface [22 pp. 28]. Detection of the torch's displacement in the vertical direction, as shown in Figure 2-57, allows detection of when the torch reaches the desired vertical limit in which case the torch oscillation direction is reversed allowing control of the deposition rate [22 pp. 28]. A similar method for deposition control in multilayer

welding is achieved by altering the welding speed [22 pp. 29]. This is done by altering the welding speed so as to achieve a displacement equal to the desired bead width [22 pp. 29].

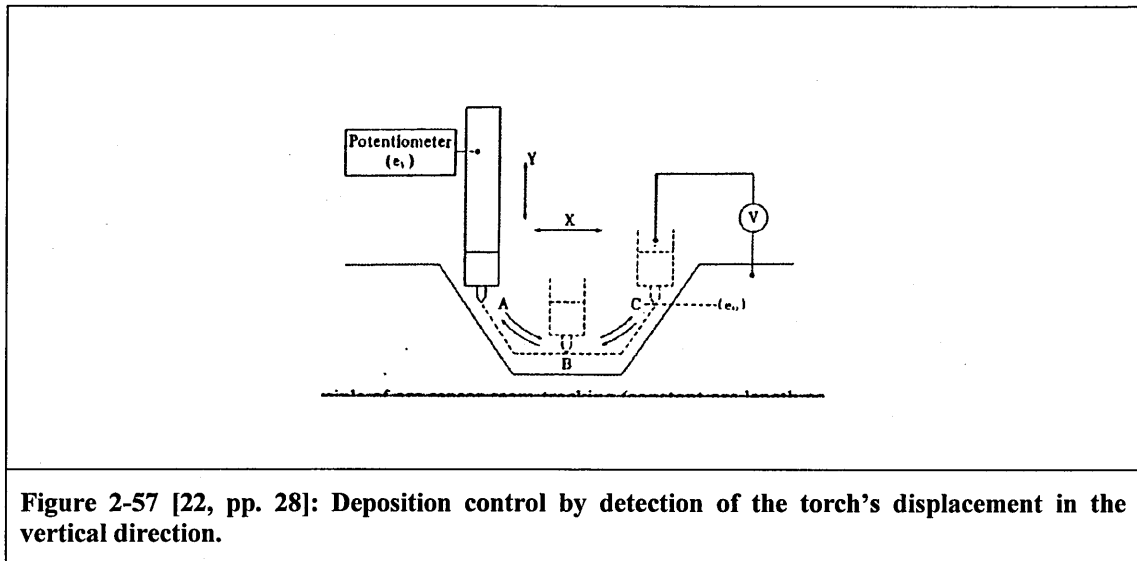


Figure 2-57 [22, pp. 28]: Deposition control by detection of the torch's displacement in the vertical direction.

Summary of the Arc Sensors

For the RPRS program, use of an arc sensor, it is not a promising solution, since weaving of the filler wire or the torch in high speed which might require the installation of additional hardware around the torch, which could be a major issue in terms of complexity and reliability. However, the arc sensor is the only type of sensor that will not be influenced from problems with defects and spatter and does not require installation of additional hardware.

2.4.7 Dip Resistance, or, Through-the-Wire Sensor

The significance of this measuring technique for the RPRS makes this type of sensor very important. This technique can be used for CTWD detection in GMAW with short-circuiting metal transfer mode [52] when high resistivity welding wires are used, like mild steel or stainless steel [52]. The principle of operation is to measure the minimum occurring liquid bridge resistance value [52] as the wire touches the weld pool. During short-circuit metallic transfer the wire dips in the weld pool effectively extinguishing the arc. At this moment, the wire's resistance can act as an indication of the distance between the weld pool and the torch, assuming that the wire touches at the torch's end which is also [ideally] the measuring point of the arc voltage. It is very important to be able to detect when an actual shorting event occurs

and make the measurement of the resistance at its lowest value when the welding arc is fully extinct. If a measurement is taken when the welding arc is present, then Ohm's law, shown in Equation 2-5 [pp. 100], cannot be applied because of the nature of the arc and the physics behind it, hence the measurement will be wrong. In addition, if the measurement is not taken at the time of the lowest value of the resistance, error can again be introduced. How significant the error is depends on the accuracy that is expected, in other words, the resolution in the torch's height we wish to obtain. Nonetheless, as it will be shown next, the very nature of this process puts limits to how accurate we can be.

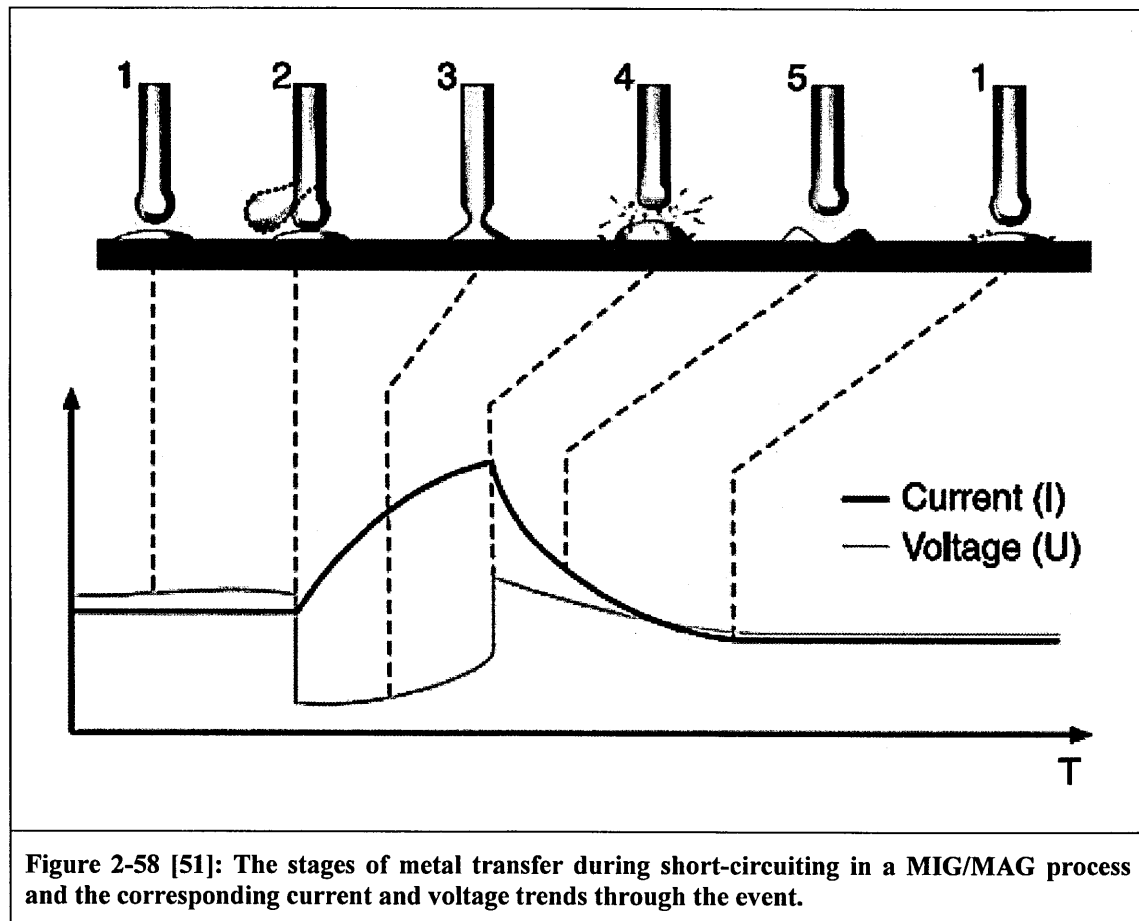
In the following paragraphs a detailed explanation is presented of the way this technique can be used in 1 Atm processes which will form the foundations for this project's work.

2.5 Dip Resistance in 1 Atm Processes

The idea to use dip resistance for the measurement and control of the CTWD in 1 Atm processes has been examined by other researches. The review and conclusions of these attempts are important and could indicate a path to follow under hyperbaric conditions. Some of these attempts are described below. Before the description of these attempts, a description of the short-circuit process will be presented so as to establish what factors can influence the measurements.

2.5.1 The Short-Circuit Event in MIG/MAG

Short-Circuit Event Analysis Under Constant Voltage Power Source Mode



In Figure 2-58 the various stages of a short-circuit event in a MIG/MAG process are shown as described by Silva *et al.* [51]. When the welding wire is fed fast enough it dips into the molten weld pool and the arc extinguishes resulting in a short-circuit event [12]. As shown, when a short-circuit event occurs [stage 2], “the current rises up a slope, on a transitional basis, since the energy source tries to impose a tension

between their exit terminals, that is, between the part and the electrode wire. The gradient of this slope is a function of the regulated voltage and of the inductance.” [51]. As the current rises rapidly [12, 51] and the cross-sectional area of the molten wire reduces [stage 3] due to the constriction of the metal bridge [51], *“the pinch effect and the axial component of the Lorentz force grows at a rate of variation that is also increasing, since they are proportional to the square of the current and to its density.”* [51]. Metal transfer [with small wire diameters and low current values [16]] takes place due to the combinatorial effect of electromagnetic pinch force, surface tension force and gravity [16]. The result [stage 4] is the metal bridge to collapse and the arc to be re-established [12, 51]. At this very moment, the current is at its highest point and the voltage exceeds its regulated value [51]. The power source responds [stage 5] and imposes a regulated voltage which results in reduction in the current value as well [51]. With the welding arc voltage reaching its regulated level the arc current also stabilises [51] [stage 1 – right hand side of the graph]. During the arcing period the current causes the formation of a new metal drop and maintains the heating effect on the weld pool [51]. If the burn-off rate is matched to the wire feed rate [12], the short-circuit event repeats at a regular frequency [12]. This process is suitable for positional work, like in pipeline construction, as it is characterised by low heat inputs which result from the low mean current levels [12].

The above analysis is based on a power source that regulates the current so as to keep the voltage constant. In the case that the power source regulates the voltage so as to keep the current constant the net result will remain the same.

Short-Circuit Event Description in Dip-Transfer MIG/MAG

Philpott [13] presents in Figure 2-59 typical traces of welding voltage, welding current and dip resistance from the system he developed for his work on dip-resistance based CTWD control for the automotive industry [13]. The figure shows the traces as they were captured with the aid of a digital storage oscilloscope. Although the description of the short-circuit event in MIG/MAG is very close to the description presented above, Philpott [13] includes a detailed description of the lower part of Figure 2-59 which shows the dip-resistance behaviour, based on cine films from other researches and the results from his theoretical and experimental research.

The description of the welding voltage, welding current and dip resistance behaviour from Philpott's work in [13] is presented below.

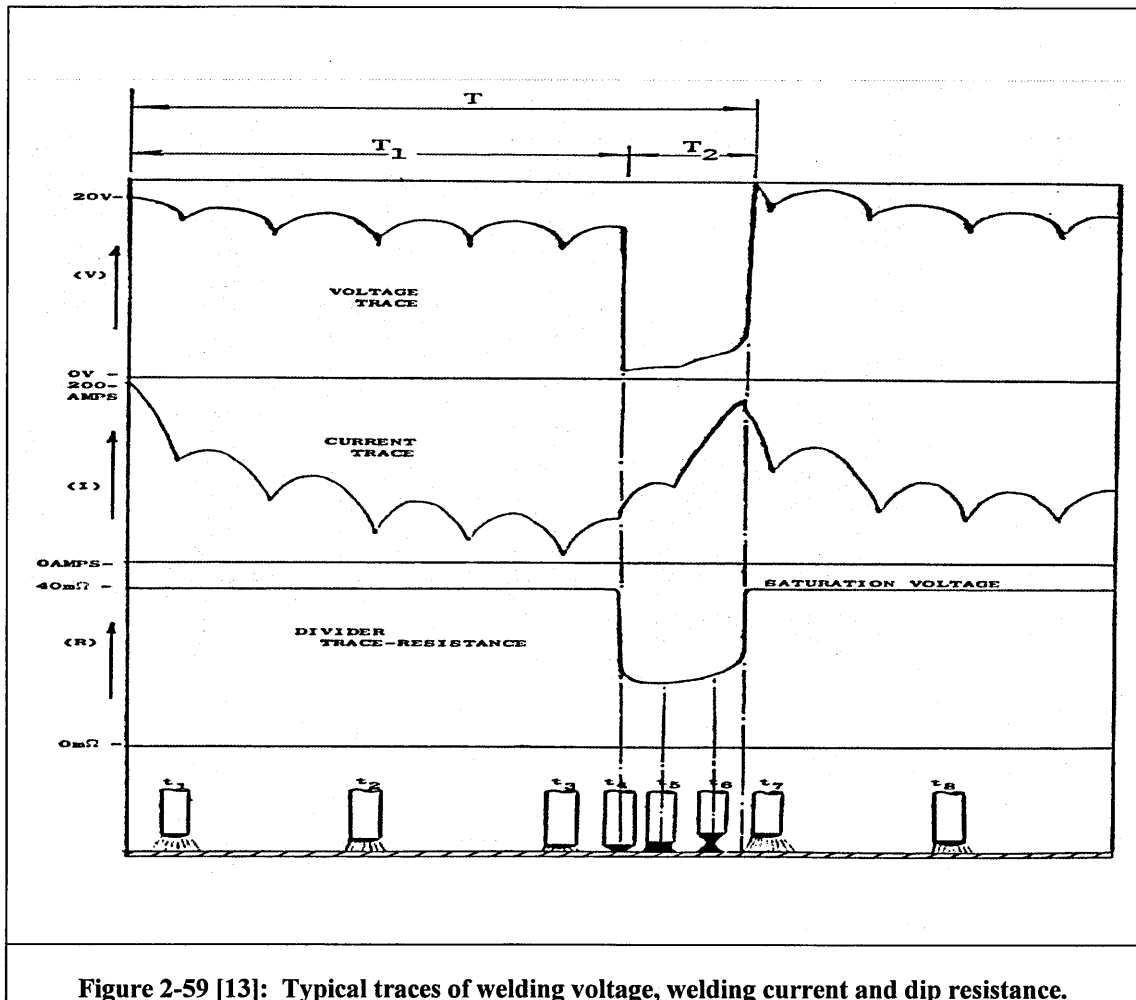


Figure 2-59 [13]: Typical traces of welding voltage, welding current and dip resistance.

For a correct operating short circuit process, the welding arc is gradually extinguished as the electrode tip approaches the parent metal as shown between the times t_1 , t_2 and t_3 of Figure 2-59. During this period the welding current and the melting rate fall. At time t_4 , surface tension forces the molten pool to move upwards to meet the approaching electrode. It is the initiation of the short circuit. Since resistance is inversely proportional to cross-sectional area as Equation 2-3 [pp. 100] shows, its value does not immediately fall to its minimum at t_4 . The resistance reaches a minimum value as the continuous feeding of wire with low welding current causes the molten metal bridge to be transferred to the molten pool and unmelted electrode enters the molten pool and the cross-sectional area of the metal interface increases momentarily between t_4 and t_5 . Consequently, this reduces the electrical resistance according to Equation 2-3 [pp. 100] and the welding current rises.

$R = \rho \times \frac{\ell}{s}$	Equation 2-3: Determination of wire's resistance from resistivity, length and cross-sectional area. <i>ρ=resistivity in $\Omega \times mm$, ℓ =length in mm, s=cross-sectional area in mm^2.</i>
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The current rises exponentially due to the inductance L of the welding circuit and [with constant R, in other words, with the wire's extension geometry unchanged] is given by Equation 2-4 below:

$I = \frac{V}{R} \times \left(1 - e^{\frac{-R \times t}{L}} \right)$	Equation 2-4 [13]: Current value through a large inductance. <i>I=current in Amperes, V=voltage in Volts, R=resistance in Ohms, t=time in seconds, L=inductance in Henry, e=Euler's constant [$e \approx 2.71828182845904523536... \text{.}$].</i>
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From Ohm's law, described by Equation 2-5 below, with constant R, as the current increases exponentially, the voltage also increases exponentially due to the increasing voltage drop in the electrode extension as the current increases.

$R = \frac{V}{I}$	Equation 2-5 [12]: Ohm's Law. <i>R = Resistance in Ohms, V = Voltage in Volts, I = Current in Amperes.</i>
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As the current rises, the magnetic pinch effect and the heating effect act together and necking occurs as shown between the times t_5 and t_6 of Figure 2-59, until the molten droplet is transferred to the molten pool and the wire bridge is broken at t_7 . Then, the welding voltage rises almost vertically and the current falls as the welding arc re-ignites at t_7 . At this point, the welding arc is at its maximum length and the cycle starts to repeat itself.

According to Philpott [13], the sudden rise in the electrical resistance after time t_5 of Figure 2-59 is due to two effects that take place. The first is that the rapid rise of the welding current causes increased power consumption by the electrode extension which increases its temperature which in turn increases its resistance. The second is that the gradual reduction of the cross-sectional area [' s ' in Equation 2-3 above] due to the pinch effect, increases the electrical resistance according to Equation 2-3 above.

As Figure 2-59 shows, during a short-circuit event the welding voltage drops to a minimum to start rising gradually and at the end of the short-circuit it rises to arcing

operating levels. The welding current on the other hand drops before the actual short-circuit event enabling the welding wire to dip inside the weld pool at which point the welding current starts to rise gradually. With the welding arc's re-ignition, the current starts to drop to nominal arcing operating levels.

Using Ohm's law, described by Equation 2-5 [pp. 100], it is possible to explain the electrical resistance's waveform shown in Figure 2-59. At time t_3 , before the short-circuit, the welding voltage has a high value and the welding current has a low value. Their ratio gives a resistance value which, in the case of Philpott's apparatus in [13], results in a saturated output [40 mOhms]. The initiation of the short-circuit at t_4 extinguishes the arc and results in low voltage and high current resulting in a ratio which, as shown, gives a lower resistance value. The 'behaviour' of the welding voltage and the welding current during the short-circuit results in their ratio to give an electrical resistance value fairly constant during the short-circuit. The end of the short-circuit and the welding arc's re-ignition results in the resistance value to reach its saturation level once more.

Further Work on The Shape of the Welding Wire's Resistance Waveform

Orszagh *et al.* [52] and Orszagh *et al.* [54] further investigated the shape of the electrical resistance during short-circuiting by studying homophase drop-pool bridging phenomena with different diameters of solid steel wire rods and different liquid and drop volumes [52, 54] in an attempt to emulate the behaviour of the GMAW process. Although the water-based 'pseudo' short-circuit event is much longer in duration in comparison to the one in the welding process, as shown in Figure 2-60, the authors found correlation between the shapes of these two otherwise different phenomena as Figure 2-60 and the right part of Figure 2-61 illustrate. What is important from the water experiments is that the resulting electrical-emulating pseudo-resistance curve was not symmetric [52, 54] and this is shown in Figure 2-60 and in Figure 2-61 which presents real short-circuit events. The results indicate that the contact radius spreading stage at the beginning of the short-circuit event was faster than the neck squeezing one towards the end of the short-circuit event [52, 54], although the opposite might be true in some occasions as shown from the fourth from the left short circuit occurrence of the left part of Figure 2-61 and for some of the

super-positioned waveforms in Figure 2-67; nonetheless, this might be because no two short circuits are the same and the influence of local instabilities which result the process to deviate from the norm as Di Pietro *et al.* report in their work in [12] which is presented later in 2.5.3.

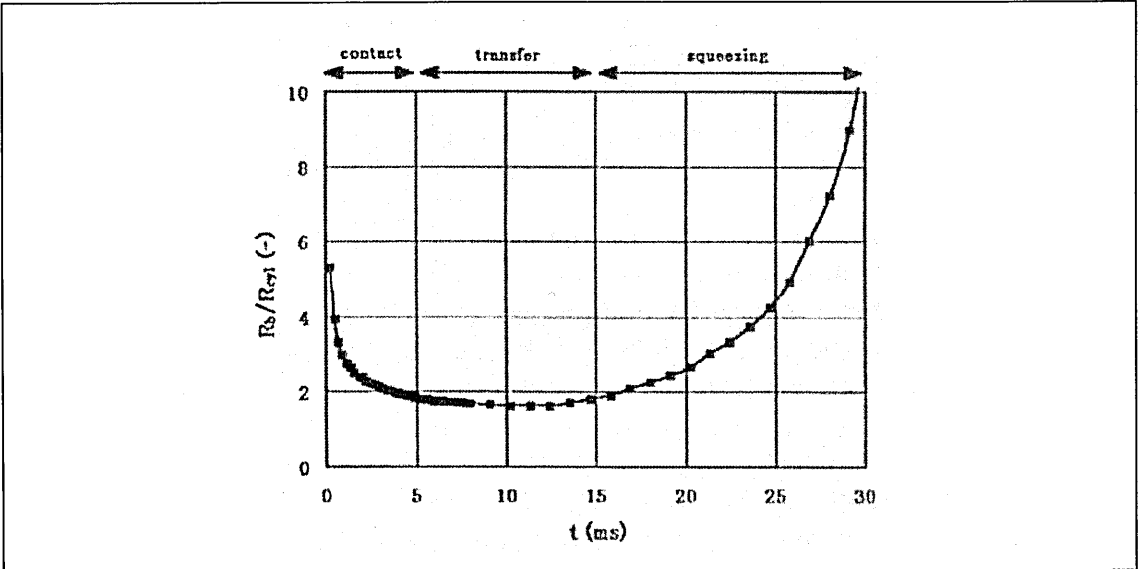


Figure 2-60 [52, 54]: A typical waveform for a liquid based droplet, showing a total detachment time of 30 ms approximately, which is about 15 times longer in duration than the average total detachment time for a molten metal droplet as shown in Figure 2-61.

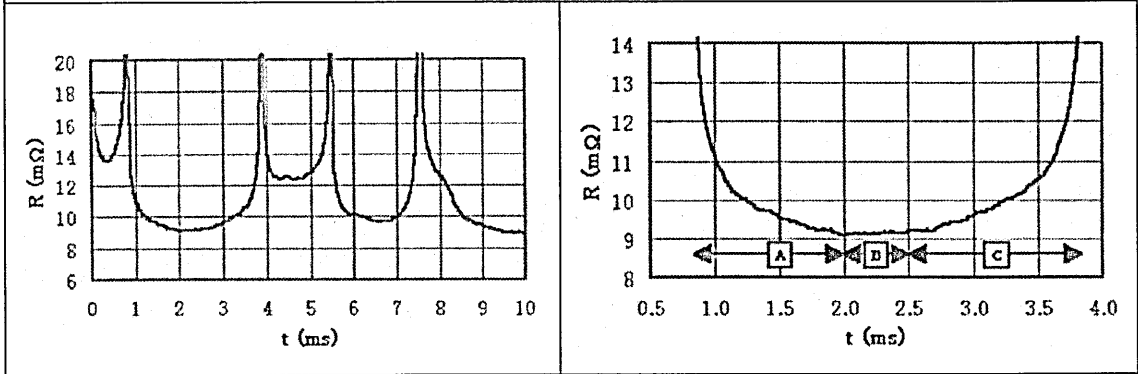


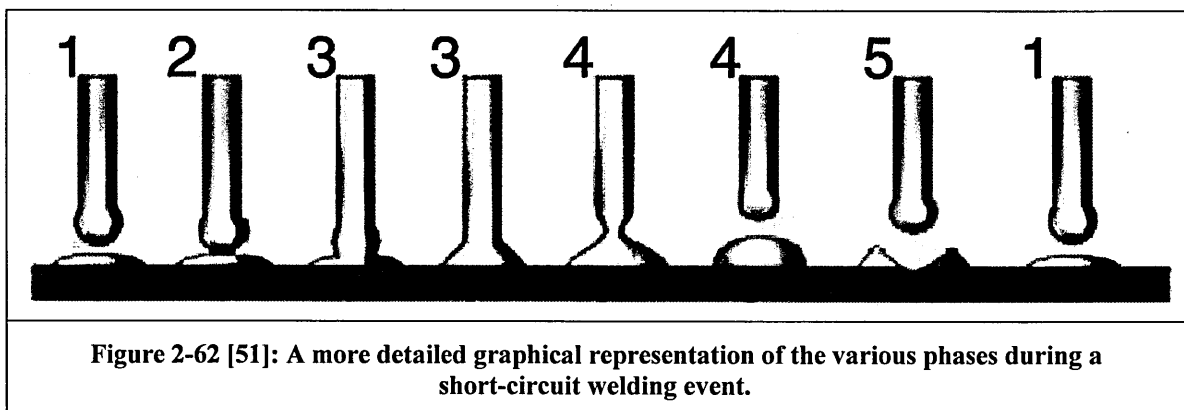
Figure 2-61 [52, 54]: Typical resistance waveform during five successive short-circuits [with the burning stages removed] on the left and on the right the second short circuit [counting from the left] of the waveform on the left is shown magnified by a factor of 2.5.

The Shape of the Molten Droplet and its Influence on the Dip Resistance’s Waveform

The following extracts from the work of Silva *et al.* [51] describe the forces acting on the molten wire which before its contact with the weld pool create a molten drop “which is initially (and ideally) spherical, starts to be constrained and takes on a cylindrical shape, forming the so-called metal bridge, which is said to be stable when it reaches the same diameter as the electrode wire along its whole length. The constriction continues, at an increasing speed, with the variation rate also growing

until finally the bridge collapses, thereby, defining the drop transfer formed during the previous arc, although a certain amount of liquid metal that is still on the point of the electrode wire is retained. The arc is then opened once again. ... In practise, the drop is not spherical or even symmetrical, and it is subject to vibration. ... The diameter of the drop (the metal bridge) falls continuously, until it reaches the same diameter as the electrode wire, at which point the metal bridge has become stable (the concept stipulated for this condition). The expansion speed of the contact diameter is greater than the speed of reduction of the drop diameter, until stability is achieved. After this, the contact areas continue to grow, although the diameter of the bridge remains stable and constant for a certain period, despite possible variations in the current. This outcome was anticipated by some authors and confirmed by others who analysed the resistive behaviour of the welding circuit during the short circuit and found a period, where the resistance remained constant ... The duration given for this period is 2 ms." [51]. Figure 2-63 [left] and Figure 2-63 [right] show graphically the tendency of the dip resistance to remain constant for a period of ≈ 2 ms as mentioned in the extract from [51] above. Further information on the duration of the short circuit is presented later in The Short-Circuit's Event Duration and Influencing Factors.

What is important from the above extracts is the implications that the shape of the molten droplet has in the shape of the dip resistance value in Figure 2-59 at the initiation of the short circuit which could be attributed to the lack of high welding current instead of necking [although it should really be both], as shown at t_4 of Figure 2-59. Figure 2-58, Figure 2-62 and Figure 2-64 help to illustrate this version.



This can be further supported by the fact that as Figure 2-59 shows the welding voltage is at its minimum at t_4 when spreading occurs and not at t_5 where the molten bridge's diameter equals that of the welding wire's; from Equation 2-3 [pp.100] with constant length and resistivity, the electrical resistance will be at its minimum when the cross-sectional area is at its maximum [time t_5]. With low welding current values Ohm's law [Equation 2-5 [pp.100]] will equate a low welding voltage value when the resistance is at its minimum which happens at t_5 of Figure 2-59. Instead, the lowest voltage is at t_4 of Figure 2-59 which seems to indicate that the graphical description of Figure 2-62 which shows at stages 2 and 3 [left] the molten bridge's diameter to be larger than the welding wire's diameter to be more accurate; however, at stage 2 spreading hasn't occur yet hence the actual contact surface area is still smaller than the welding wire's diameter so it restricts the welding current by exhibiting higher electrical resistance. If stage 2 of Figure 2-62 is considered to be very short in duration, then for the waveform of the welding voltage in Figure 2-59, the left stage 3 of Figure 2-62 takes place at the time t_4 in Figure 2-59. The dip-resistance is still not in its lowest value because the welding current cannot rise so rapidly due to the welding inductance [13, 51] and the regulated welding voltage [51] that the power source tries to keep constant by altering the welding current in a predetermined rate.

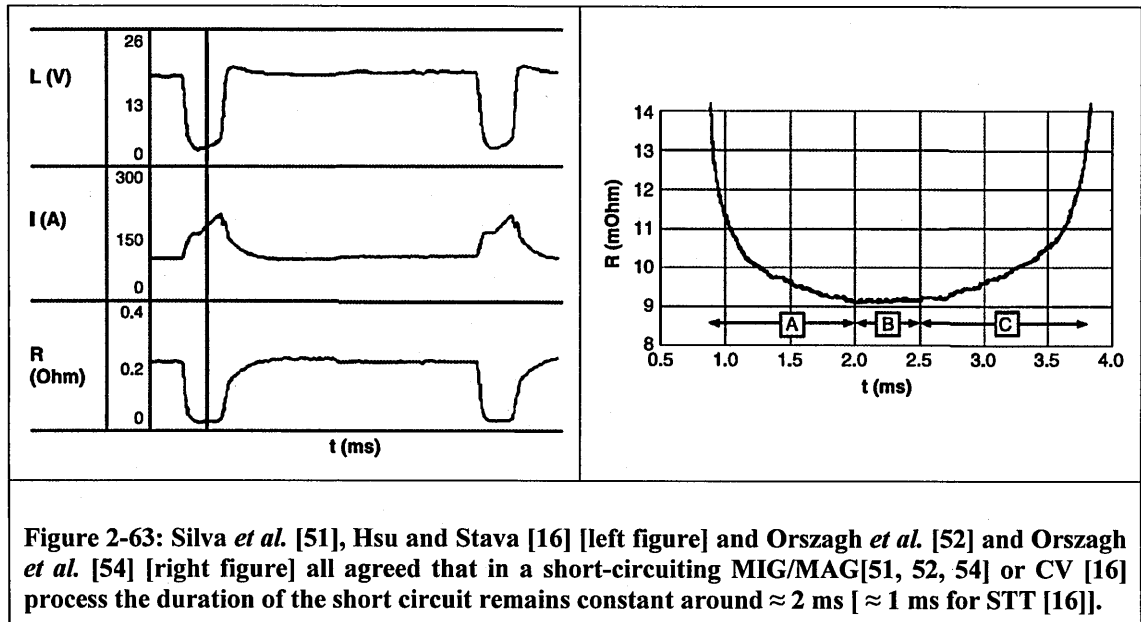
If the part of the welding wire that melts is forming a molten drop which when it touches the weld pool or the contact area has diameter different than the actual diameter of the wire, [as it happens during the spreading and necking stages as shown by the left stage 3 and the left stage 4 of Figure 2-62] then the measurement might not be exact if the samples are taken at this instance because of two reasons. The first one is that the welding voltage is at its lowest value due to the low welding current, since according to Equation 2-5 [pp. 100] if the welding current doesn't have a high value the voltage drop across a resistor is small. The second one is given by Equation 2-3 [pp. 100] which indicates that the cross-sectional area 's' should be uniform over the length of the wire. If it is less, then the measured resistance will be greater than the actual one, whilst if it is more, then the actual resistance will be shown to be smaller than the actual one. As a result of the two reasons, the actual dip resistance and consequently the actual length of the conductor [the stick-out which equals the CTWD in the short-circuit event] will be determined to be larger or smaller

respectively than the original one if the diameter is not consistent but changes with random behaviour. However, as it will be reported later in 2.5.3 and shown graphically in Figure 2-80, the control tactic from Di Pietro *et al.* in [12] with the use of thresholds enables the validity of the assumption that the influence of the molten metal's diameter at stages 2 and 3 [left] of Figure 2-62 [when it is larger than the welding wire's diameter hence this section has a smaller electrical resistance as per Equation 2-3 [pp. 100]] is negligible, something that in practice however might be inaccurate. If it is not negligible, the welding current should peak in this part of the short-circuit event; however, due to the large inductance of the welding setup(s) the rate of increase for the welding current will be limited although the welding voltage will be at its minimum as Figure 2-59 shows. The previous mean that since its process is different experimental examination is needed in order to establish if the threshold based tactic of Di Pietro *et al.* in [12] is required and the value that the threshold levels must have.

The Short-Circuit's Event Duration and Influencing Factors

As shown in the top of Figure 2-59, there are two main periods ' T_1 ' and ' T_2 ' which constitute the total cycle time ' T '. The period of ' T ' was found to be between 10 msec and 25 msec, but as Philpott reports in [13] this duration was found to vary in a random fashion. The interval ' T_1 ' is the Arcing Time and the interval ' T_2 ' is the Short-Circuit time. The latter characterizes the power source. The rate of rise for the current at the beginning of the short-circuit is a function of the power source slope characteristic and the inductance L that is connected in series with the welding circuit. By varying ' L ' the duration of the short circuit can be controlled. The duration of ' T_2 ' was found by Philpott [13] to be between 1 msec to 8 msec and under stable conditions it did not vary much.

What is very important to note is that as Silva *et al.* [51] reports, the average duration of the short circuit is basically constant, around 2 ms [51]. This is further supported by the works of Hsu and Stava [16] and Orszagh *et al.* [52] and Orszagh *et al.* [54] as shown in the left and right parts of Figure 2-63.



A last point to remember is that lower current levels and droplet's volume influences the time for the detachment, in other words, the duration of the short-circuit [51]. The duration of the total time of detachment [the time from closing the short circuit to the time of the arc's re-ignition] is inversely proportional to the welding current and directly proportional to the drop's volume [51]. This is illustrated in the simulation results of Figure 2-64 and is fundamentally important to be taken into account when control of the process via control of the short-circuit duration and frequency is to be achieved. The results indicate that the detachment time increases as the welding current decreases and/or the drop's volume increases.

In addition to the welding current and liquid metal droplet volume, Orszagh *et al.* [52] and Orszagh *et al.* [54] found that the welding voltage also plays a role in the duration of the short-circuit as well as in the short-circuit frequency [52, 54]. The higher the voltage, the shorter the short-circuit duration, and fewer short-circuit occurrences take place [52, 54]. More details on this are presented in 2.5.2. Philpott [13] also reports that the voltage affects the total period 'T' -defined in Figure 2-59- and consequently the short circuit frequency and that, as Philpott cites in [13], the main conclusion from the work other researchers have done is that the higher the short circuit frequency the more stable the process is, thus the welding voltage should be adjusted to maximize the short circuit frequency.

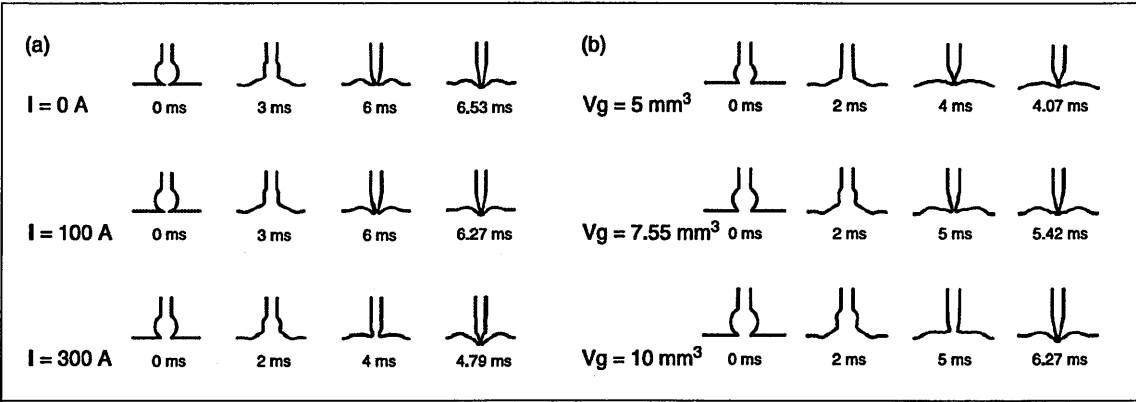


Figure 2-64 [51, 56]: The inverse proportionality of the detachment time with the welding current value is shown on the left and on the right the direct proportionality of the detachment time with the drop's volume is shown.

Process Stability Vs. Electrical Stability

Regarding Philpott's suggestion in [13] that the welding voltage must be adjusted so as to maximise the short-circuit frequency, care must be taken, since as Richardson *et al.* [6] and Nixon *et al.* [59] suggest, process stability does not necessary imply electrical stability. As Richardson *et al.* [6] and Nixon *et al.* [59] report, the overall process stability might be difficult to be quantified and for their work on the hyperbaric GMA a subjective estimation was made based on visual assessment of arc stability, spatter levels and resultant bead appearance. This is demonstrated in Figure 2-65 where good process stability was obtained with moderate electrical stability as shown in the middle graph [6, 59] and a good electrical stability resulted in poor process stability as shown on the top graph [6, 59]. In contrast with Philpott's [13] suggestion above for maximising the short circuit frequency, Richardson *et al.* [6] and Nixon *et al.* [59] reported that the lower graph of Figure 2-65 present poor process stability and poor electrical stability although the short-circuiting frequency was maximised. The conclusion from these three works [[6], [59] and [13]] is that each process is different, at least when hyperbaric and non-hyperbaric processes are compared.

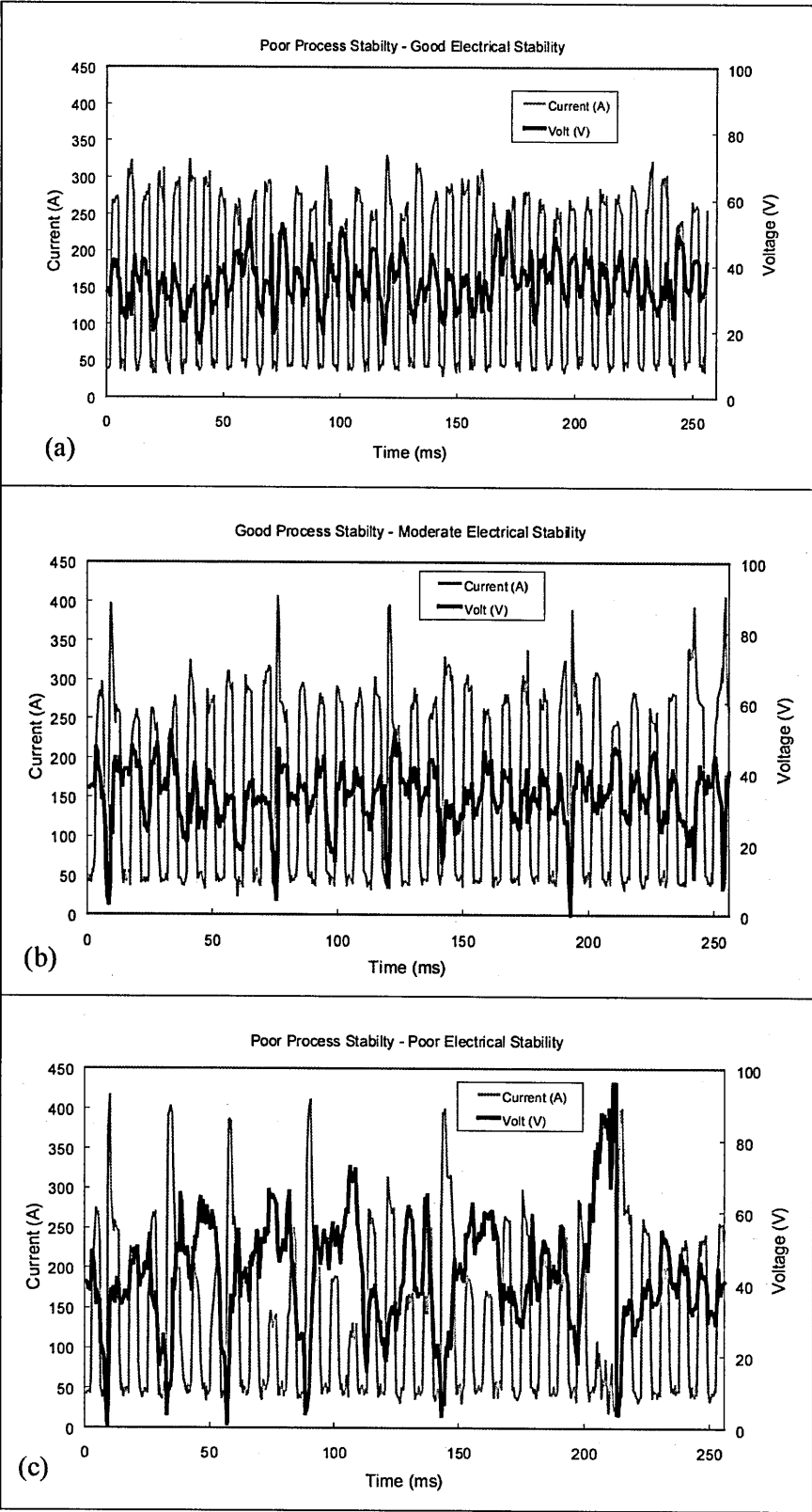
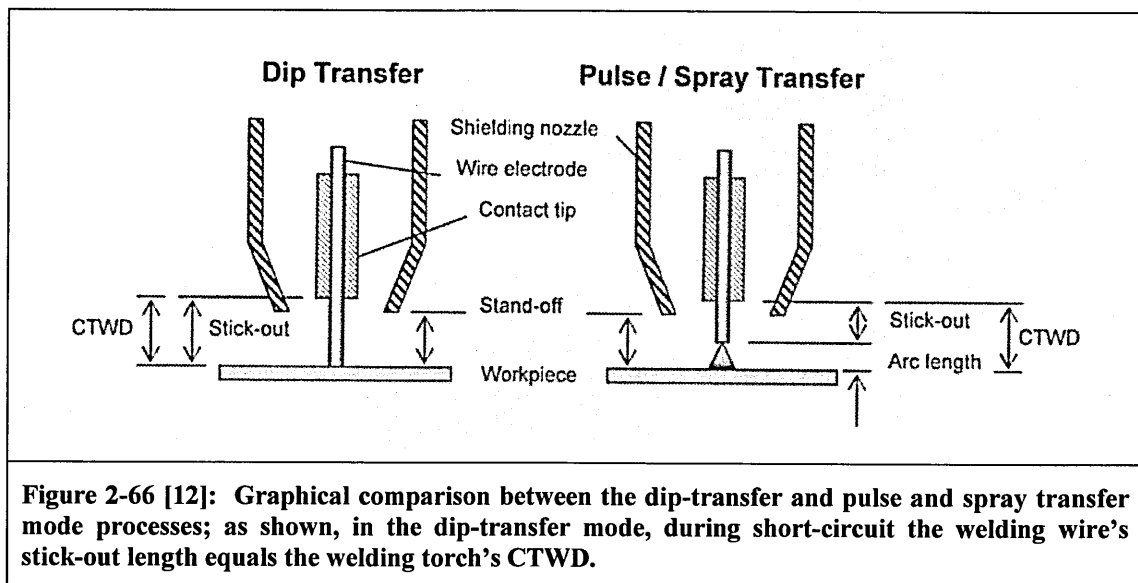


Figure 2-65 [6]: Process stability might be achieved in Hyperbaric GMAW without having electrical stability. The top figure [(a)] shows an example of an unstable process with good electrical stability, the middle figure [(b)] shows an example of a stable process with moderate electrical stability and the lower figure [(c)] shows an example of poor electrical stability for an unstable process.

Method of Operation for Dip Resistance Measurement

Based on the behaviour of the homophase drop-pool presented earlier in Further Work on The Shape of the Welding Wire's Resistance Waveform, Orszagh *et al.* [52] and Orszagh *et al.* [54] proposed how a detection method of the CTWD value could be implemented. In short-circuiting or Constant Voltage [CV] welding [16], simplification of the welding arc model occurs since the welding arc collapses at regular intervals and physical contact occurs between the electrode and the molten weld pool [16]. The welding arc's collapse removes the anode, cathode and column voltage drops from the welding voltage measurement [16]. Based on these, during the short-circuit, the extension of the wire equals the CTWD, hence a measurement of its electrical resistance can be correlated with its length [52, 54]; this is shown graphically in Figure 2-66 where the comparison of dip-transfer with pulse and spray-transfer mode is presented [12].



In order to avoid a high resistance of the drop-pool contact region when initiation of the short-circuit occurs, the resistance value should be based on the samples taken after the contact radius is wide enough [$t > 1$ ms] [52, 54], for example after t_4 in Figure 2-59. This will aid to minimise the error induced by the difference in the wire's cross-sectional area and the contact area [52, 54] during the spreading stage. Nonetheless, very late samples, for example at t_6 of Figure 2-59 are again less indicative of the true resistance since necking occurs which alters the cross-sectional area [the neck is very narrow] of the liquefied wire hence presents a higher resistance value [52, 54].

Measuring the Dip Resistance Value

In order to measure the electrical resistance of the wire during a short circuit, Ohm's law can be used [12, 16] to extract the extension of the wire which is proportional to its length [16] since the arc is collapsed and does not contribute to voltage drop [16]. The mathematical expression of Ohm's law is shown in Equation 2-5 [pp. 100]. As the equation describes, the electrical resistance of a conductor is given by the voltage across the conductor over the current that flows through the conductor. The resistance of a conductor can be 'loosely' said to express the difficulty that the electrons have to flow through the conductor. In order to measure the dip resistance we need to measure the voltage across the welding wire's stick-out length [which during the short circuit event will equal the CTWD] and the current through the welding wire. This will give us the electrical resistance of the wire's stick-out which we can then convert to units of length, by comparing it with a reference value; the reference value is the welding wire's electrical resistance per unit length which can be measured or calculated using Equation 2-3 [pp. 100] if resistivity ' ρ ' is known or can be measured experimentally under welding conditions as Philpott did in [13] and is described in 2.5.5. In order for this to be done correctly the following assumptions must hold true:

- 1) The pick-up points for voltage measurement must be exactly at the tip of the torch and under the weld pool's point at the same height as the original parent metal's height,
- 2) The welding wire's must have electrical contact with the tip of the torch,
- 3) The welding wire extension is straight and of uniform volume, equal to the reference welding wire's value, volume per unit length, and of the same constitution so as resistivity ' ρ ' to be the same.
- 4) The current through the welding circuit flows through the arc without leaking through other conductive parts between the points of voltage feedback measurement.

In practice, the most challenging task is to hold true the first assumption. The reason is that the feedback points are usually located away from the torch's tip and the weld pool for practical reasons. However, since the electrical resistance of a conductor

depends on its geometrical characteristics and, according to Equation 2-3 [pp. 100] at a large extend its cross-sectional area [which compared to a welding wire's cross-sectional area are extremely large for both the parent metal and the welding torch] we can consider the value of the “added” resistance small and fairly constant for the duration of the weld. In other words, even if an error exists, it will be constant for each measurement [or fairly constant as the welding torch moves around the parent metal whilst at least one of the feedback points remain stationary], thus by examining the difference in electrical resistance values between successive measurements we can extrapolate the true change in the welding wire's resistance, hence its length according to Equation 2-3 [pp. 100]. Therefore we can assume that the measured voltage value is almost identical to the voltage drop between the tip of the welding torch and the top of the weld pool.

Electrical Resistance and Power Source Mode of Operation

In practice, when the power source operates in Constant Voltage [CV] mode, it will ‘try’ to keep the arc voltage constant by altering the current value based on Ohm's law described by Equation 2-5 [pp. 100]. For a given [feedback] welding voltage value, the higher the welding current, the lower the electrical resistance value hence the shorter the welding wire's extension. The lower the welding current value, the higher the electrical resistance value, hence the larger the welding wire's extension.

A power source that operates in Constant Current [CC] mode, will try to keep the welding current constant through the welding circuit by altering the applied welding voltage. For a given [feedback] welding current value, the higher the applied welding voltage, the higher the electrical resistance hence the larger the welding wire's extension. The lower the applied welding voltage value, the lower the electrical resistance value, hence the shorter the welding wire's extension.

From the above it is evident that no matter what mode of operation is employed, if reliable welding voltage and welding current measurement values are ensured, Ohm's law [Equation 2-5 [pp. 100]] can be used to extract the electrical resistance value for the welding wire, hence its length.

Electrical Resistance and Temperature

It is a fact of the physical world that conductor's electrical resistance changes with as their temperature changes. In dip-transfer mode the wire's extension is subjected to resistive heating [12]. A conductor might have a Positive Temperature Coefficient [PTC] or a Negative Temperature Coefficient [NTC]. A PTC conductor expresses higher electrical resistance as its temperature rises and a NTC conductor expresses lower electrical resistance as its temperature rises. For a steel-based welding wire, the electrical resistance rises as the temperature rises [13]. Although this property of electrical conductors offers itself as an advantage for numerous applications, in the case of the dip resistance measurement imposes a significant question: "does the alteration of the welding wire's temperature during welding and the temperature of the rest of the welding circuit's components [namely the parent metal and the welding torch] affects the electrical resistance measured in such a degree so as to distort the measurement and estimation of the welding wire's extension?" As Keats states [42 pp. 5, 7], the temperature inside the arc's plasma can exceed 5,000 °C, 2/3 of which is distributed on the positive pole of the welding circuit and 1/3 is distributed on the negative pole. In addition to this, everything in the vicinity of the arc's ultraviolet and infrared emitted radiation will experience heat transfer phenomena. These 'extreme' conditions can easily lead us to the conclusion that the change in the resistance can be large for the dip resistance application. However, a compensating factor is that because of the small volume of the welding wire, and the relatively large cross-sectional areas of the welding torch and the parent metals [resulting in large heat capacity], the heat distribution should evolve rapidly and should remain constant between welding passes. In the examples that follow some authors performed an analysis of the effect of the temperature and their results could act as a guide to this project's work.

2.5.2 Dip Resistance Sensor for GMA/CO₂

Orszagh *et al.* [52] and Orszagh *et al.* [54] developed a CTWD detection technique based on dip resistance for GMA/CO₂. Much of their work has been mentioned earlier in 2.5.1 and here details of the actual sensor system will be presented.

Algorithm for CTWD detection

The algorithm for CTWD detection was constructed based on welding voltage and welding current waveforms regardless of large variations in their instantaneous values. The authors found that CTWD could be detected reliably from the dip resistance values during short-circuit events. The authors tested the sensor under different welding conditions and verified its applicability using real time monitoring of the sensor signal. Their suggested technique has been mentioned earlier in 2.5.1. The principle that was adopted for the sensor was to select data at the centre of the curve during short-circuiting events as pointed by the arrow in Figure 2-67. At this point, the welding resistance reaches a local minimum and its first time derivative is zero [52, 54], in other words, remains the same for a period of time. As the authors say, this selection satisfies both conditions, the contact area to be wide enough and the neck region not to be significantly developed yet [52, 54] which can be graphically approximated by stage 2 in Figure 2-58. This should be the point(s) in time where the resistance of the liquid droplet will be at its minimum value according to Equation 2-3 and should best reflect the value of CTWD [52, 54].

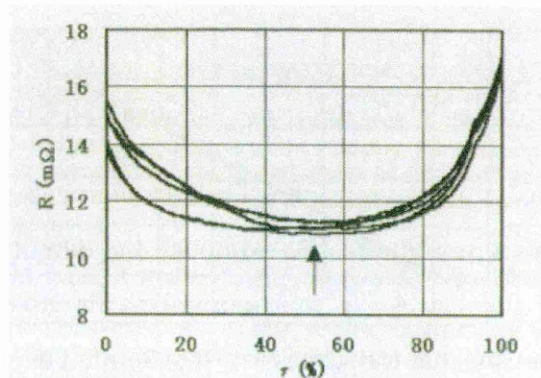


Figure 2-67 [52, 54]: Superposition of six successive short-circuiting occurrences with duration more than 2 ms [time scale is dimensionless and the short-circuiting time is normalised in 0 % to 100 % scale] which shows that in most cases the necking-stage lasts longer than the spreading-stage.

The Necessity for Repeatable Electrical Characteristics and Factors of Influence

As the authors of [54] say, in order for the sensor to give an appropriate signal for control [a signal that only changes when the measured quantity changes], the resistance of the liquid droplet and the resistance of the solid wire extension [54] must not change between subsequent short-circuits [assuming constant CTWD]. This implies that the profile of the molten metal droplet and the temperature distribution in the solid part of the wire [54] [and for the same reason the temperature profile of the parent metals] do not present significant changes [54]. The authors suggest that under most welding parameters both approximations are quite acceptable [54]. As illustrated in Figure 2-67, the resistance for constant CTWD should not present significant changes; Figure 2-66 shows the super-position of the measured resistance profile over six short-circuit occurrences during the welding run [not subsequent short-circuit occurrences]. The arrow in Figure 2-66 indicates the point when the resistance of the molten metal droplet is at its minimum, where the measurement(s) must be taken. However, as the result from the same authors proved in [52] and [54] showed and presented in the left part of Figure 2-61 and in Figure 2-68, although over the duration of the welding run with constant CTWD indicative short-circuit events which have the same dip resistance profile as Figure 2-66 illustrates do exist, no two subsequent short circuit events are the same, as is also reported by Di Pietro *et al.* in [12]. This must have to do with the fact that the geometry of the formed molten droplet changes and is not constant during the process as reported by Silva *et al.* [51] and presented earlier in The Shape of the Molten Droplet and its Influence on the Dip Resistance's Waveform [pp. 102].

Correlation of Dip Resistance Variation with CTWD

The authors took measurements with the CTWD changing between 8 mm to 23 mm and the results are shown in Figure 2-68. Although the output for each CTWD level varies during welding for successive short-circuit events, as the left part of Figure 2-61 suggests, which means that for successive short-circuit events the is not as steady as in the case of Figure 2-67, there is a clear distinction between each level [52, 54]. The dip resistance increases as the CTWD increases and this trend can be used for torch height manipulation [52, 54] reasons.

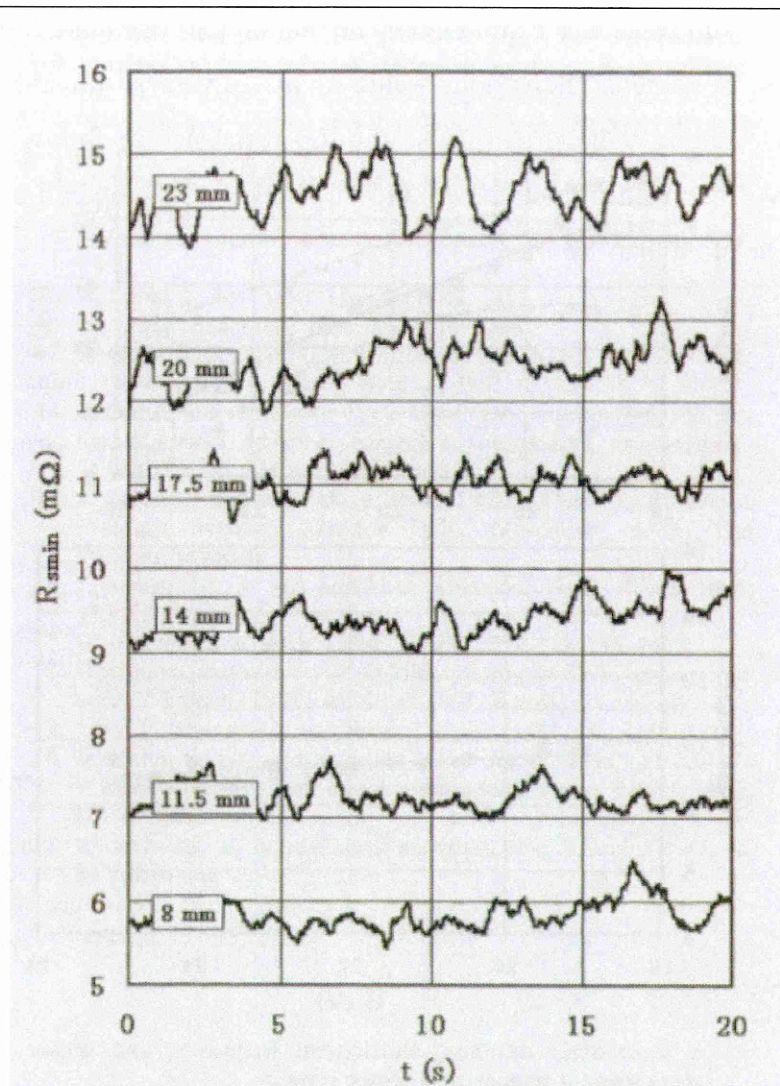


Figure 2-68 [52, 54]: The measured dip resistance's fluctuation of the sensor system for various CTWDs using the same welding conditions.

Influence of Welding Voltage on Short Circuit's Duration

As mentioned earlier in 2.5.1, the authors of [52] and [54] discovered a correlation between the welding voltage and the short-circuit event duration, frequency and the sensors measured frequency as shown in the top part of Figure 2-69. More specifically, a change of the welding voltage from 19 V to 25 V induced a reduction of the short-circuit event duration from 4 ms to 1 ms, short-circuit frequency reduction from 60 Hz to 35 Hz and the sensor measurement frequency was reduced from 40 Hz down to 12 Hz [52, 54]. It has to be noted that the authors do not explain what exactly they mean by the term 'sensor measurement frequency' and it is assumed to be the number of short-circuit occurrences that the algorithm considered to be valid, out of the total number of short-circuit type voltage and current values, so

as to be used for dip resistance estimation. The bottom part of Figure 2-69 shows the output of the sensor against the various welding voltage values. It can be seen that a change in the welding voltage can cause the dip resistance to follow a downward trend. However, the values fluctuate around this trend and the overall variation does not appear to be more than 1.5 mOhms.

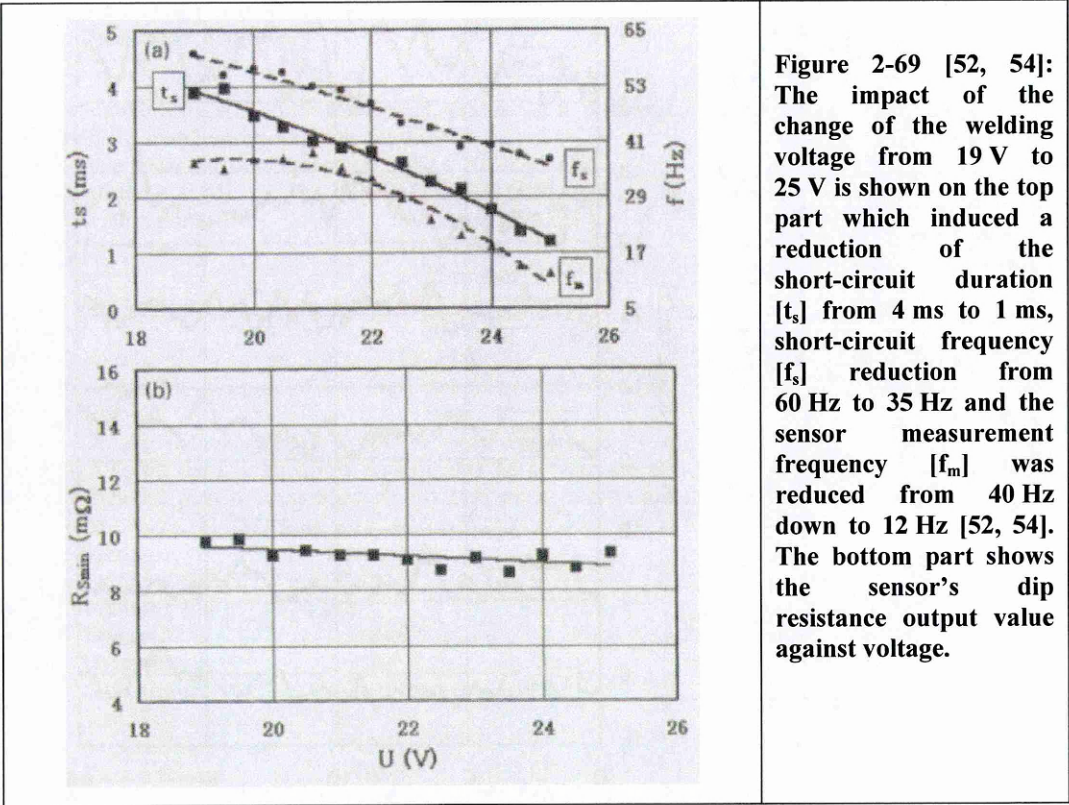


Figure 2-69 [52, 54]: The impact of the change of the welding voltage from 19 V to 25 V is shown on the top part which induced a reduction of the short-circuit duration $[t_s]$ from 4 ms to 1 ms, short-circuit frequency $[f_s]$ reduction from 60 Hz to 35 Hz and the sensor measurement frequency $[f_m]$ was reduced from 40 Hz down to 12 Hz [52, 54]. The bottom part shows the sensor's dip resistance output value against voltage.

Sensor’s Static Characteristic

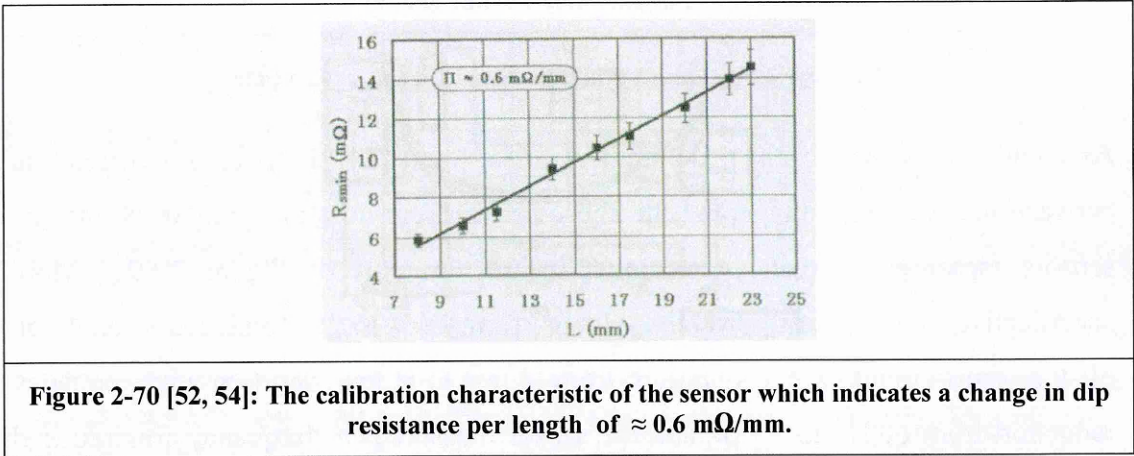


Figure 2-70 [52, 54]: The calibration characteristic of the sensor which indicates a change in dip resistance per length of $\approx 0.6 \text{ m}\Omega/\text{mm}$.

From the results of the work on the Influence of Welding Voltage on Short Circuit’s Duration [pp. 115], the authors constructed a static characteristic for their sensor which is shown in Figure 2-70 and clearly indicated that there is a linear correlation

[for the torch's stated height variation] between the dip resistance value and the CTWD of ≈ 0.6 mOhms/mm.

Influence of Power Source Characteristic on Short-Circuit Parameters

The authors of [52] and [54] also studied the effect of changing the power source characteristic and the effect of this change is shown graphically in Figure 2-71. The top part of Figure 2-71 shows that an increase in the power source characteristic from 31 kA/sec to 200 kA/sec significantly reduces the short circuit duration 6 ms to 1 ms, the short-circuit frequency fluctuates between 35 Hz to 75 Hz and the sensor's measured frequency fluctuates from 15 Hz to 60 Hz. The bottom graph however reassures us that a constant upwards trend exists which can be used as a control variable for CTWD detection and adjustment; the overall variation in dip resistance value is around 2 mOhms. The effect on the short-circuit's parameters from the power source current slope characteristic can be attributed to two effects. Firstly, the heat input to the process changes which means that the melting behaviour changes. Secondly, different welding current waveform will result in the generation of different electromagnetic forces as explained in 2.5.3 which will result in different weld pool and molten droplet characteristics with direct effect on the part of the process that the welding wire is in contact with the weld pool before the welding arc re-establishes itself.

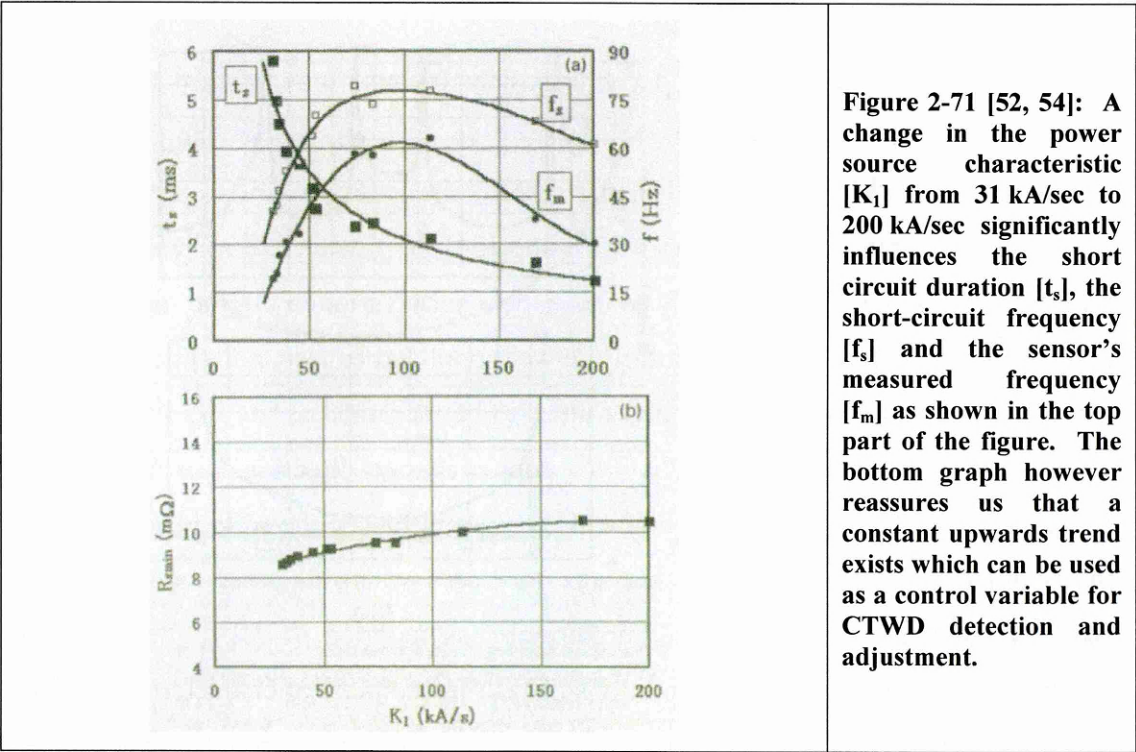


Figure 2-71 [52, 54]: A change in the power source characteristic [K_1] from 31 kA/sec to 200 kA/sec significantly influences the short circuit duration [t_s], the short-circuit frequency [f_s] and the sensor's measured frequency [f_m] as shown in the top part of the figure. The bottom graph however reassures us that a constant upwards trend exists which can be used as a control variable for CTWD detection and adjustment.

Influence of Weld's Bead Characteristics

The authors of [52] and [54] made test run(s) with downhill and uphill welding directions and compared the results. The results are presented graphically in the top part of Figure 2-73 for the downhill direction and on the bottom part of the same figure for the uphill direction. For the downhill test the CTWD was changed from 13 mm to 23 mm and the sensor's output changed from 8.5 mOhms to 15.5 mOhms with the calibration characteristic of Figure 2-73 to 'predict' a change from 12.5 mOhms to 23.5 mOhms. For the uphill test the CTWD changed from 23 mm to 9 mm and the result was that the sensor's dip resistance output decreased from 14.5 mOhms to 7 mOhms. This means that the sensor measured a CTWD change from 22.5 mm down to 10 mm according to the calibration characteristic of Figure 2-70. The authors of [52] and [54] explain the difference in CTWD measurement between the downhill and uphill tests [≈ 1 mm] in the appearance of the weld bead formation during the tests, something that is attributed to the principle of operation of the sensor since the CTWD is the distance between the torch's tip and the weld pool; different weld bead appearance is the result of different weld pool characteristics as the sensor's principle is to measure the torch-to-pool distance [52, 54]. The weld pool's characteristics and its implications in the measurement of dip resistance and CTWD estimation are presented and discussed in 2.5.3.

These results are very important for this project because they suggest the vertical movement of the welding torch [towards or away from the welding specimen] influence the CTWD estimation. In the case of the RPRS where welding is to be performed orbitally, the results from [52] and [54] presented here indicate that it is possible even with constant CTWD and no pipe ovality variation or other disturbances [ideal conditions] the characteristics of the weld pool and consequently the weld bead could result in different dip resistance values to be measured as the welding position moves around the pipe and gravitational forces change direction. In addition, as Richardson and Nixon [9] report, ambient pressure influence the weld bead geometry the width of which increases as pressure increases when all other parameters are fixed, as shown in Figure 2-72. Furthermore, as reported in 2.2.1, the increased cooling rates under hyperbaric conditions affect the geometrical characteristics of the deposited weld beads which exhibit steeper wetting angles and rough surface finish

[6] which is attributed to the fully turbulent conditions which are at least partially responsible for the weld pool's disturbance [6]. This means that in this project, the influence of the welding geometry's variations on the estimated dip resistance values can be even greater than in the case of 1 Atm welding.

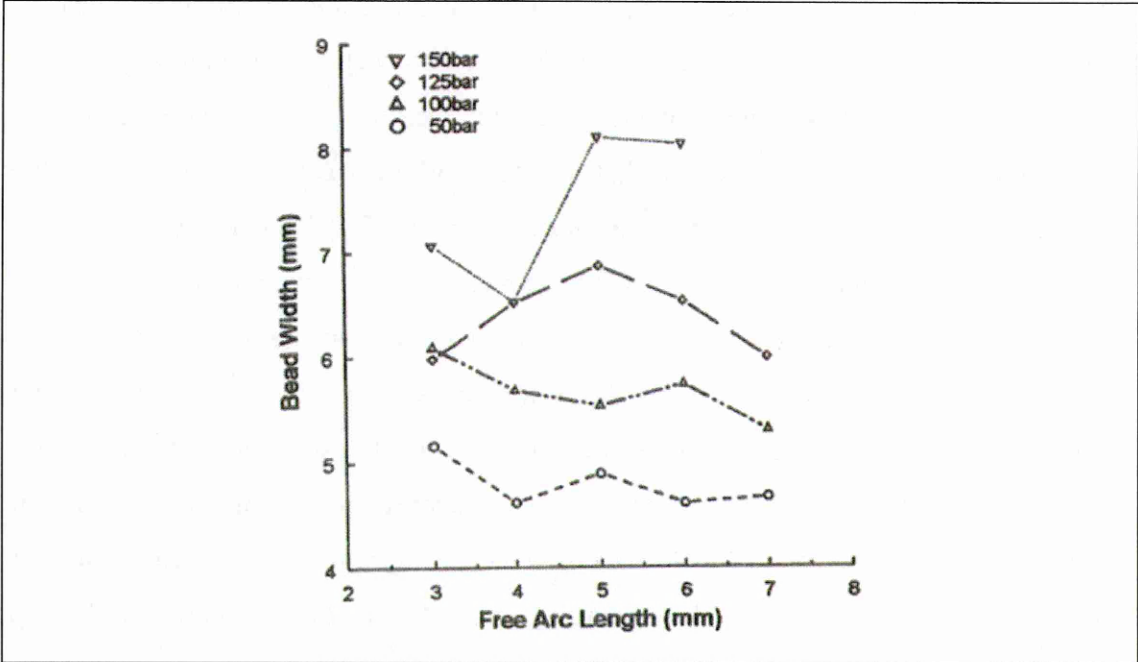


Figure 2-72 [9]: The influence the free arc length can have on weld bead width with different ambient pressures using argon atmosphere for hyperbaric welding as studied by Richardson and Nixon [9].

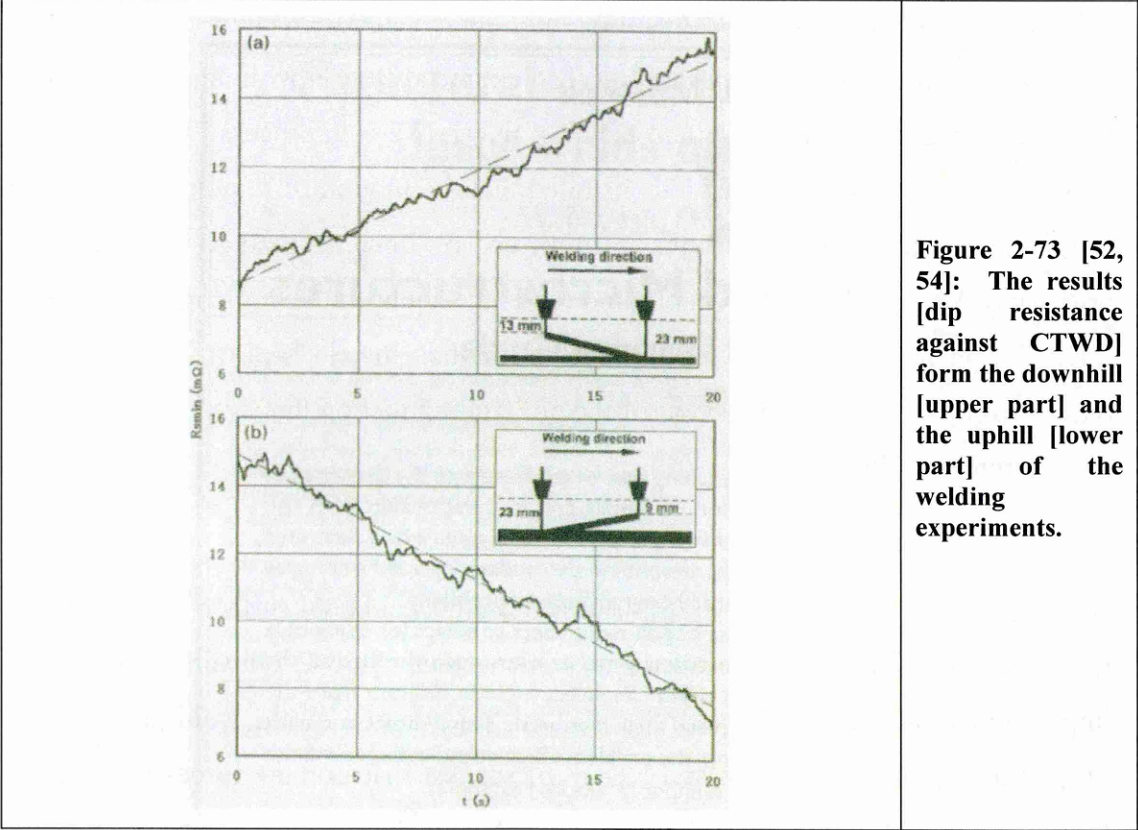


Figure 2-73 [52, 54]: The results [dip resistance against CTWD] form the downhill [upper part] and the uphill [lower part] of the welding experiments.

2.5.3 Weld Pool's Characteristics

As mentioned earlier in Influence of Weld's Bead Characteristics [pp. 118], the welding conditions have an effect on the weld bead's which influences the measurement of dip resistance. The geometrical characteristics of the weld bead are directly related to the weld pool characteristics. It has been reported already in 2.2.1 that alterations in the welding geometry affect the weld bead's characteristics due to the welding pool's disturbance and that the fully turbulent conditions governing the welding arc's behaviour are at least responsible for this [6]. Also, as it is reported in [1, 5, 6 and 38] and presented in 2.2.4 above, there is a mismatch between the relatively high frequency ranges of the welding arc's instabilities and the low frequency response of the weld pool. According to the work from Woods and Millner [74], Lawson and Kerr [75] and Lawson and Kerr [76], the weld pool characteristics responsible for the weld bead's geometry are influenced from a number of different factors. Portions from these three pieces of work are presented below because of their significance in understanding the underlying reasons for the behaviour of the dip resistance waveform, hence measured value, during a short circuit.

It has been observed in GTAW, GMAW and Submerged Arc Welding processes that weld pool fluid motion takes place [76]. Molten metal fluid flow in an arc weld pool has been recognised as an important factor of the arc welding process [77]. The work of Woods and Milner [74] has demonstrated that the motion of a molten pool is the result of two factors [74], and this is confirmed by Laurence and Kerr [76]. The primary reason for the molten pool's motion is the action of electromagnetic Lorentz force due to the current flowing through the molten metal [74, 76]. A secondary reason for this motion is the action of the arc's plasma jet on the weld pool's surface if the torch is angled [74].

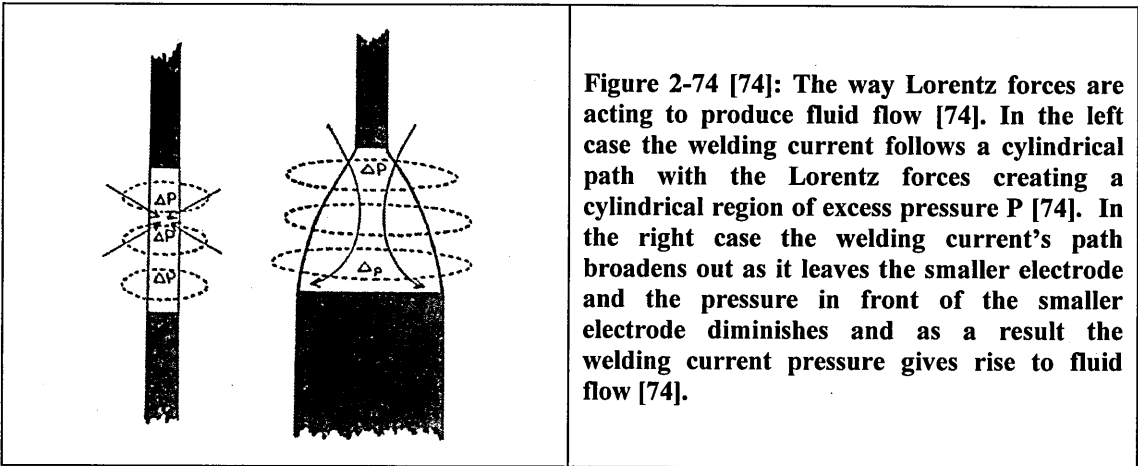
According to a different theory [76] the crater on the weld pool surface is the result of high velocity plasma impingement which then flows outwards from the impingement area and causes same direction fluid motion on the weld pool surface [76]. Simulations by Lawson and Kerr [76] suggest that Lorentz forces are causing the presence of the crater on the surface of the pool [76], which also means that

existence of crater does not necessarily imply significant arc impingement forces since no arc was present in the simulations [76].

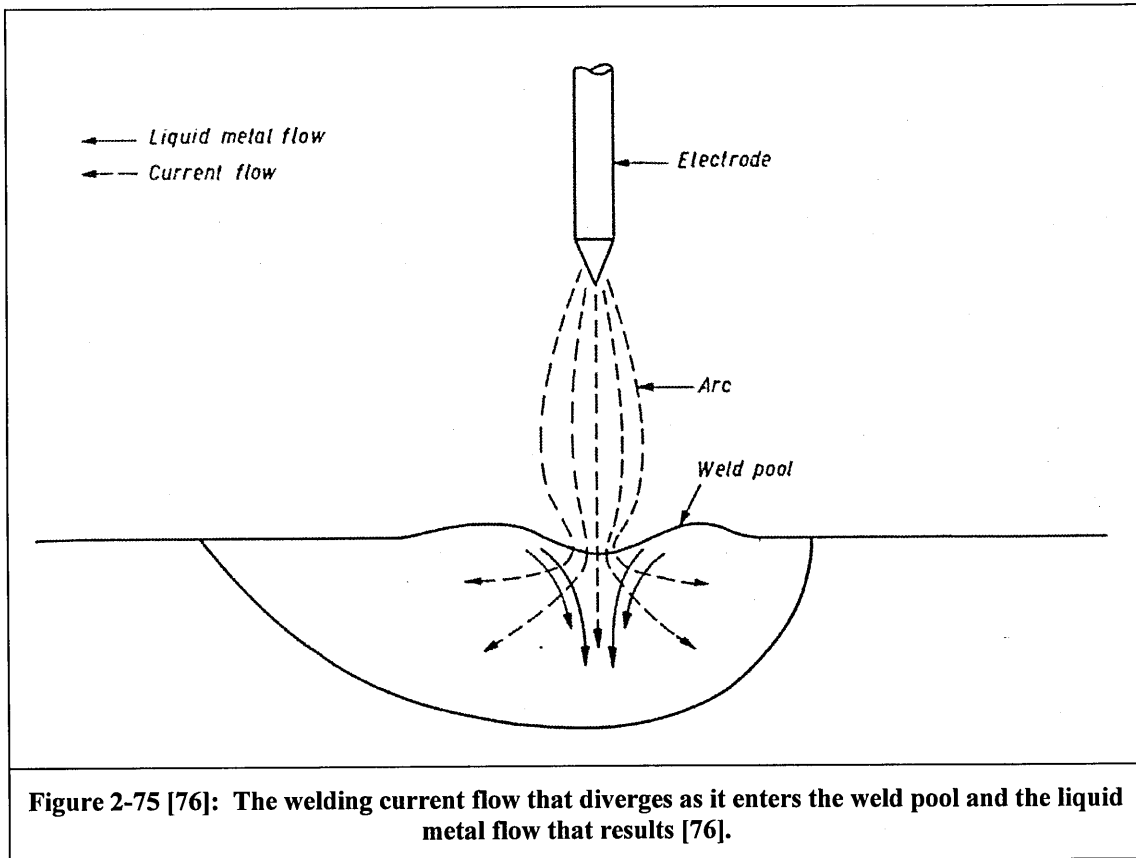
Another theory suggests that in addition to high velocity plasma impingement surface tension variations have been proposed as the driving force of weld pool fluid motion [76]. Although surface tension variations alone are known of being capable for bulk fluid motion and their effects have been the topic of investigations for weld pool's geometry [76], the dominance of the surface tension mechanism in producing fluid motion in arc welding is questionable [76].

Influence of the Welding Current's Characteristics on the Weld Pool

Influence of Welding Current's Path Flow Geometry



As can be seen in Figure 2-74, a current which follows a cylindrical path through a fluid will induce a magnetic field which will interact with the current that generates it [74]; the result of the interaction is an inwards acting force and an excess pressure is applied on the fluid with a magnitude and direction equal and opposite to Lorentz force's [74]. The Lorentz forces are the result of the flow of the welding current [74], interacting with its own [or other] magnetic fields [76] and more specifically its constriction at the arc's root [74]; the constriction causes fluid flow in other parts of the weld pool, not directly under the high current density region [74]. This is shown graphically in [Figure 2-75] where a fluid jet is induced in the weld pool from the divergence flow of welding current that enters the weld pool [76].



The force and consequently the pressure increase are proportional to the product of the current density and field strength [74]. As the current flows from a smaller diameter electrode to a larger diameter one, a streaming flow occurs away from the smaller constricting electrode towards the larger one [74]. In this case where the current flow path is not cylindrical as it is shown in the left part of Figure 2-74 but it broadens out as shown in the right part of Figure 2-74, the current density will decrease [74] as the flowing area increases; as a result, a pressure gradient is created away from the region with the highest current density which causes fluid to flow away from this region as shown in the right part of Figure 2-74 [74]. This shows that the fluid motion is Lorentz force induced but it does not explain how the different forms of double circulation and pure rotation arise [74]. If the welding current's path travels through and out of the weld pool in a symmetric manner, the form of the motion will be a double circulation [74]. When the welding current's travel path is not symmetric, one half of this double circulation pattern will become dominant and as a result a pure rotation of the weld pool's fluid will occur [74]. The effect of the asymmetric welding current path is increased even further from the action of the magnetic fields [74, 76].

Welding Current Magnitude and Path, Fluidic Rotation and Electrode Location

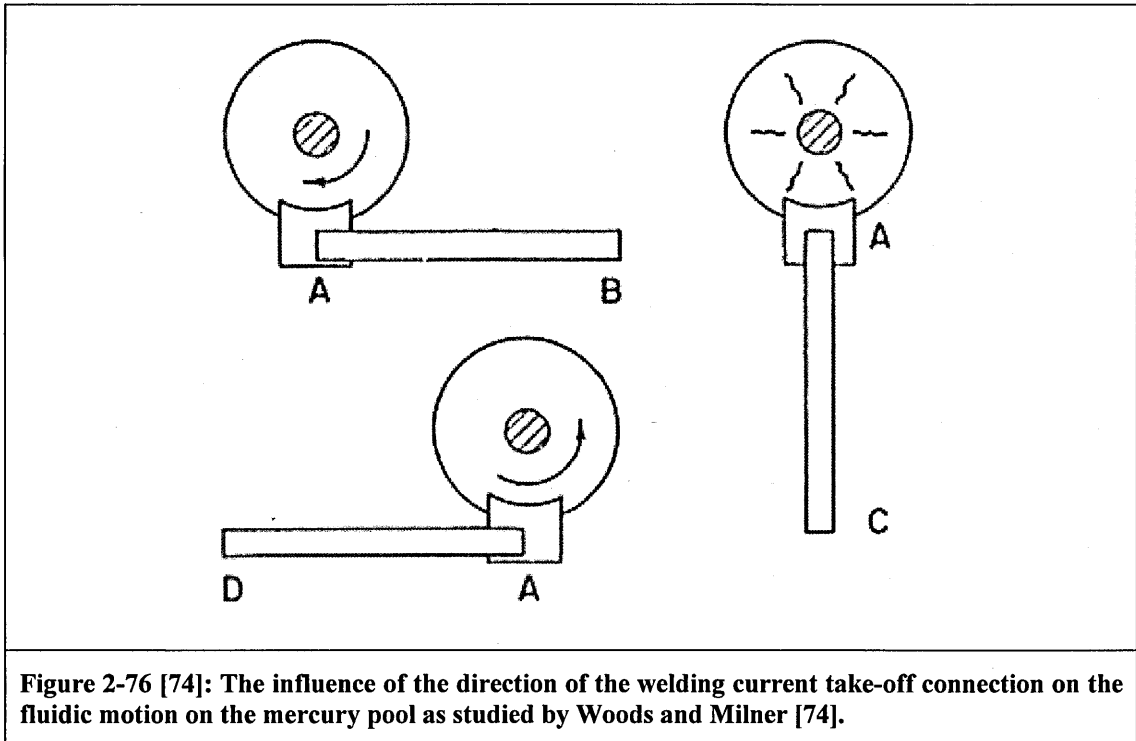
Simulations with Mercury Pools

During welding operations *“the arc impinges vertically onto the weld pool and the current then flows through the weld pool and the base plate to the current take-off contact which usually be lying at right angles to the arc”* [74]. Woods and Milner [74] simulated this geometry by constructing a cylindrical crucible from a non-conducting material with the current being passed into a mercury pool inside the crucible through a long vertical length of 1 cm in diameter copper bar, as shown in Figure 2-76 [74]. The second current contact could be made in three different ways; (i) via a 1 cm diameter copper bar fitted into the base of the crucible could be used, or (ii), via a 5 cm diameter bar which formed the complete crucible’s base, or (iii), via a 2 cm wide copper strip bent over the side of the crucible dipping into the mercury pool [74].

With the aid of the experimental apparatus shown graphically in Figure 2-76 Woods and Milner [74] examined the influence of the welding current’s path and magnitude on the pool’s behaviour. Using the first (i) connecting method [top left in Figure 2-76], turbulence with no clear defined fluid flow occurred with a current up to 200 A [74]. Using the second way (ii) [bottom left in Figure 2-76], a rotational fluid flow was observed in the mercury pool with a current level of approximately 100 A [74]. The third connecting way (iii) [right in Figure 2-76] resulted in the most intense rotation [74]. The direction of rotation was depended on the current’s flow path as it left the pool [74].

When the connecting bar was in position ‘AB’ of Figure 2-76, very fast clockwise rotation occurred with currents of the order of 70 A [74]. Rotating the bar towards position ‘AC’ of Figure 2-76, the clockwise rotation was gradually reduced until at position ‘AC’ of Figure 2-76 no rotation occurred with current levels of up to 200 A but turbulence on the pool existed [74]. Moving the connecting bar even further towards position ‘AD’ of Figure 2-76, counter-clockwise fluid flow started to occur in the pool which became gradually more intense as the bar approached position ‘AD’

[74]. In a similar way, by maintaining the current take-off electrode at position ‘AC’ and the smaller electrode angled to the pool from either side, rotation occurred with direction dependant on the side of the pool on which the small electrode was located [74]. Woods and Milner [74] concluded that the direction of the welding current’s path and its magnitude are important on the behaviour of the welding pool [74].

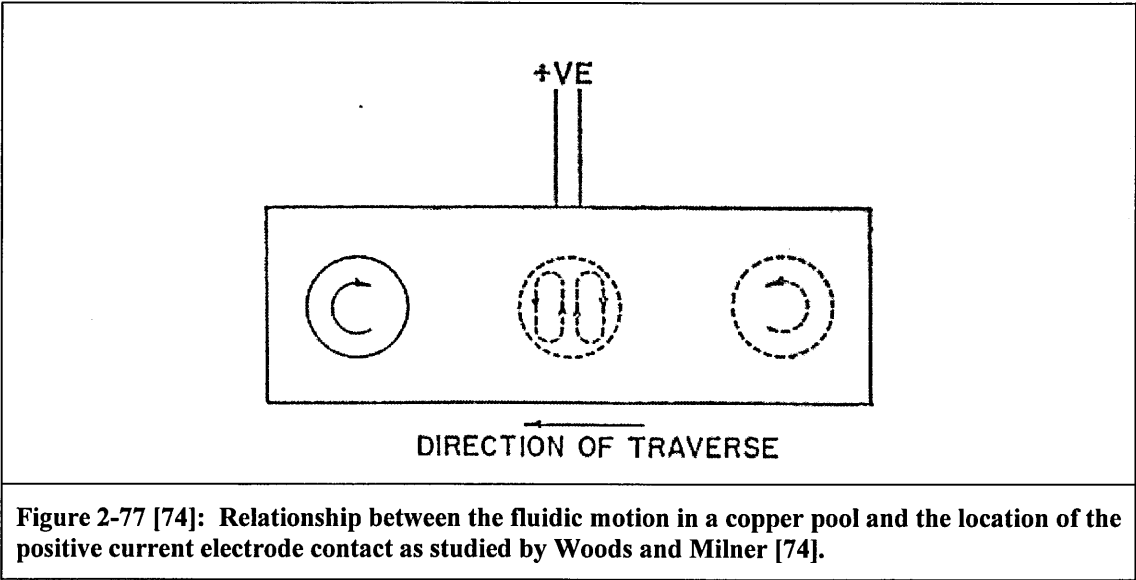


Lawson and Kerr [76] report that their simulation results are in contrast with the simulation results from Woods and Milner [74]. According to Lawson and Kerr [76] no effect from the ground location was found. The ground effect reported in [74] is explained in [76] as a result of the geometry used since the ground path was through a spot of limited area on the pool’s wall. In the simulation experiments reported in [76] a change in the position of the connection of the copper sheet might not be able to significantly alter the current path because of the copper’s high electrical conductivity [76]. However, a change on the location where the electrode touches the mercury pool surface had an influence on the observed pattern [76]; moving the electrode closer to any edge resulted in surface flow from the electrode to the nearest region of the mercury’s pool surface [76]. According to Lawson and Kerr [76] this pattern was similar to the one observed by Woods and Milner in [74] when the current flowing from the smaller to the larger electrode gave rise to the same flow pattern [76]. As Lawson and Kerr [76] report, in real welds the fluid flow also tends to melt the solid metal on which it impringes, therefore the current path cannot necessarily be

shortened in this way [76]. Lawson and Kerr [76] also report that the electrical resistivity differences between liquid mercury and solid copper are much greater from the usual ones between the solid and liquid phases of any material close to its melting point; therefore, in a real weld the welding current's path sensitivity to geometrical asymmetry would be less [76].

Experiments on Metals

Experimental data from Woods and Milner [74], indicate that an asymmetry in the current flow results in pure [unidirectional] fluid's rotation [74], as shown in Figure 2-77. As reported by Woods and Milner [74] and is shown in Figure 2-77, the rotation of the weld pool's fluid depends on the relative position of the positive [in this case] contact and the position of the weld pool [74]. Initially there was a clear counter-clockwise rotation which changed to a double circulation as the weld pool aligned with the welding current take-off contact location and ended to a clockwise fluid flow as the weld pool passed to the left of the welding current take-off contact location [74]. Woods and Milner [74] concluded that the type of motion [direction or rotation] is dependent on the geometry of the welding current's flow path [74]. As Lawson and Kerr [77] report, welding arc impingement causes hot liquefied metal to flow outwards from the welding arc's spot location along the weld pool's surface [77] and Lorentz forces result in a jet formed from hot liquid to be directed into the weld pool [77]. The authors of [77] predict that the qualitative dependence of these two mechanisms on asymmetrical electrode positioning or welding current path asymmetry to be the same [77].

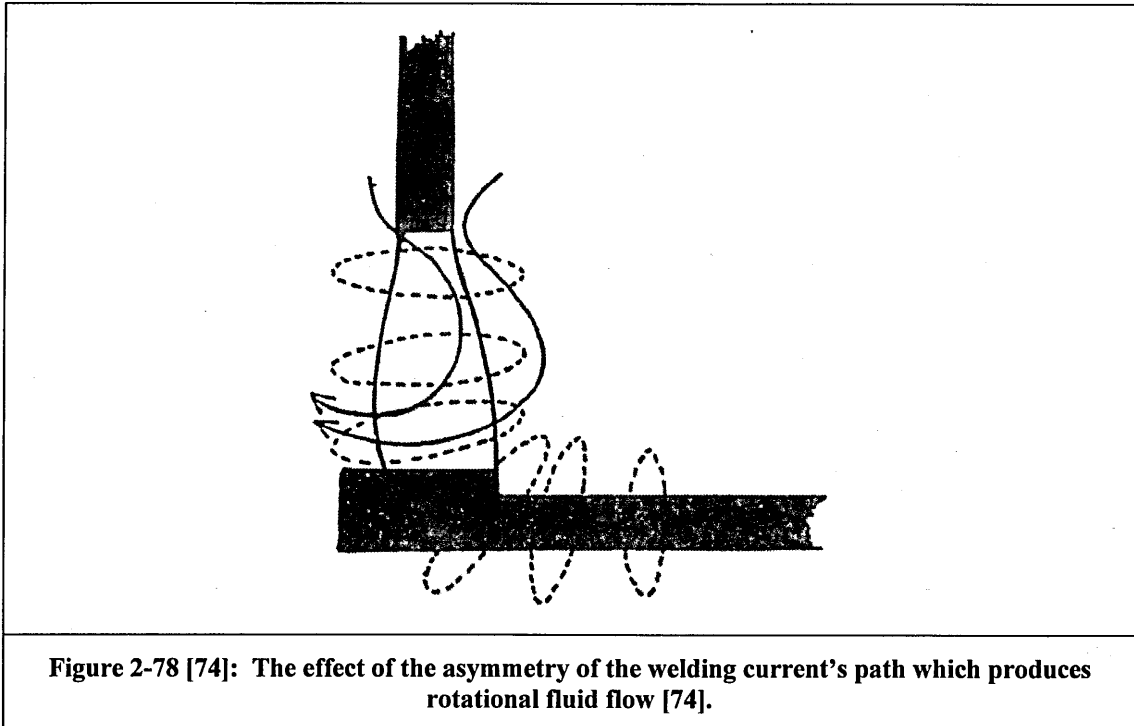


Lawson and Kerr [76] performed experiments in mild steel to examine the influence of ground location as function for the flow patterns [76]. Since for a given geometry the welding current also influences the flow patterns [76] the welding current and speed were also varied to maintain a nearly constant pool volume [76]. The result was that for the welding current range between 200 A to 300 A ground location was very important for the flow pattern [76]. When the welding current connection was behind the weld pool [at the start of the weld bead] the flow pattern was a swirling pattern [76]. With a welding current level around 100 A in 3.1 mm thick mild steel specimen, ground location had no significant effect [77]. However, below 200 A on a 12.7 mm thick mild steel specimen ground location was important [77]. For welds made towards the ground location, regardless of electrode tilt, penetration was concentrated towards the rear of the weld pool and the leading edge had a smaller slope [77].

Experimental results from Woods and Milner [74] also show that in many instances rotation arose from one half which grew at the expense of the other half in a basically double circulation flow pattern [74]. In addition, based on the experiments that Lawson and Kerr performed [76] the exact ground location had a direct influence on the weld pool symmetry; either swirl could be enlarged at the expense of the other even with lateral asymmetry [76].

With asymmetric welding current flow the resulting magnetic field is stronger on one side as shown in Figure 2-78 [74]. Therefore, the magnitude of the Lorentz force will be greater on the side of the high field strength and asymmetry will occur in the fluid's flow [74]. As Lawson and Kerr [76] observed, artefacts on the weld pool 's surface showed that the flow from the welding arc's anode region was moving away from the ground location [76]. The welding pool became longer and narrower when the ground was placed directly ahead of the pool and nickel tracer [used to examine the flow patterns] and artefact motion occurred indicating that flow takes place away from the ground, more specifically, from the welding arc's anode spot centrally rearwards along the weld pool axis [76]. The results of the experiments that Lawson and Kerr [76] performed showed that for the welding conditions they employed, mild

steel flow was found to be more sensitive to ground location in comparison with the indications from their simulation experiments with mercury pools [76].



The experimental results from Lawson and Kerr [76] also showed that the influence of ground position must be caused by the Lorentz force mechanism [76]. This is justified because the curvature of the welding current's path towards ground should result in the magnetic flux being concentrated on the ground side which will result in a greater force at this point moving the jet axis away from ground [76]. Impringement forces also play a role since the expected movement for the arc is also away from the ground location. When the magnitude of the welding current was below 200 A the effect of the ground was again important and lateral asymmetry of the ground position resulted in the symmetry of the double swirling to be affected [76]. With welding current magnitude above 200 A, Lawson and Kerr [77] observed a remarkable effect on weld pool shape from the ground location on the pool's shape [77].

With higher welding current, in mild steel, and regardless of the ground location and electrode inclination, the welding speed was also increased in an attempt to maintain the pool's shape [77] and this resulted in changes like loss of penetration, increase in pool's length and/or width and concentration of the penetration at the rear of the weld pool [77].

In aluminium weld pools the effect of ground location was weakened compared to the case of mild steel [76]. No clearly detectable change occurred in the circulation pattern with the ground either ahead or behind the weld pool [76]. As Lawson and Kerr [76] report, their experimental results do not provide a clear explanation why the flow pattern was less sensitive to the ground position in the case of aluminium weld pools or the mercury pool simulation experiments compared to the case of the mild steel [76] where changing the location of the ground connection could completely alter the flow pattern since the flow from the arc's anode spot tended to be completely deflected away from the ground location [76]. A tendency existed for penetration to move towards the ground location in contrast with steel which moved away [77] but reproducibility was not possible [77]. However, the researchers said that fluid flow does not strongly carry the heat away from the ground location in the case of aluminium [77].

Lawson and Kerr [77] carried experiments on Inconel 600 and found little effect of the ground location on the characteristics of the weld pool [77]. With joints of dissimilar metals [mild steel to 304 stainless steel], welding away from the ground location caused the weld pool to become wider and shorter and more penetration was concentrated in the front half [77], a ground effect comparable only with mild steel [77]. With another combination of metals [mild steel to Inconel 600] similar ground location effects were observed with very different lateral asymmetry [77]; the welding arc was deflected towards the Inconel 600's side with the pool's tail and most of the penetration to be concentrated on the mild steel's side [77]. As Lawson and Kerr report, the arc deflection was consistent to welding arc blow away from ground location [mild steel] since Inconel 600 has significant higher resistivity [77]. The authors of [77] also report that the flow was attracted towards mild steel possibly due to ferromagnetism and that arc deflection and weld melting do not coincide indicating that with low welding currents the melting process is not dominated by welding arc impingement forces [77]. For Nickel and Monel, the response to ground location was similar to the response of mild steel [77].

Current Electrode Inclination/Tilting

Simulations with Mercury Pools

The angle of the small current electrode appeared to play a role as well [74]. Double circulation and transition to unidirectional rotation was evident when the smaller electrode was angled in line with the current off-take point from the mercury pool with right-angled connections outside the pool [74] [the current was led out of the pool via a flat ended 2.5 cm diameter bar cemented into the crucible's side instead of having a strip bent over its side [74]]. With the smaller electrode lowered by 20° below the horizontal plane a clearly defined double circulation fluid flow pattern occurred [74]. Raising the electrode resulted in one of the patterns to grow at the expense of the other pattern until a pure rotation occurred [74].

Just like in the case of Woods and Milner [74] Lawson and Kerr [76] report, that their simulation experiments with mercury pools also produce similar results with regards to the influence of the electrode tilting in asymmetrical pools [76]; considerable tilting effects were present in the asymmetrical pools produced by Lawson and Kerr [76]. A symmetrical double swirling pattern was developed when the electrode was tilted in the direction of the pool's long axis [76]. In this pattern the jet originating at the electrode has the tendency of remaining coaxial to the electrode rather than having a vertical downwards flow [76]. In general, it is considered that the Lorentz jet will not influence the current flow of a liquid metal's pool [76]. Thus, the jet's tilting must be a result of asymmetrical magnetic fields [76] which, in this case, are the result of a current flowing through the electrode which results in stronger fields inside the pool directly under the tilted electrode [76]. The localised increase of the magnetic field enhances the local Lorentz forces which move the jet away from this region towards the area which the electrode points [76]. With the electrode tilting to one side of the long axis, rapid rotary circulation ensued [76], with velocity which was increasing as the lateral tilt was also increasing [76]. Lawson and Kerr [76] report that these results in asymmetry are a consequence of the interaction of asymmetry of both current path and magnetic fields [76].

Experiments on Metals

Lawson and Kerr [76] performed experiments in mild steel to examine the influence of welding electrode inclination as function for the flow patterns [76]. In Lawson's and Kerr's experiments [76] the centrally rearwards circulation pattern produced with the electrode ahead of the pool stopped when the welding electrode was in a vertical position [76]. Results in 3.7 mm thick mild steel [77] indicate small effect of electrode tilt on weld pool shape [77], however existence of a shift of the increased melting area from front to rear as the welding electrode inclination was changed from front to rear was observed [77]. In 12.7 mm thick mild steel specimens the position of maximum penetration to electrode inclination was similar but less in comparison to the smaller specimens [77]. Welding towards ground in mild steel shadows the effect of welding electrode tilt [77], however, changing welding electrode inclination with the ground location constant produced smooth change of the weld pool's leading edge's slope [77]. With welding current above 200 A in 12.7 mm thick mild steel, welding electrode inclination changed the shape of the weld pool but the leading role belonged to the ground location [77]. In aluminium weld pools Lawson and Kerr [76] observed that the effect of the welding electrode tilt was very much weakened for both forward and rearward welding electrode tilt [76, 77]. The pool's shape became longer and the trailing surface less steeply as the welding electrode was tilted rearwards [77]. Like in the case of the ground position, Lawson and Kerr [76] report, that their experimental results do not provide any clear explanation why the flow pattern was less sensitive to the welding electrode's inclination in the case of aluminium weld pools compared to the case of the mild steel [76].

For Inconel 600 the welding electrode inclination was important [77]. Maximum penetration was achieved with vertical welding electrode [77]. Forward tilt resulted in increased depth for the front half and rearward tilt reduced forward penetration and produced a longer shallow weld pool [77]. Welding a dissimilar joint of mild steel and 304 stainless steel, where the mild steel has a higher melting point, with the electrode being coplanar to the unwelded joint, the pool was larger in the side of the stainless steel although [77]. However, tilting the welding electrode laterally by 15° pointing towards the stainless steel with its axis still pointing the top line of the intersection resulted the pool's tail to move over to the side of the stainless steel and

streaks of unmixed stainless steel to be included in the bead indicating reversal in the direction of swirling as a result of the electrode's tilt [77]. With Nickel and Monel welds, electrode inclination had similar effects as in the case of mild steel welds [77].

Resistance Heating

The experiments of Woods and Milner [74], showed that some metal's pools exhibit more rapid motion and for the metals with the most intense motion [iron and steel] the most erratic behaviour was also observed [74]. Steel was intense and erratic whilst aluminium was regular and slow [74, 76]. As Woods and Milner [74] report, "*the intensity of the motion is related to the degree of constriction at the anode spot*" [74]. According to Woods and Milner [74], this was attributed to the difference of the size the welding arc anode spot has [74, 76] but Lawson and Kerr [76] indicate that there is no information on its dimensions on the liquid metal surfaces [76], however, it is unclear if they refer to their experiments or the experiments from Woods and Milner [74].

As Woods and Milner [74] report that resistance heating occurs where the welding current enters the weld pool and in the case of a restricted current path by a small welding arc anode spot the resulting resistance heating in the immediately adjacent area will be greater [74] and this might be the origin of the "hot spot" observed in the molten pools of thin sheets [74]. Resistance heating creates a local increase in molten metal's temperature [74]. The resistance of molten metal increases as temperature increases [74], and makes it increasingly difficult for the current to flow through this path [74]. Therefore the welding current is flowing through a new path, the "hot spot" follows and as a result the fluid motion associated with the concentration of welding current becomes erratic [74].

Shape and Motion of the Weld Pool

Woods and Milner [74] observed a correlation between the pool's shape and the type of motion inside the pool [74]. The authors of [74] produced specimens in iron, nickel and copper with vertical and inclined welding arcs with current level of 130 A in order to correlate the pool's motion with its shape [74]. As the researchers report

in [74], the shape of the pool is dependent on the material used as well as the welding arc's inclination due to the influence on the pool's fluid flow circulation [74].

According to Woods and Milner [74], a pool only 0.075 inches thick can have marked changes of the flow pattern with the top surface to exhibit double circulation and the bottom surface to exhibit pure rotation [74]. Woods and Milner [74] observed that the dominance of one half over the other half in a double circulation can be so great that only one half may penetrate through to the bottom of the pool to induce a pure rotation [74]. Nonetheless, Woods and Milner [74] report that the rotation on the bottom surface appears to be caused by the welding current flow through the pool and the double circulation on the top surface by the plasma jet action on the pool's surface [74]. Woods and Milner [74] concluded this because with the welding electrode in an angle the rotation on the bottom of the welding pool remains unaffected whilst the double circulation on the top surface of the weld pool changed according to the direction in which the welding electrode was pointing [74].

The weld pool's motion is largely independent of the welding current's polarity [74], occurs to the same extent with either AC or DC welding current [74] and becomes more intense as the degree of constriction at the welding current's entry point increases [74]. The previous indicate that the motion is induced by the action of the Lorentz force [74]. Woods and Milner [74] performed work which showed that for arc melted pools of metals the motion's intensity and form of the pool depends on the type of metal, the angle of the welding torch, and the position of the current off-take contact [74].

General Discussion

In arc welding, the expansion of the current flow away from a constriction might be the reason for non-homogeneity in welds between different base and filler metals [74]. In addition, arc welding exhibits a notorious behaviour for lacking reproducibility even under rigorously controlled conditions [74]. Woods and Milner [74] argue that one of the reasons for this might be that fluid flow is affected by

factors like the location of the current take-off contact which in turn affects the heat transfer which affects the penetration [74].

The results are difficult to be interpreted as two mechanisms, arc impringement and electromagnetic forces are predicted to have similar dependence on asymmetrical current path and asymmetrical magnetic field(s) [77]. The study of Lawson and Kerr [77] has explained qualitatively the fluid flow and pool shapes in general but the researchers report in [77] that the magnitude of the response to factors like electrode inclination, ground location, specimen thickness and welding current levels could not be predicted at that time [77]. The reasons were the lack of mathematical modelling and the necessity of quantitative values for a lot of parameters [77] like the surface current density and its rate of divergence and the properties of high temperature liquid metal [77]. Especially for the case of mild steel the flow of the molten metal proved to be sensitive to electrode orientation, ground position and current levels [77]. Lawson and Kerr [77] made a comment of general engineering interest in arc welding; welding studies often measure the heat input $[I \times V]$ per unit distance [77]. Based on their study presented in [77], different current levels will result in different forces acting within the molten pool and consequently to different weld pool shapes [77]. This can explain two phenomena: firstly, the change in spacing of isotherms due to conduction when different welding speeds are employed; secondly, that for a given heat input per unit distance the resulting weld profiles can be very different [77] due to the different current levels employed to maintain the heat input levels as other parameters change.

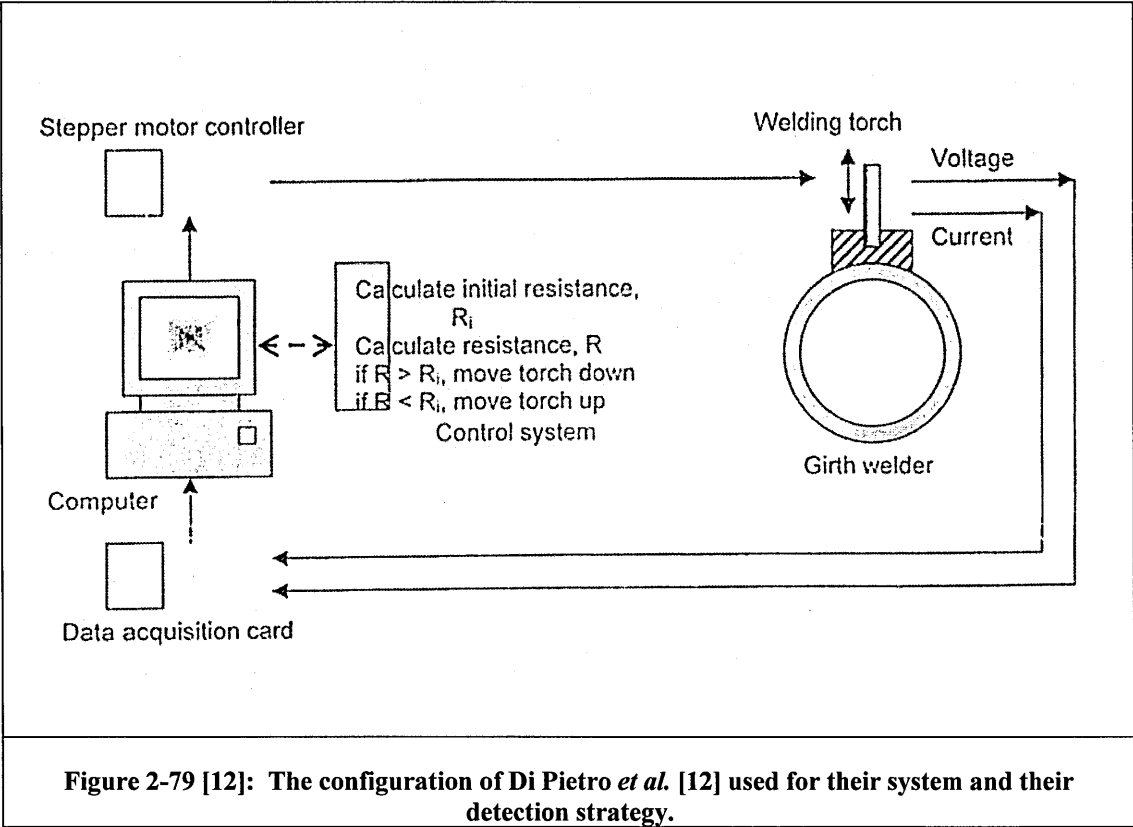
Since the weld pool's geometrical characteristics influence the weld bead's geometrical characteristics and, as already mentioned in Influence of Weld's Bead Characteristics [pp. 118], this affects the dip resistance value therefore the CTWD estimation when the welding path is not horizontal. Since for the RPRS orbital welding is going to be used it means that the geometrical characteristics of the weld pool and weld bead will be influenced even more as gravitational forces will also be acting on it, hence the effect might be even more intense and proper investigation and treatment is needed.

2.5.4 Dip Resistance Based Control in Mechanised Girth Welding Systems

Di Pietro *et al.* [12] developed a system that used the dip resistance information in order to demonstrate the feasibility of the method for detection and control of the CTWD for mechanized girth welding systems. Their work involved the development of a data acquisition system at 5 kHz sampling rate that was used to capture the voltage and current signals in order to determine the dip resistance values. Then these values were statistically processed in order to produce an error signal for use in their closed loop control.

Detection and CTWD Control Strategy

The strategy they used was to calculate the resistance in the beginning of the weld and then to use this value as the reference value. If during welding the measured dip resistance was lower than the reference value, the welding torch should go up. If the value was higher than the reference value, the torch should go down. Figure 2-79 shows the configuration that Di Pietro *et al.* [12] used in order to design and test their method.

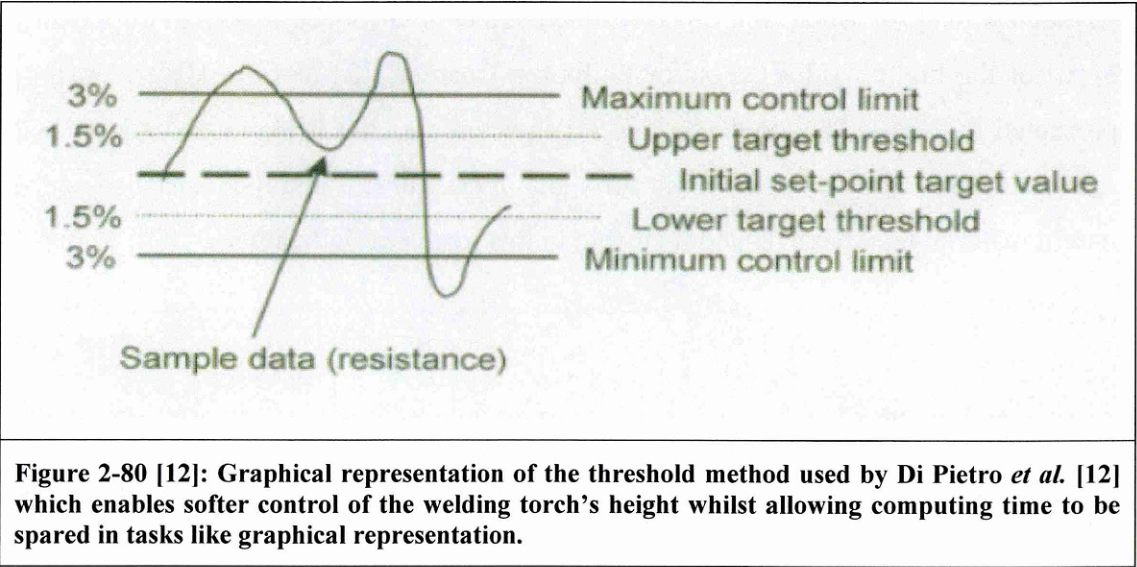


However, Di Pietro *et al.* [12] suggest that the CTWD should not be controlled each time a resistance value is determined, since as they experimentally verified, even if

the CTWD is kept constant no two resistance values are the same due to inherent instabilities [12]. This might explain the difference in the super-imposed resistance waveforms of Figure 2-67 and is in agreement with the results of successive short-circuiting event shown on the left of Figure 2-61. Thus, they report that the best method of analysis was to average all the dip resistance values obtained. In order to make the method more flexible so as to be used in other processes as well, they implemented the strategy of determining a moving average of all the dip resistance values in a sample period and then to halve the result. The result is a value less than the false resistance values [the false resistance values estimated erroneously not during a short circuit mode which include arc's impedance] but higher than the minimum resistance values hence the false resistance values could be detected and rejected. This was based on the observation that during short-circuiting the dip-resistance value is far more than 50 % of all average resistances. Therefore, resistance values below the halved mean level can simply averaged to give the target short-circuiting resistance set-point. A computer based control system was build and the model was tested.

Method's Conclusions

Based on the experimental results of the computer based control system Di Pietro *et al.* [12] concluded that it was is feasible to control the CTWD by using the method of threshold adaptive system, which is graphically described in Figure 2-80, as it provides softer control which matches the gradual variation in pipe ovality and enables real-time charting to be implemented method.



The strategy they used is very good if the method is to be applied in various combinations of parent material and welding consumables since no previous knowledge of the nominal resistance is required. Nevertheless, it assumes proper original position of the torch over the welding surface at the beginning of the run for the reference value to be exact. Otherwise, the dip resistance reference value will be wrong and the process will have errors throughout.

Limitations

It should be noted that there is no record in their work that they took into consideration other factors like e.g. temperature, so there is no discussion if such factors influence the results, since they assumed from the beginning that such a method does not require the wire resistivity profile or the temperature profile. It also has the advantage of not being affected by the parent metal temperature before each run or the heating effect on the wire since the small volume of the wire should allow for it to reach its 'operating temperature' almost instantly, hence, taking reference value(s) in the beginning of the run should eliminate any errors due to temperature rise during welding. However, by using more than one short-circuiting occurrences in the beginning when the welding torch ought to be correctly positioned and the welding wire heated the lack of taking into account the temperature should be compensated. As far as can be said from Figure 2-81 [due to its insufficient resolution and the details presented in [12], the resistance values even at the lowest parts were in the range of tenths of mOhms somewhat different [increased] but close to the ones from the work of others, for example Orszagh *et al.* [52] and Orszagh *et al.* [54] where the dip resistance values seem to be less than 20 mOhms even for the highest CTWDs or for Philpott's work in [13] or from Hsu *et al.* [16] presented in 2.5.6. This could be true for their process but it may also suggest that factors like temperature or the point for signal measurement and the resistance of the parent material may have played their role in this increased indication.

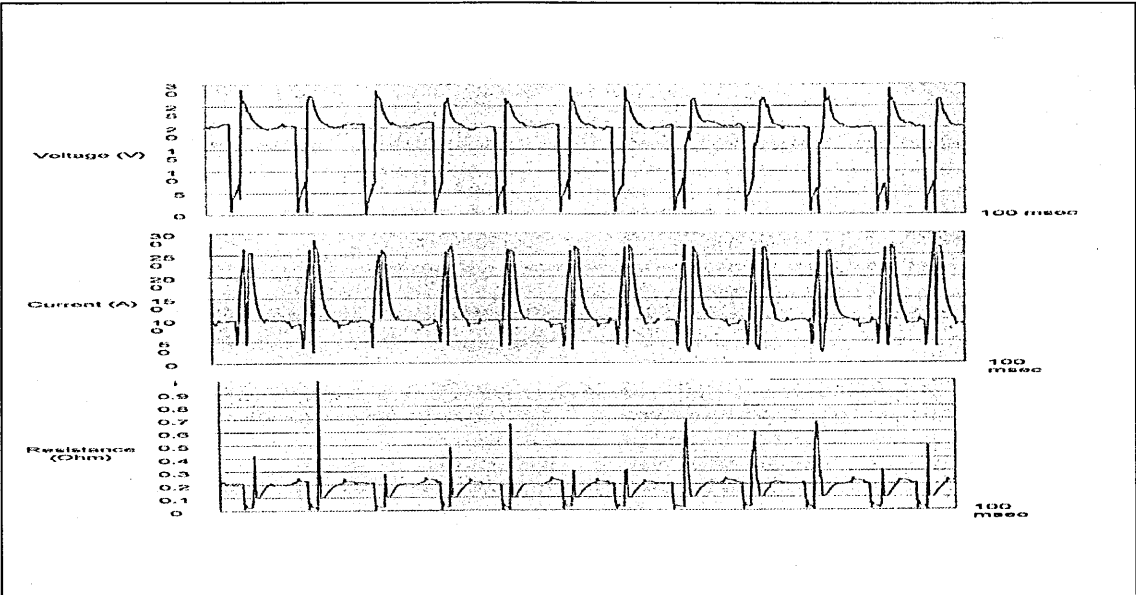


Figure 2-81 [12]: Voltage Current and resistance values from Di Pietro *et al.* [12].

2.5.5 Dip-Resistance Based Control in Automotive Manufacturing

Philpott [13] made another very interesting work on dip resistance for 1 Atm processes for the automotive industry in the mid '80s at Cranfield Institute of Technology [*now Cranfield University*]. His work included analysis and explanation of the short-circuit phenomena and he took into consideration the temperature of the wire and part of his work presented in [13] is summarised below.

Mathematical Modelling

Philpott also produced a mathematical model for analysis of the short circuit period described earlier in Short-Circuit Event Description in Dip-Transfer MIG/MAG [pp. 98]. The conclusion from this mathematical modelling was that CTWD is directly proportional to the short circuit resistance and is given from Equation 2-6 below:

$l = \frac{s \times R}{\rho} = \frac{s}{\rho} \times \frac{V}{I}$	Equation 2-6 [13]: Dependence of CTWD with the wire's electrical resistance. ρ is the welding wire's material resistivity in $\Omega \times \text{mm}$, ℓ is the wire's length in mm, s is the cross-sectional area in mm^2, I is the current in Amperes, V is the voltage in Volts, R is the resistance in Ohms
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Philpott conducted a number of experiments in order to test the theory and the mathematical model. He also measured with the aid of a measurement bridge the

electrical resistivity of the filler wire at 20 °C and it was found to be equal to:

$$\rho_{20} = 0.342 \times 10^{-3} \Omega \times mm.$$

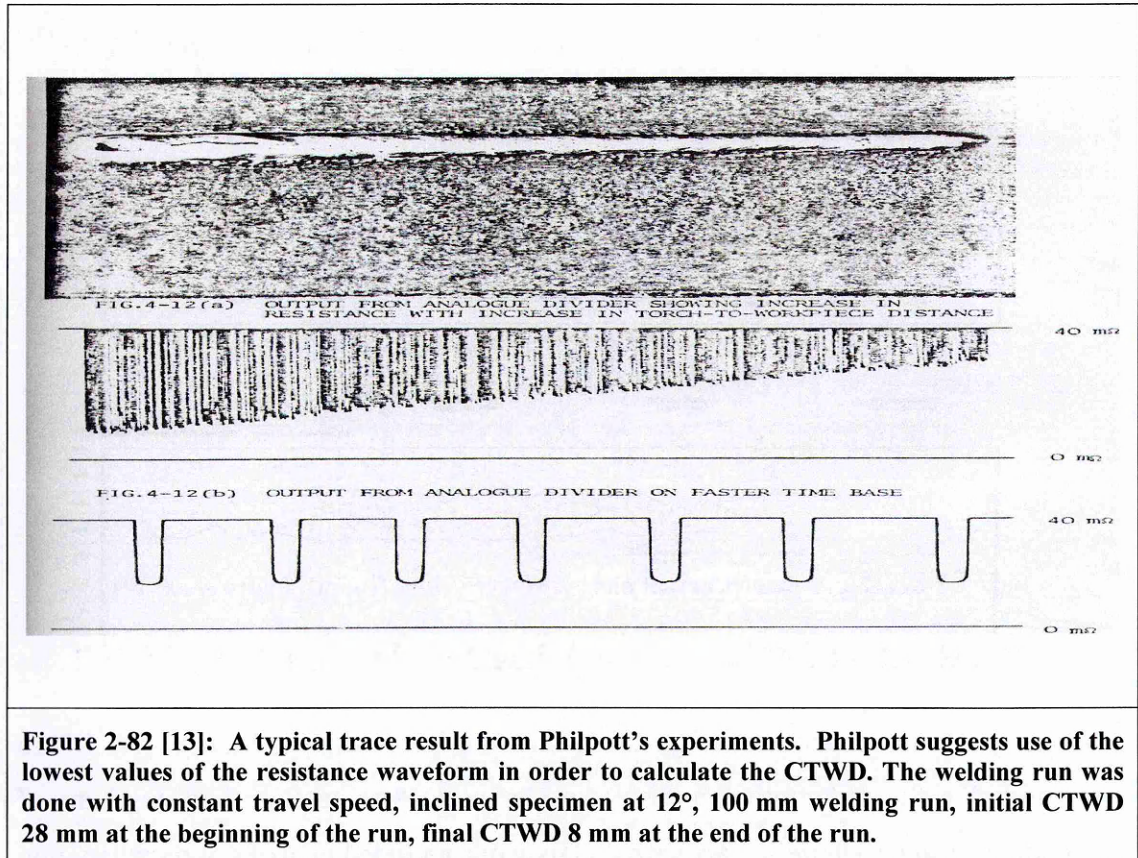


Figure 2-82 [13]: A typical trace result from Philpott's experiments. Philpott suggests use of the lowest values of the resistance waveform in order to calculate the CTWD. The welding run was done with constant travel speed, inclined specimen at 12°, 100 mm welding run, initial CTWD 28 mm at the beginning of the run, final CTWD 8 mm at the end of the run.

Figure 2-82 shows a typical trace result from Philpott's experiments in [13]. The specific output is the result from a weld bead on an inclined specimen at 12° with the welding torch travelling at a constant speed. The run was 100 mm long and because of the inclined specimen the CTWD was changed from 28 mm at the start of the run down to 8 mm at the end of the run. In Figure 2-82, a photograph is included on the top part, showing the weld bead's size and penetration to increase as the CTWD shortens due to the increase in the welding current. The theoretical approach described by Equation 2-6 suggests that under these welding conditions, the dip resistance values should alter linearly as the CTWD was changed. Philpott [13] conducted various experiments and he concluded that the slope of the resistance change with respect to the CTWD change in all cases is linear and approximately equal to $\approx 1 \text{ m}\Omega/\text{mm}$. Using Equation 2-6, Philpott [13] calculated the average resistivity ρ of the wire to be equal to $\rho = 0.785 \times 10^{-3} \Omega \times mm$, a value double of the measured one at the room temperature of 20 °C [$\rho_{20} = 0.342 \times 10^{-3} \Omega \times mm$].

Resistivity ' ρ ' Vs. Temperature

Philpott [13] cross-checked the difference of the average resistivity of the welding wire from the value at 20 °C by using Equation 2-7 below to calculate the value of the temperature coefficient of resistance, ' α ', for his welding wire at various temperatures with the aid of lab measurements using an industrial oven. From his measurements the value of α was found to be equal to $\alpha = 0.00183$.

$R = R_0 \times (1 + \alpha \times t)$	Equation 2-7 [13]: Formula describing the resistance of an electrical conductor with variation in temperature and in correlation to the temperature coefficient of resistance. <i>R is the resistance of the conductor at the desired temperature t, R₀ is the resistance of the conductor at 0 °C and α is the temperature coefficient of resistance for the given metal conductor.</i>
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Using Equation 2-8 below, Philpott [13] extrapolated that the resistivity at 0 °C to be $\rho_0 = 0.322 \times 10^{-3} \Omega \times mm$. Having the values of resistivity at 0 °C and at welding temperature [ρ], Philpott used Equation 2-8 again and this time he calculated that the average wire electrode temperature to be 785 °C in order to have a resistivity of $\rho_{785} = 0.785 \times 10^{-3} \Omega \times mm$.

$\rho = \rho_0 \times (1 + \alpha \times t)$	Equation 2-8 [13]: Formula describing the resistivity of an electrical conductor with variation in temperature and in correlation to the temperature coefficient of resistivity. <i>ρ is the resistivity of the conductor at the desired temperature t, ρ_0 is the resistivity of the conductor at 0 °C and α is the temperature coefficient of resistivity for the given metal conductor.</i>
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Philpott [13] used the results from another researcher to explain the temperature of the welding wire's stick-out. Based on this work that Philpott cites in [13], the temperature at the tip of the wire has been shown to be equal to the melting point of the material, namely 1,430 °C. The other end of the welding wire' stick-out was at an average temperature of 35 °C based on the temperature of the water used to cool the welding torch. Assuming a linear temperature gradient across the welding wire's stick-out the average electrode temperature was found to be 732 °C, very close to the calculated 785 °C.

This is further supported from Keats [42 pp. 5, 7] who mentions that the arc's plasma temperature can exceed 5,000 °C out of which ⅓ 'drops' on the cathode [≈ 1,660 °C] and ⅔ 'drops' on the anode [≈ 3,240 °C] of the welding circuit; assuming an electrically negative welding wire polarity, the wire's tip temperature must be ≈ 1,660 °C and this value is very close to the value of 1,430 °C that Philpott cites in [13].

Average Resistivity ' ρ_{avg} ' and Average Temperature ' t_{avg} ' Vs. CTWD

Based on the linearity of the wire's resistance ' R ' alteration with CTWD, ≈ 1 mOhm/mm, which Philpott [13] observed experimentally, Philpott [13] made the important assumption that the wire's average resistivity ' ρ ' and therefore average temperature is not a function of CTWD. In order to substantiate this important assumption, Philpott made further work and proved that nominal current and wire feed speed do not alter the average resistance ' R ' of ≈ 1 mOhm/mm. Even with higher wire feed speed, as the heat input increases with the current increase the added heat is used to melt more electrode. For this reason Philpott constructed a computer program which was calculating the "minimum dip resistance", ' R_{min} ', at the end of each welding run, for every short circuit, at the point t_5 of Figure 2-59. A number of experiments were made at various CTWDs with various welding wire diameters [0.8 mm, 1.0 mm and 1.2 mm]. The results showed that the average resistivity, ' ρ_{avg} ', to be equal to $\rho_{avg} = 0.801 \times 10^{-3} \Omega \times mm$.

Real Time Description of CTWD

Based on the value of the welding wire's average resistivity, Philpott [13] concluded that based on Equation 2-6, the welding wire's extension during a short circuit at t_5 of Figure 2-59 can be described in real time by Equation 2-9 below:

$l = \frac{\left(\frac{\pi \times D^2}{4} \right) \times R}{0.801 \times 10^{-3}}$	Equation 2-9 [13]: Philpott's formula for calculation CTWD from dip resistance measurements. <i>l is the CTWD in mm, R dip resistance in mΩ, D is the welding wire's diameter in mm, π is a mathematical constant [≈ 3.14...].</i>
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Summary and Significant Conclusions

Summarizing, although the temperature and the geometry of the wire can have significant effects on the resistance of the wire at the various phases of the short circuit, it is possible to rule out these difficult to measure factors and to use a mathematical model in real time which can give the CTWD provided that the dip resistance is measured at its lowest point [t_5 of Figure 2-59] and a reference measurement of the wire's 'true' dip-resistance at operating temperature has been taken after the arc's ignition provided that the welding torch's initial CTWD position is at the correct level.

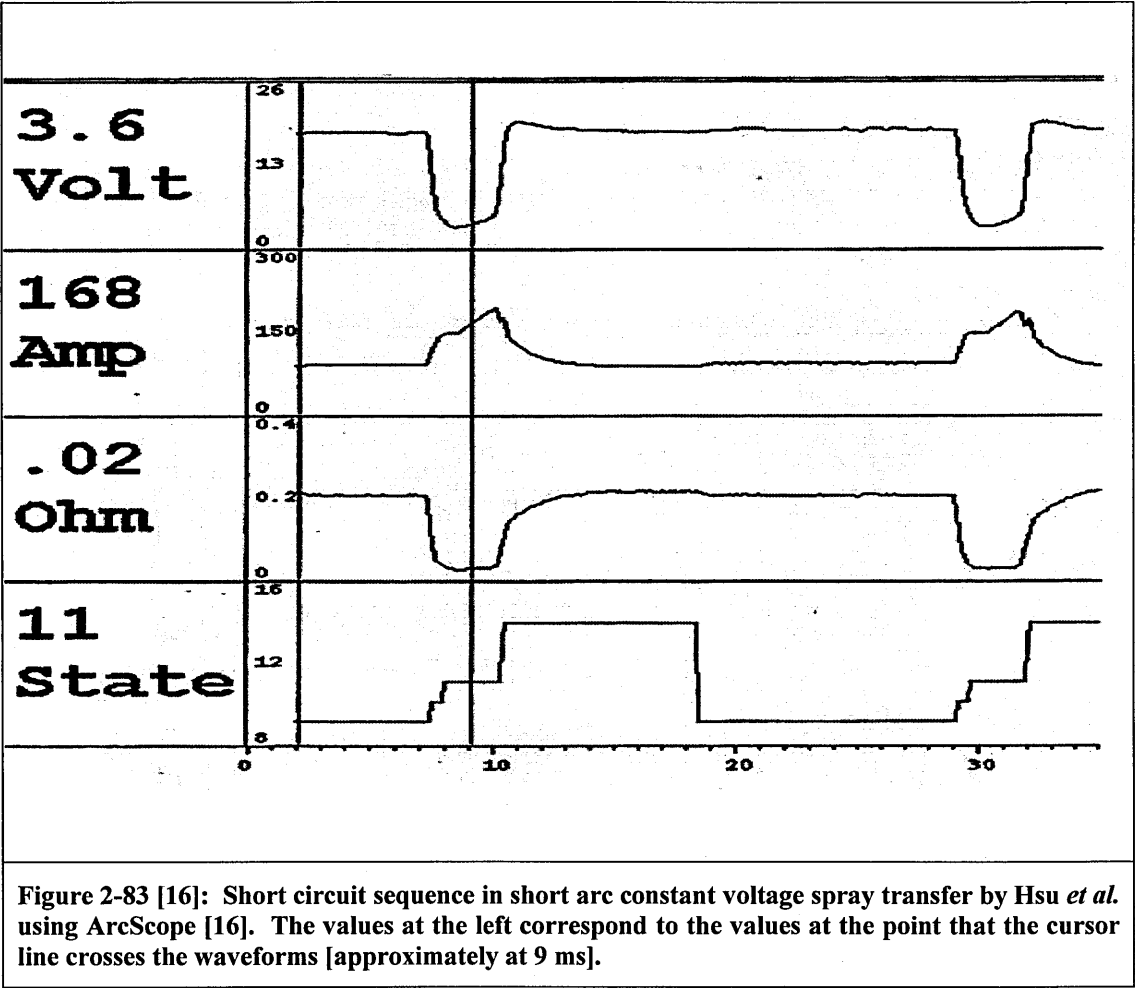
2.5.6 Dip-Resistance Value Based CTWD Control in Short-Arc CV and STT

The application of dip resistance for real-time measurement and control of the CTWD through the short circuit period has also been studied in other types of metal transfer. For constant voltage short arc length spray and surface tension transfer has been investigated and described by HSU *et al.* [16]. For data acquisition, the authors of [16] used a 40 kHz sampling rate was used and the data were filtered at 10 kHz. The software that Hsu *et al.* [16] used operates like a state machine, where each state corresponds to a specific event or a series of events and produces a specific output.

Typical Short-Circuit Event in CV Process

Figure 2-83 shows a typical SC event as captured using ArcScope for short arc Constant Voltage [CV] welding, and its description from [16] is summarized next. The drop of the welding arc voltage below 12 V triggered the initiation of a short circuit. The system used was limiting the arc current to a fixed value for the first 0.4 ms, in order to limit the sudden current rise. The wire's dip resistance at this point was reduced to 20 mOhms. The welding current starts a controlled rise and the arc voltage drops. This lasts for a period of 2 ms and the electrical resistance of the wire stays the same. The measurement of the wire's extension is taken during this period. After that, necking occurs as the molten metal is transferred into the welding pool, the electrical resistance increases and the welding voltage increases as the current falls. The bottom graph indicates the state at which the software implemented state machine is currently operating. Each level of the bottom graph represents a different state. Although only two short-circuit events are shown in Figure 2-83, the similarity of the

state sequences of the state diagram the state machine produces for these two events indicates that a state machine can “sense” a similarity between the short-circuiting events and operate correctly.



Typical Short-Circuit Event in STT

For the STT transfer the procedure is almost the same. The application of the dip-resistance method in STT is presented on the basis of proving that the methodology can be generalised in other processes except MIG/MAG and that the first moments during a short-circuit, the surface tension is the predominant force that governs the dynamics of the molten droplet’s transfer [51] making it relevant to GMAW that is the main focus of this project. More specifically, surface tension transfer takes place in phase 2 [51] of the short-circuit event as shown in Figure 2-62. Figure 2-84 shows a typical trace and a description of the process from [16] is summarized next.

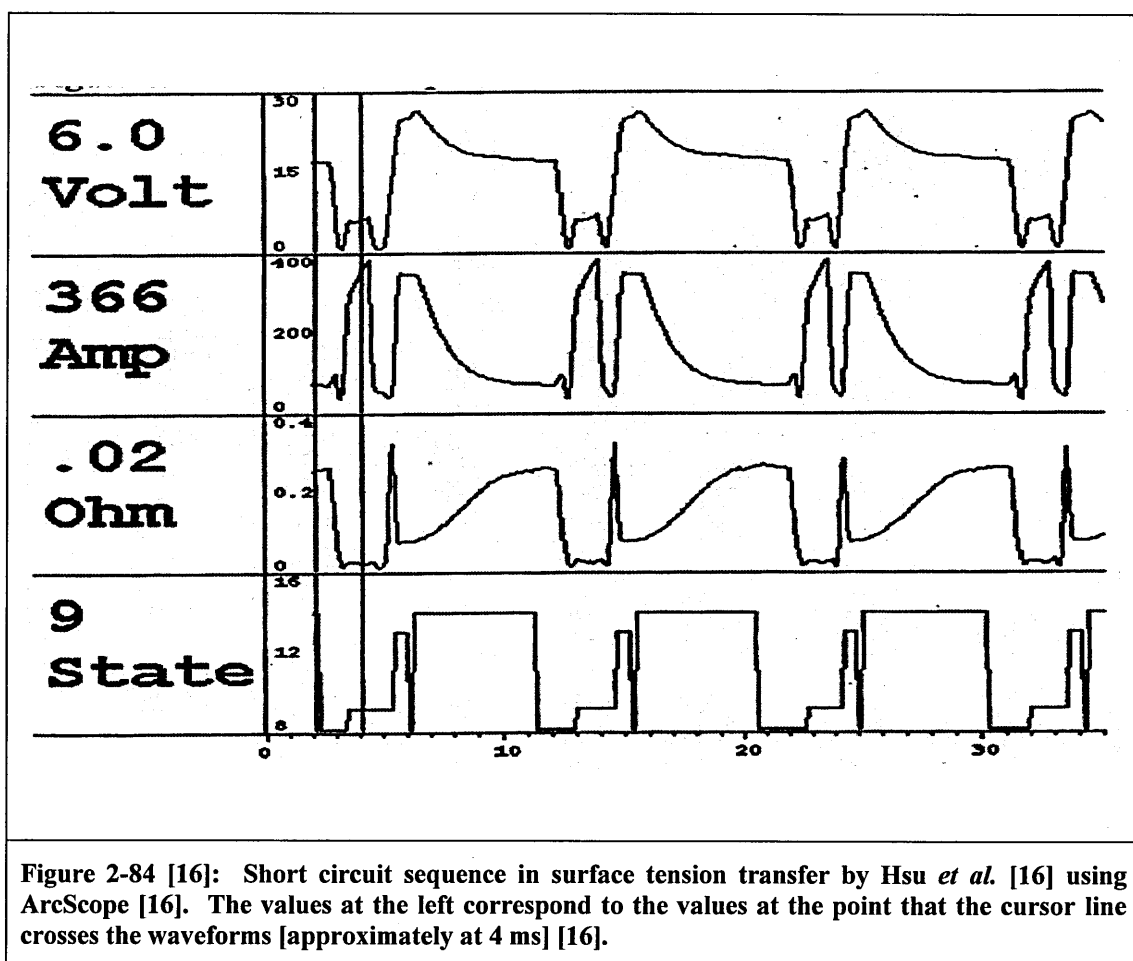


Figure 2-84 [16]: Short circuit sequence in surface tension transfer by Hsu *et al.* [16] using ArcScope [16]. The values at the left correspond to the values at the point that the cursor line crosses the waveforms [approximately at 4 ms] [16].

A welding voltage drop below a predetermined threshold means that a short circuit event has been initiated. The current drops for about 0.75 ms [a]. At this period the molten drop fuses into the pool and a pinch current is applied [b]. The latter creates a magnetic pinch effect which acts together with the surface tension to complete the metal transfer. During the time that the pinch current is applied, the voltage slightly increases [c] but the dip-resistance value remains almost the same for about 1 ms [d]. This is the time where the measurement of the resistance takes place. Then the necking of the wire starts to occur and the machine drops the current [e] just before the short breaks in order to minimize spatter.

Method Verification via Fillet Weld Profile

Hsu *et al.* [16] programmed the real time system to take a measurement when the resistance is at its lowest level. The method was tested on a fillet joint where a 6.35 mm change existed. Figure 2-85 shows the trace of the resistance values measurements. The graph shows the step change approximately around the time of 4.2 sec. A change of almost 12 mOhms in the resistance value is noted.

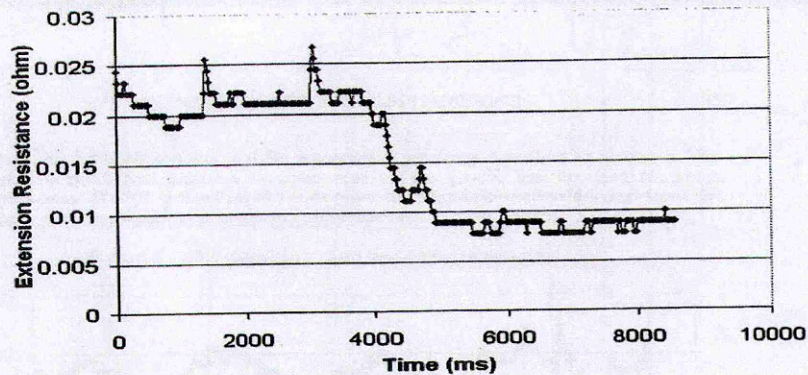


Figure 2-85 [16]: The change of the resistance at the electrode extension when used for a fillet weld with a 6.35 mm step change.

Method Verification via Root Gap Profile Variation

Hsu *et al.* [16] also tested the sensitivity of the method for root opening variations in a fillet joint. The specimen included a gap reduction of 3.175 mm. Figure 2-86 shows the results obtained. The reduction in the resistance is due to the rise of the puddle surface because of the smaller root opening. The smaller root opening meant that the same amount of metal will fill more space, so the puddle will rise and the CTWD will be reduced.

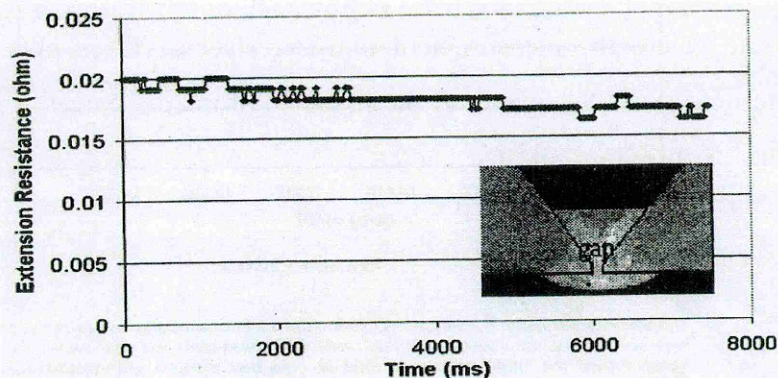
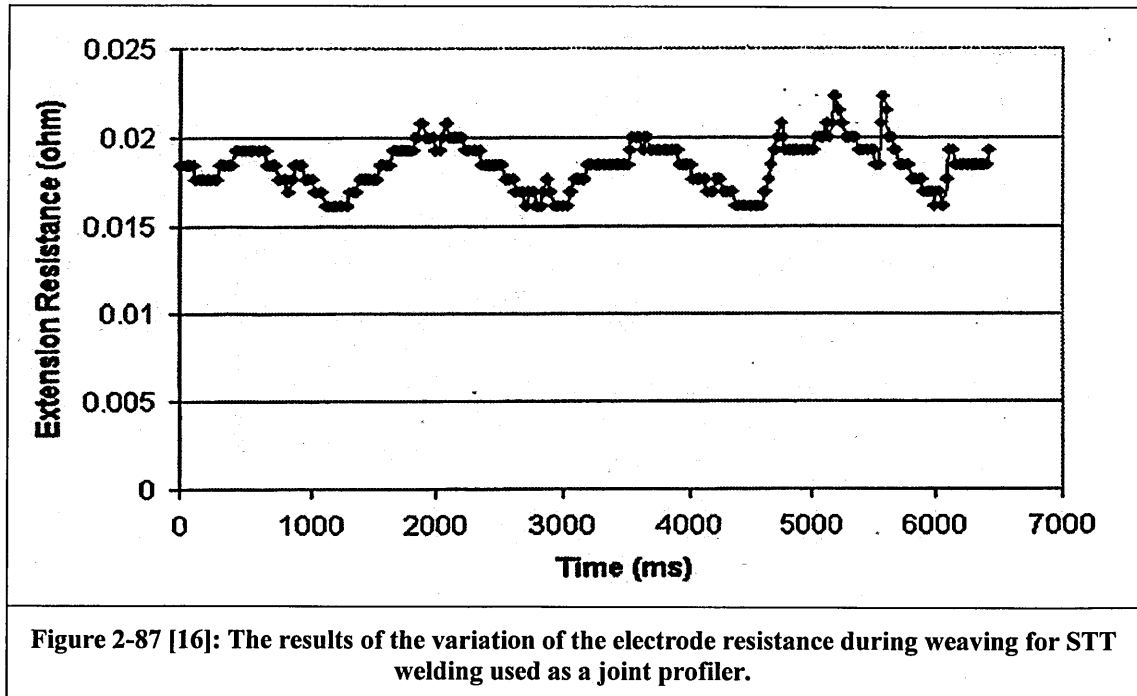


Figure 2-86 [16]: The results obtained for a root gap decrease of 3.175 mm in a fillet joint by Hsu *et al.* [16].

Method Verification via Torch Weaving Joint Profiler

Finally, the method was tested as a joint profiler with the aid of torch weaving as shown in Figure 2-87.



Conclusions

The authors concluded that there is a time window of 1 ms to 2 ms where the resistance is constantly kept at its minimum value and can be used for CTWD estimation and control. They also conclude that real-time CTWD estimation using dip resistance can be used as joint profiler and to be applied for adaptive fill and seam tracking applications. The ability to memorize the root pass CTWD estimation while weaving allows the rest of the passes to be done at higher speeds using a higher deposition spray transfer. Hsu *et al.* [16] suggested that in the case of the torch weaving Joint Profiler the relative peak and duration on each side of the groove can be used for seam tracking purposes. The authors also suggested that if the STT is to be used in the root pass, the joint information derived from the measurement could be memorized and then used as a guide for subsequent fill and cap passes.

Limitations

From the above it is evident that Hsu *et al.* [16] did not take into account the effect of the temperature, but according to their results, their method seemed to work without taking any action for the change of the resistance with the temperature. The authors

do not mention the welding wire's temperature at all and it is assumed that they either used the method that Di Pietro *et al.* [12] used and calculated a reference value from the initial short-circuits, or, they simply looked at the trend of the method's results with the CTWD variation without looking at specific characterisation. Nonetheless, based on the graphical results that Hsu *et al.* present in [16], the following can be said.

According to Figure 2-83 and Figure 2-84, for constant voltage spray transfer, a dip-resistance value of 20 mOhms is recorded but the CTWD is unknown as well as the welding wire's type and other welding parameters. From Figure 2-85, a step change of 6.35 mm resulted in approximately 2 mOhm/mm dip resistance value variation and from Figure 2-86 a gap decrease of 3.175 mm resulted in approximately 1 mOhm/mm dip resistance variation. Perhaps the most important result to note from the work of Hsu *et al.* [16], is what is indicated by Figure 2-87, where weaving was used as a joint profiler in STT; as shown, the response of the dip resistance method with the CTWD change is quite satisfactory.

Nonetheless, the two different weld geometry profiles gave significantly different results; an increase of the electrical resistance of 100 % per millimetre of change in the geometry was noted in the results. This can be attributed to the influence of the weld bead's geometry and the weld pool's characteristics as discussed in Influence of Weld's Bead Characteristics [pp. 118] and 2.5.3 respectively.

2.6 Summary and Significance of 1 Atm Work

The various works presented in 2.5 provide a wealth of information significant for this project. Although the hyperbaric process might be proven to be completely different from any previous work presented above, the following are considered to be significant and important to be 'kept in mind' since they might arise in this project as well. In addition, the points presented in these works can be used as starting points for this project.

Dependence on Welding Process

First of all, the range of the dip resistance values will be different depending on the process, the welding wire and the welding cell setup. This means that during this project it should be kept in mind that the levels of various parameters might be completely different and this will not necessarily mean that there is something wrong; it might simply be the nature of the hyperbaric process. The short-circuit duration is a good example. In most cases the short-circuit duration has been shown to be around 1 ms to 2 ms; however, as can be seen in The Short-Circuit's Event Duration and Influencing Factors [pp. 105] a short-circuit event can last more than 2 ms and there are a lot of factors that can influence the duration of a short-circuit event.

Defining the System's Specifications

From the work of various researchers presented earlier it can be concluded that there is a fraction of the short-circuit event between the spreading and necking stages in which the resistance is at its minimum. Although this is true, the difference of the resistance value outside this fraction is around 1 mOhms to 2 mOhms, as Figure 2-61 shows. This in addition to the conclusion from experimental research that no two successive short-circuit events are the same and threshold values must be used for smooth control, as suggested in Figure 2-67, Figure 2-68, Figure 2-73 and Figure 2-80, creates an interesting dilemma. The dilemma is to decide if it is necessary to build a detection system which will be able to sample a lot more than one point during the short circuit, so as to detect the minimum value, or just one point is enough. A higher sampling rate system will require increases the instrumentation's complexity and system's cost. A lower sampling rate system is much simpler and less expensive.

As Figure 2-59, Figure 2-63, Figure 2-61, Figure 2-67 and Figure 2-82 suggest, the difference between the minimum resistance and the resistance during the spreading and necking stages is a couple mOhms. As mentioned, no two successive samples will have the same value [possibly due to differences in the time of measurement during the short circuit event together with inherent instabilities] and threshold values and averaging should be adopted, so inaccuracy of a few mOhms should be possible to be tolerated. This suggests that a lower sampling rate must provide a good compromise between complexity, cost and accuracy.

Temperature

As has been proven from Philpott in [13] and presented here in 2.5.5, resistivity is influenced by temperature and as a consequence the value of resistance that is measured can be influenced; however, by applying the method by Di Pietro *et al.* [12] presented here in 2.5.4, reference value(s) of resistance can be taken in the initial part of the weld run under nominal operating temperature which will eliminate errors due to temperature influence. A positive contribution to the solution of this is the fact that for the RPRS there is a limited set of parent metals and only one welding wire that is going to be used so it should be possible to establish experimentally the correct reference value for each case [if desired].

Weld Bead's and Weld Pool's Geometrical Characteristics

What it should also be kept in mind is that as examined in [52] and [54], reported and presented here in Influence of Weld's Bead Characteristics [pp. 118], depending on the slope [uphill or downhill], the geometry of the weld pool changes which means that, like Figure 2-73 illustrates, the dip-resistance rate of change with CTWD will be different. In addition to that, the work from [74], [76], and [77] portions of which were summarised in 2.5.3 has a direct influence in this project for the same reason. First of all, it was shown that turbulence and molten metal fluidic motion influence the weld pool's height, consequently the resulting weld bead's geometry, therefore the dip resistance measurement and the accuracy in estimating the CTWD from it. Welding current influences the turbulence and fluidic motion. So, during welding, the short circuit welding current magnitude changes as the height of the weld pool and the rest of its geometrical characteristics and the material properties of the surrounding area change. This turbulence must be part [at least] of the reason(s) for the shift in dip

resistance values shown in Figure 2-73. As mentioned earlier in General Discussion [pp. 132], arc welding is notoriously difficult to be reproduced which contributes to the fluctuation of the dip resistance values around a mean level. Since for the RPRS the method of welding is to perform orbital welds, this factor must be taken into account and future work must be directed into investigating the effect on RPRS.

Another factor of influence is that for the RPRS the welding torch weaves the inclination of the electrode is changing and the weld pool's geometrical characteristics can be influenced, hence the dip resistance during short circuit even if the CTWD remains the same. The geometrical changes might be very small but the wire's resistance per unit length is very small too. Woods and Milner [74] observed a correlation between the pool's shape and the type of motion inside the pool [74] which means it will influence the bead's shape, which correlates with the uphill/downhill dependence described in Influence of Weld's Bead Characteristics [pp. 118]. The above are mostly related to TIG which is more sensitive to magnetic fields; however, underwater the magnetic fields are very strong so MIG could be influenced too. In addition, the dipping of the welding wire in the weld pool and arc's extinction and re-establishment are additional causes of disturbance on the weld pool's motion. From the above it is concluded that thresholds must be used in estimating the CTWD and not every short circuit dip resistance value should be used to control the CTWD, like Di Pietro *et al.* [12] did as described in 2.5.4 and is shown graphically in Figure 2-80; this will limit influence from the weld pool's characteristics and the almost certain non-reproducibility of arc welding 100 % [74].

Power Source's Characteristics

In addition to the weld pool geometry, the welding voltage and the welding current, consequently the power source current characteristic, influences the process' behaviour by influencing the short-circuit frequency, duration and even the volume of the molten metal's droplet as Orzagh *et al.* [52] and Orzagh *et al.* [54] reported and presented here in 2.5.2. These can create a trend of the dip-resistance values with the welding voltage and current values. The existence of such a trend and its potential importance must be investigated in the case of the RPRS process as well since it must be taken into account in structuring a control strategy.

2.7 Process Control

There are two reasons for the implementation of a control system. These reasons are:

- 1) To compensate for the effect of disturbances,
- 2) To compensate for process parameter variations.

A process is controlled by the input signal(s) which describes what the required output characteristics must be. Disturbances are the undesired inputs to the process which can influence the outcome. Although there is no control over disturbances and are mostly chaotic in nature, their parameters can be quantified and their effects can be reversed [compensated] if it has been taken into account during the design of the control system. Process parameter variations can be generated from changes in the characteristics of a process' parts. They too can affect the process outcome just like disturbances, but the direct measurement of them is not as easy as it is with the disturbances, since they are internal and not external factors of a process, for example, degradation of a sensor's transducer. Short summaries of the main categories of control systems are reported below.

2.7.1 Open Loop Control Vs. Closed Loop Control

There are two main categories of control: open loop control, and closed loop control. In an open loop system the controller accepts a command and produces the required signal which is delivered to the actuator. The actuator in turn, produces the required output which is delivered to the process. The process then acts so as to deliver the controlled variable. The advantage of this control method is the simplicity of the system. As long as it is known what needs to be done in order for the output to produce the correct result, then all the stages can be implemented. Figure 2-88 shows an example of an analogue open loop control system used for the control of a ROBOT's arm.

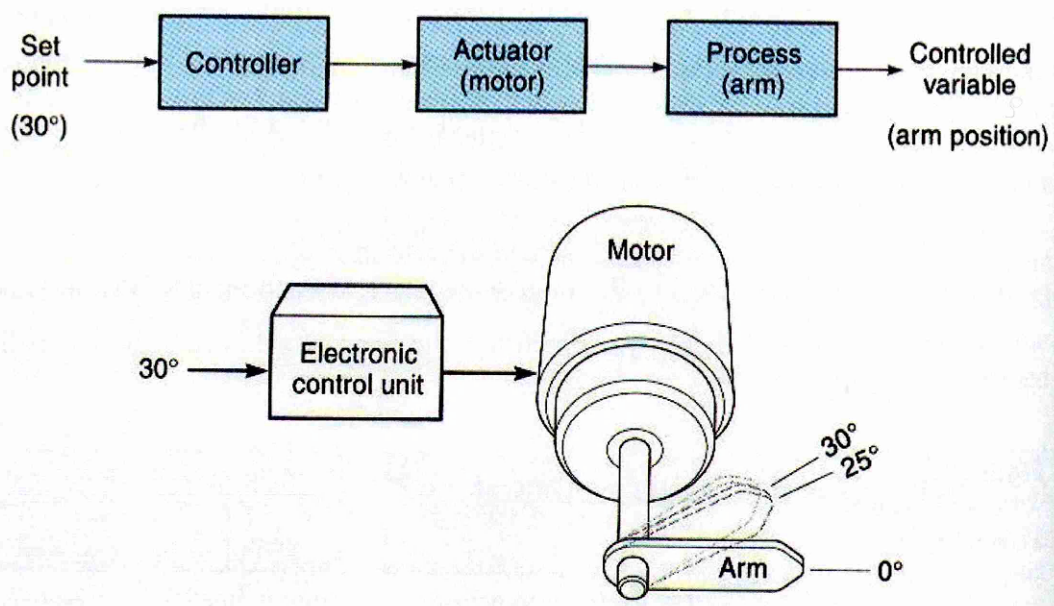


Figure 2-88 [14]: Example of an open loop control system.

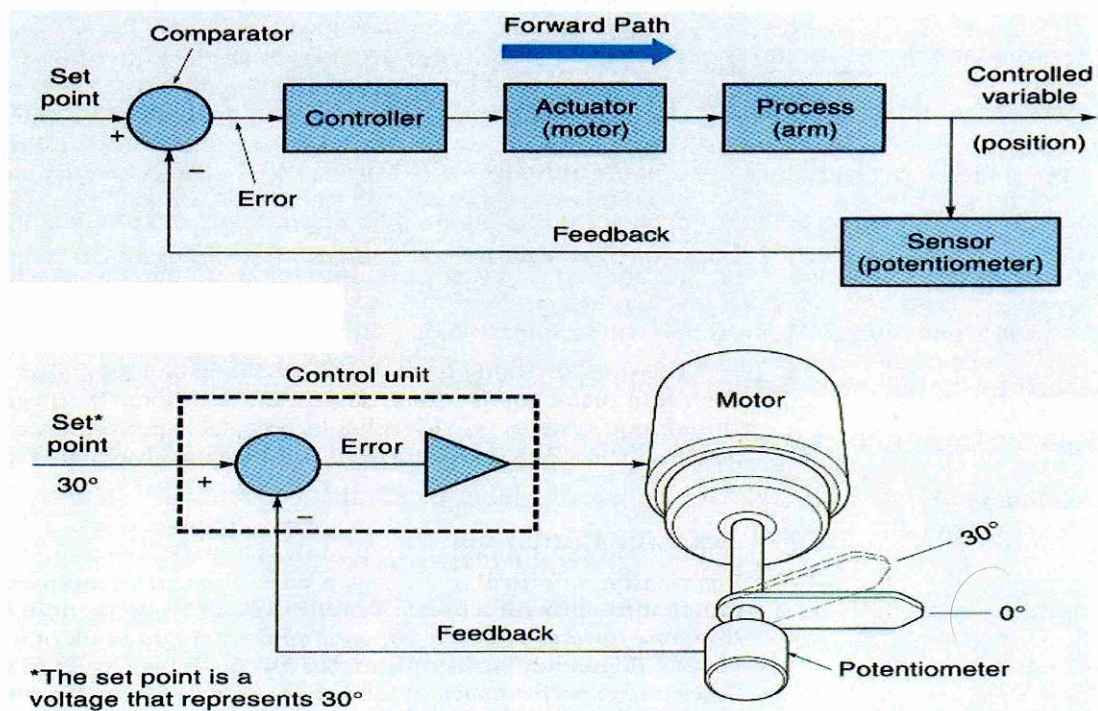


Figure 2-89 [14]: The example of the open loop control with the addition of the extra blocks in order to be converted to closed loop.

The drawback of the open loop control is that it is not known if the output is going to produce the correct result since disturbances –for example electrical noise- or parameter variations –for example change in the resistance of the windings. This is where the closed loop control is required. The closed loop control has all the steps of an open loop plus a sensor element at the output which produces a feedback signal which is compared with the command input and the subtraction of the two is the error signal which commands the controller to take the necessary action, as shown in Figure 2-89. If the difference of these two is zero, i.e. the error signal is zero then no action is required.

2.7.2 Analogue Control Vs. Digital Control

Control systems can be either analogue or digital. In an analogue control system all the elements are made from analogue devices. The advantage of such a system is that any error is immediately sensed and the correction output is produced without any delays. For a digital control system, the various elements are made using digital circuits. The inputs and the outputs are converted in digital signals so as to be able to be processed by a digital system. The digital system is usually some form of computer, embedded or not. The advantages of such a system is that the digital systems are less sensitive to interference and the same system can be pre-programmed so as to be adapted to a wide range of applications. The disadvantage is that such a system induces a delay from the moment that a new command in the input will produce a new controlled variable, or in the case that an error at the output will be sensed to the moment that an action will be taken. This is because the conversion from analogue to digital and vice-versa takes time, plus the fact that the computers execute a program over and over again. The latter means that each input is scanned at a specific time inside the program and not immediately like the case of the analogue control. By using low-level interrupts, this effect can be minimized, but it will never be vanished like in the case of the analogue control. However, modern control systems should be able to minimise this delay in the range of nanoseconds or microseconds, or for the low-end systems, in the range of a few milliseconds. These timescales are very small and for most systems, like the CTWD control of this project, are not important. Figure 2-90 shows the digital version of the closed loop control system of Figure 2-89.

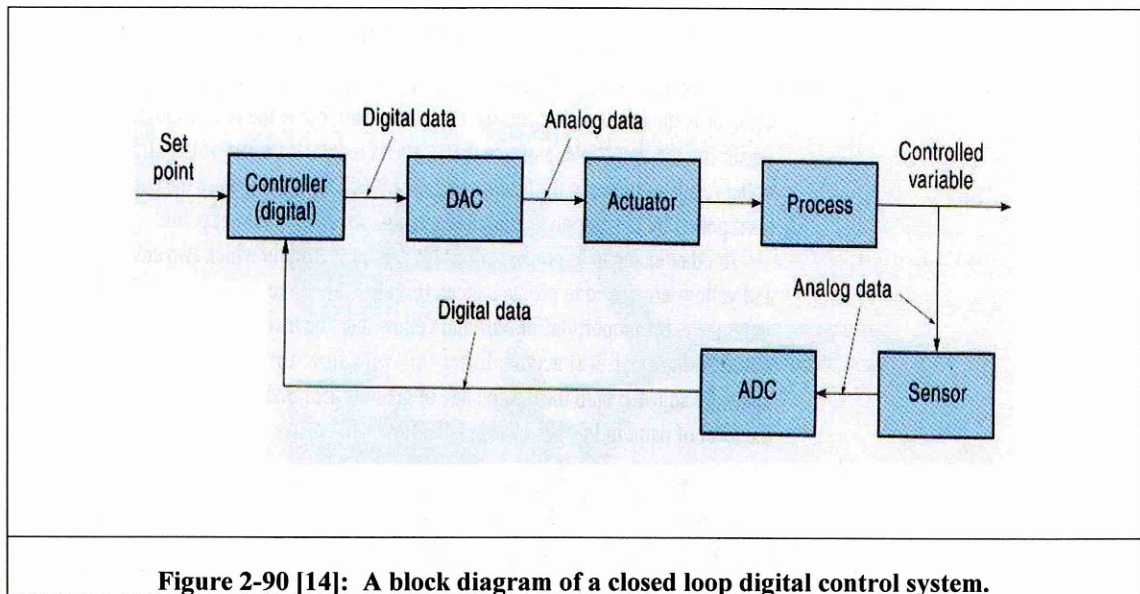


Figure 2-90 [14]: A block diagram of a closed loop digital control system.

2.7.3 Multiprocess Control

A control system may be required to control a single process or multiple processes. The later can be implemented using one of three different ways. These are the Individual Local Control, the Single Computer Multiple Control and the Computer Supervised Distributed Control. These methods are shortly described next.

Individual Local Control

In this case each process has its own controller, analogue or digital, which controls it. The drawback is that in a case where these processes are linked together, then if a change is required for one of the processes only, then each controller should be adjusted separately. A block diagram representation of such system is shown in Figure 2-91.

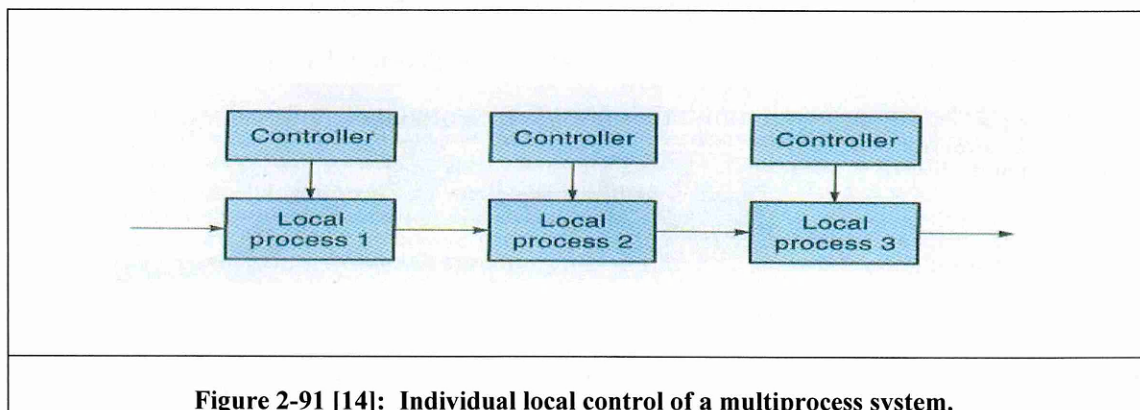
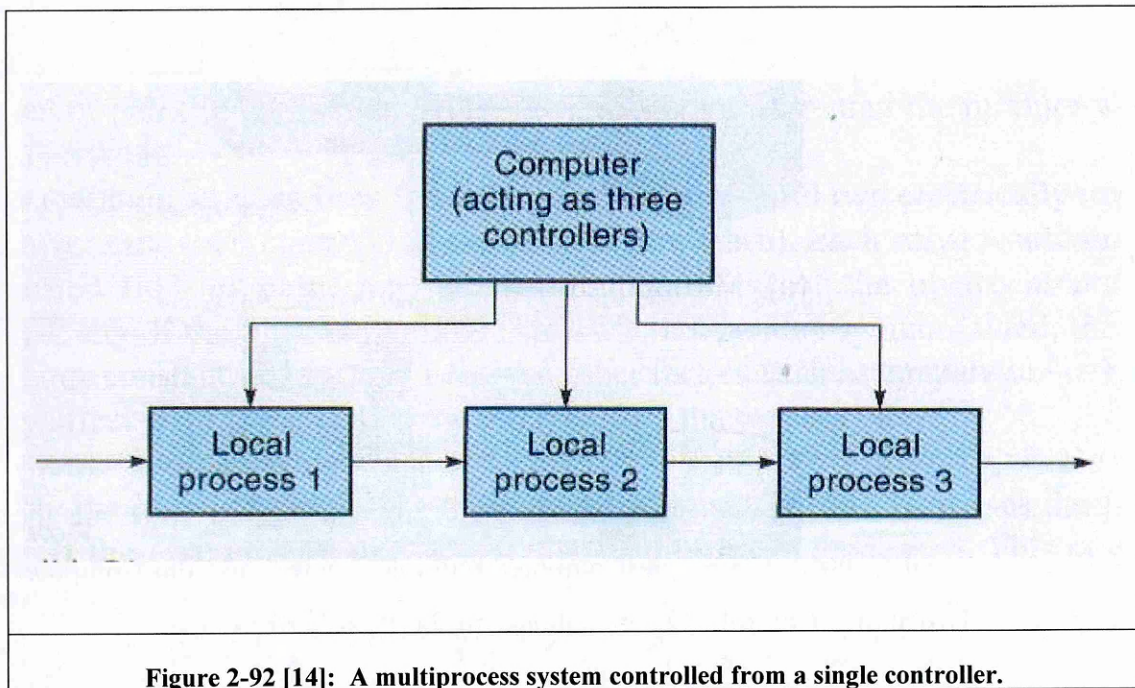


Figure 2-91 [14]: Individual local control of a multiprocess system.

Single Computer Multiple Control

The advantage is that all the processes are controlled from a single place. Thus if a change is required in one of the processes, it is easy to re-adjust the control for the rest of the processes. The disadvantage is that if the computer fails, then no process can be controlled and the complete operation must stop until the problem is rectified. Such a system is illustrated in Figure 2-92.



Computer Supervised Distributed Control [Master-Slave Configuration]

The third option is the use of a single Master computer and multiple Slave computers [Master-Slave configuration]. This configuration is shown in Figure 2-93, with the master computer to be the supervisory computer and the slave computers to be the controllers which are connected to the master computer via a network. In this configuration, the initial adjustment of the slave computers is done via the master computer and from then on, the processes are controlled locally. Even in the event of a failure of the supervisory computer on a number of slave computers, the rest of the controllers can still operate.

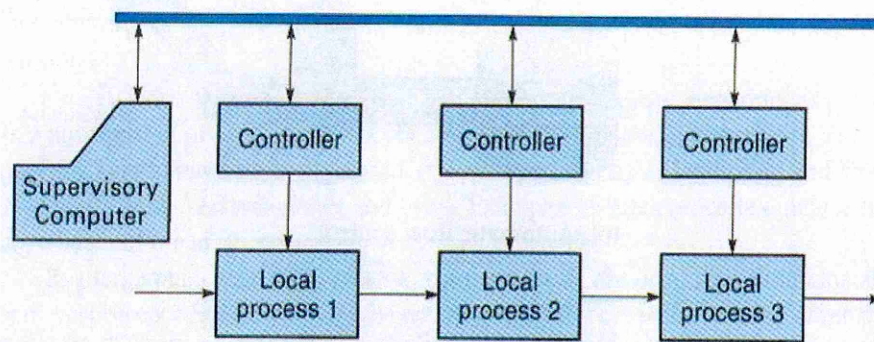


Figure 2-93 [14]: A distributed control system with individual controllers networked together and supervised from a single computer.

2.7.4 Multivariable Control

So far, it was assumed that each process is controlled from a single input variable. Many times though this is not the case. Many processes are dependent from a set of input variables. In this case, the design of a control system it is much more complex and it is better the control to implement some form of computer. That way, the hardware of the system can be greatly simplified, something that can have great effect not only in the initial installation of the system but also in its maintenance as well. Figure 2-94, Figure 2-95 and Figure 2-96 show examples of such a system.

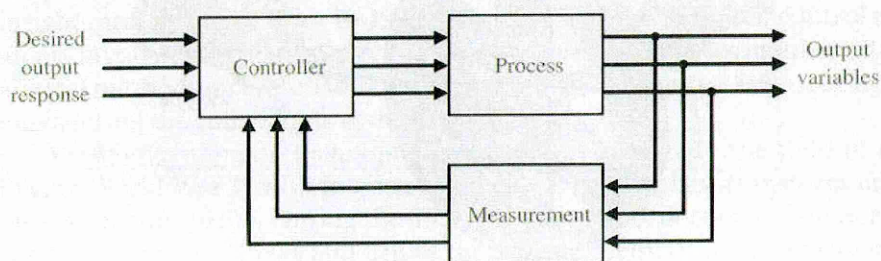


Figure 2-94 [18]: A multivariable closed loop control system.

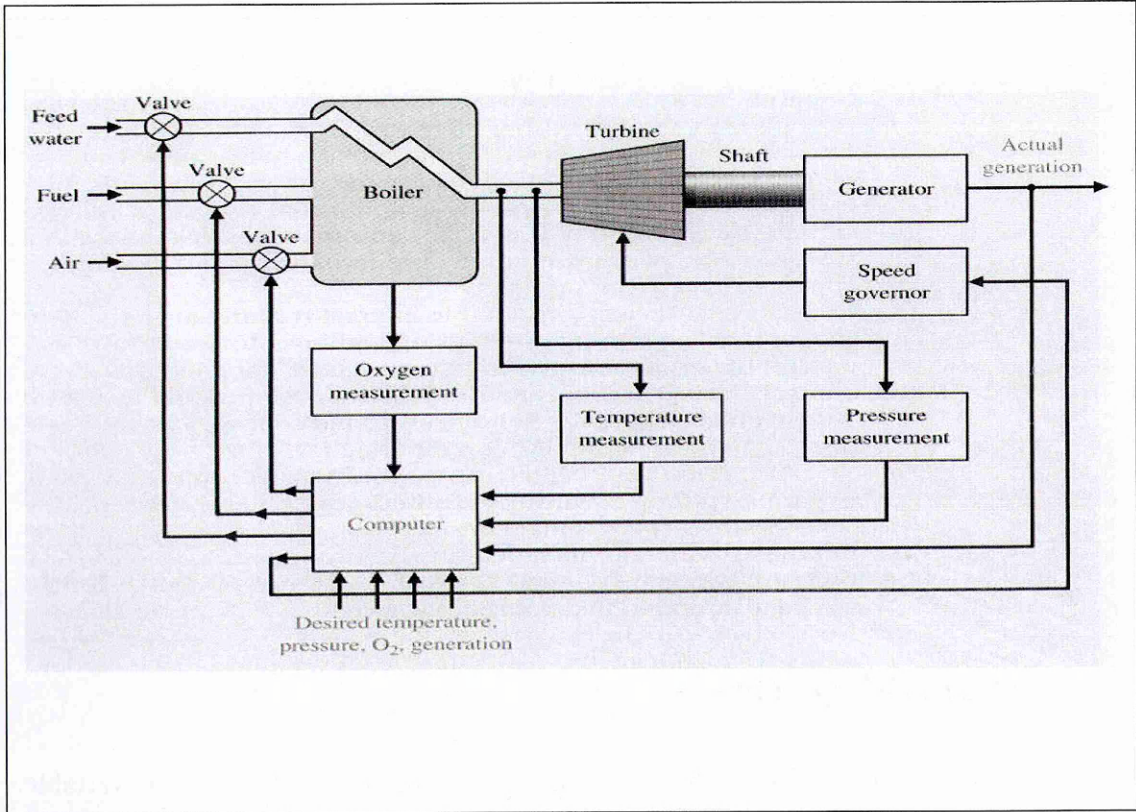


Figure 2-95 [18]: An example of a multivariable closed loop control system.

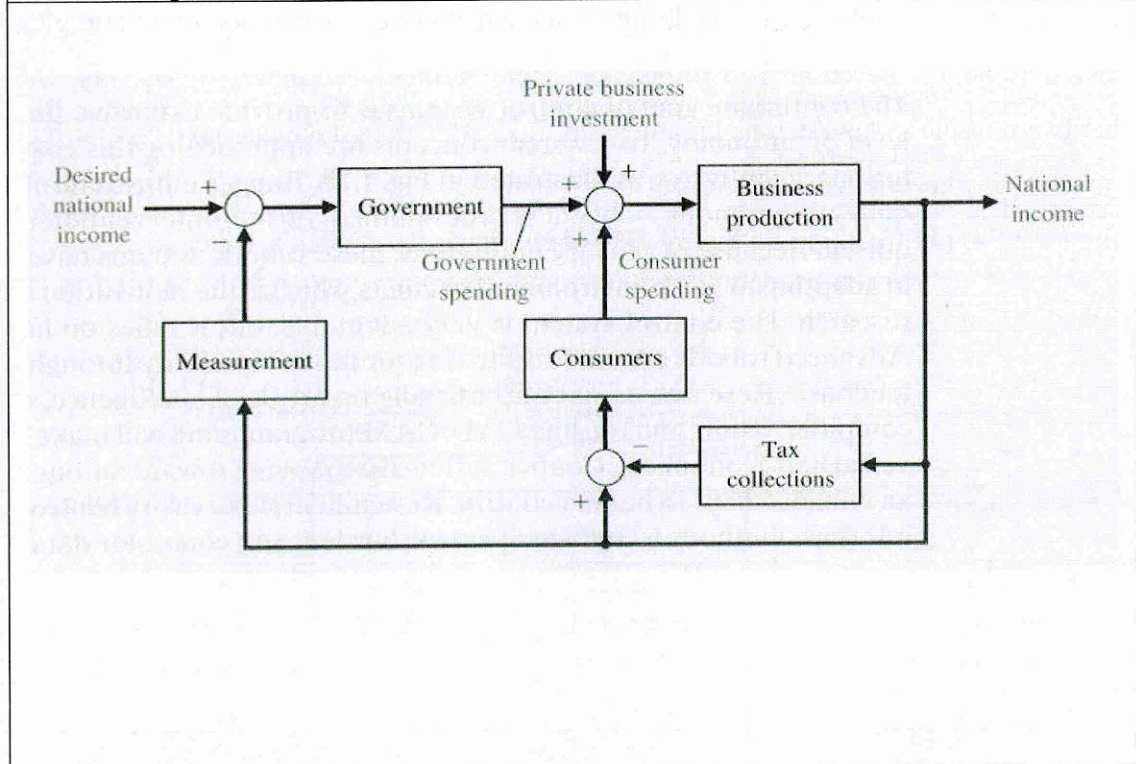


Figure 2-96 [18]: A block diagram representation of a multivariable closed loop system.

2.8 Data Acquisition

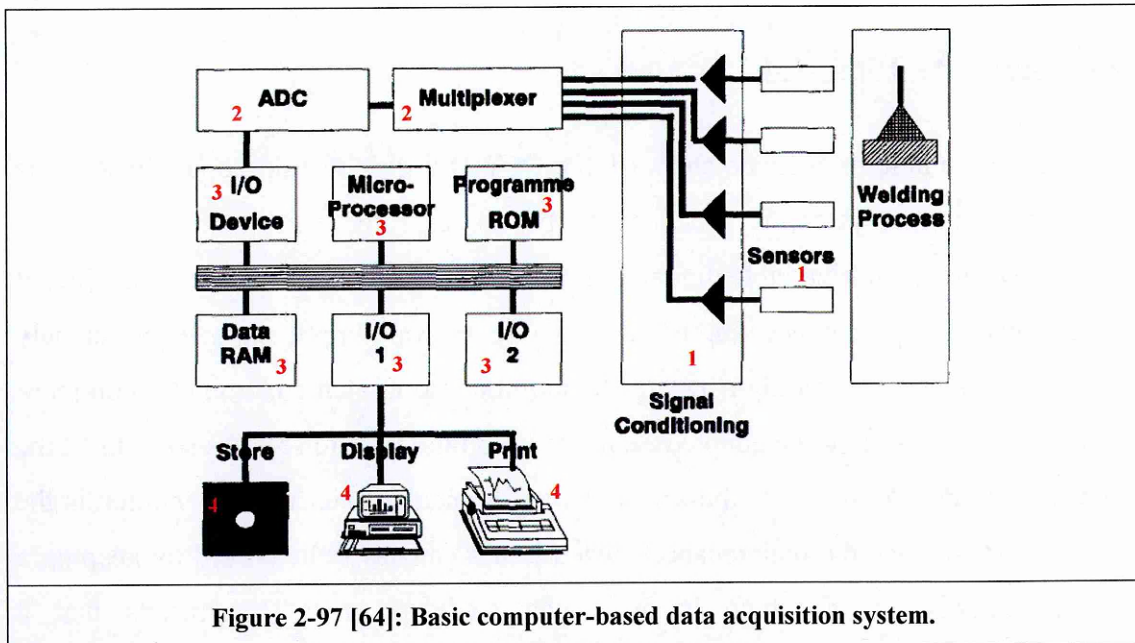
In order to be able to estimate and vary the CTWD during welding operations, some sort of a control system is necessary to be implemented. From the above it is concluded that a multivariable digital control system would be the best option since it will allow taking into account more than one relevant input parameters, namely welding voltage and welding current]. In addition, the implementation of a computer will allow the system to be adopted easily based on the research results so as to fit the process' needs. Also, an off-the-self system will enable easier implementation is the RPRS system since the maintenance related issues can easily be solved by keeping a stock of spare parts which is an inexpensive option. This means that a Data Acquisition [DAQ] system is required in order to enable the implementation of a closed loop digital control system. This DAQ should be computer based in order to enable the development of a Graphical User Interface [GUI] that will allow the operator to monitor and control the procedure.

2.8.1 Basic Data Acquisition System

A basic modern DAQ system, like the one shown in Figure 2-97, consists of five basic building blocks, these are the:

- 1) Sensors and Signal Conditioning Unit(s),
- 2) Analogue-to-Digital Conversion,
- 3) Data Processing,
- 4) Data Storage and Display,
- 5) Clock.

Various adaptations may be used in order to match the requirements of an application [64]. A short description of the roles of each block is given next.



Sensors and Signal Conditioning

The first block is the sensors and the signal conditioning. A sensor is a ‘complete’ unit which includes the transducers used to convert a physical measurable quantity in another form of information [in most case an electric signal], or to alter the measured signals physical characteristics [for example voltage shift] and to perform the initial required signal amplification and filtering [in some cases] so as to make the measured information easier to work with. The signal conditioning block serves a number of different roles. The first one is to provide impedance matching between the sensors and the instrumentation amplifiers. This is a very important task, since an impedance mismatch can distort the output signals from the transducers resulting in wrong and inadequate measurements. The second task of the signal conditioning block is to amplify the small level signals and to improve the Signal-to-Noise Ratio [SNR] by rejecting the noise, which will improve the accuracy of the measurements. The third task is to attenuate if necessary any large level signals to be within the capabilities of the Analogue-to-Digital Converter [ADC] which is the next stage, otherwise a part of the signal will be lost as the amplifiers’ input(s) will saturate and there is the possibility of permanent damage to the system.

Analogue to Digital Conversion

The second block consists of three main parts, the Multiplexer, Programmable Gain Instrumentation Amplifier [PGIA] and the ADC. The Multiplexer is used to reduce the cost of a system as it allows multiple inputs to be processed from one PGIA and ADC reducing this way the cost; nonetheless, the trade-off is that the channels inputs are sampled with a slight delay between them. The PGIA has the important role to amplify the input signals in such a way so as to reject the noise. Their extremes should be as close as possible to the higher and lower boundaries of the ADC. That way, the full resolution of the ADC can be used. This type of amplifier has the ability to vary its gain according to the signal levels that is going to be acquired. This is very useful since that way for each signal that is going to be measured, the gain can be adjusted accordingly. The ADC is one of the most important parts of the DAQ system. Its role is to convert the analogue information that are around us to a form that is understandable from the modern computers, in other words, to digital signals.

Data Processing

The next block is the data processing part of the DAQ system. This is the combined use of hardware and software system resources to recreate the original measured signals. The signals are still in digital form, but are presented in such a way so as to make sense and to revile the important information they contain. Depending on the program, this block may also perform real-time analysis on the acquired data.

Data Storage and Display

The fourth block of the system is the data storage and display part. The data storage is that part of the system that will organize the acquired information in a suitable way for storage in a computer file for archiving and further off-line analysis. The display part serves the purpose of displaying to the system operator the acquired data usually in real time using a Graphical User Interface [GUI].

Clock

The final block of the system is the clock signal. This signal controls most or all of the operations in the DAQ system. It is very important to be extremely accurate,

otherwise everything will be without any real value since parameters like the sampling rate will not be accurate.

2.8.2 Multiple Signal Acquisition

When there is the need to acquire more than one signal, then there are two ways that this can be realised. One way is to use a dedicated pair of PGIA and ADC for each signal/channel. This way offers the following advantages:

- 1) Is the best for very high-speed data acquisition,
- 2) Enables simultaneous sampling of the signals in every sampling period,
- 3) The sampling rate does not decrease as the number of channels increases.

These factors are very important in high-end data acquisition systems for extremely demanding applications.

The second solution is to use only a single pair PGIA and ADC. In order for that to happen, a Multiplexer [MUX] must be added before the PGIA. Then, each signal to be digitized will be driven in the input of the PGIA in turn. This method offers the advantage of low cost compared to the previous one, but has a number of disadvantages. These are:

- 1) Simultaneous sampling is not possible,
- 2) The maximum sampling rate of the hardware is now divided between the inputs.

The second disadvantage means that the maximum sampling rate decreases as the number of inputs increases. This sampling rate decreases even further as the difference between the signals levels for each channel increases as the PGIA components need to settle to different operating conditions.

The limitation of sampling rate per channel is a very serious one and in many cases limits the effectiveness of a system. There is a technique to select some channels to be sampled in every clock pulse and some slow varying signals to be samples every n^{th} clock pulse, but it is not available in every system and makes the system more

complex overall. However, for MIG welding applications where things are relatively slow, such a system could be implemented and configured in such a way so as to be adequate for the process.

2.8.3 Closing the Loop

A data acquisition system like the one described in 2.8.1 and 2.8.2 can easily be altered to act as a real time control system. What is necessary in order for that to happen is to process the data in real time and to give an output that could interact with the real world. This would then act as the error signal that exists in all the closed loop control systems.

3 Project Scope Aims and Objectives

The ultimate scope of the project is the research and development of a combined real time hardware-software Through-The-Wire system that will determine and control the CTWD using the value of the Dip Resistance calculated from the measured welding voltage and welding current signals during the short circuit events.

The aim of this research work was to test and establish the feasibility of the Dip Resistance method for CTWD estimation and control under Hyperbaric GMA Welding Conditions developed for the RPRS. The objectives of this project that satisfy this aim are:

- 1) The main objective is the research and development of a combined real time hardware–software Through-The-Wire system that will estimate and maintain a constant CTWD using information such as the Dip Resistance calculated from the measured welding voltage and welding current signals during short circuits in the hyperbaric GMA process developed for the RPRS,
- 2) 1 Atm experiments and analysis, in order to perform a preliminary investigation for the detection of a short circuit occurrence and algorithm development for the measurement of the welding wire’s electrical resistance during the short circuit period,
- 3) Analysis of the 1 Atm experimental data using MS Excel[®] in order evaluate the effectiveness of MS Excel[®] as data analysis tool for welding applications,
- 4) Determination of hardware system requirements for a data acquisition system for welding applications,
- 5) Development and implementation of the new data acquisition equipment in the hyperbaric system to work in parallel with the system in use,
- 6) Software development for acquiring and analyzing the welding parameters in real-time mode,
- 7) Hyperbaric GMA welding experiments in 27 Atm ambient pressure [mid-point of the RPRS’s intended operating depth] in order to examine and establish

experimentally the potential feasibility of the dip-resistance during the short circuit events as a method suitable for the estimation and control of the CTWD under hyperbaric conditions.

4 Research Project Strategy and Milestones

As stated earlier in 3 the main objective is *'the research and development of a combined real time hardware–software Through-The-Wire system that will estimate and maintain a constant CTWD using information such as the Dip-Resistance calculated from the measured welding voltage and welding current signals during short circuit'*. The experimental work was focused on the collection and analysis of pure data under ideal lab conditions. This would establish the feasibility or not of the method without the influence from any source of error that could influence the judgement as far as it concerns the question: “Is the method feasible or not?” It was considered appropriate to re-examine and re-evaluate the experimental strategy after each set of experiments has been analyzed as new questions arose from the analysis of the results. In order for the previous to be achieved, the strategy of this research project was focused in the following key areas.

The first milestone was to establish how the resistance values would be extracted and determined should be established. After that, the rest of the experimental approach could be structured in such a way, so as to help this strategy. A second milestone was to establish if the equipment provided –mainly the DAQ system- was adequate or new equipment should be acquired or built. If the result of the previous milestone was to acquire or build a new DAQ system, then the next milestone would be that the specifications of that system must be set and after that, the system should be build. Following that, the next milestone was to program –if necessary- this equipment based on the project needs to make the rest of the work easier. After the project had reached this state successfully, the next milestone would be to design and perform a series of experiments to establish the feasibility of the method of the Dip Resistance measurement for Remotely Controlled Hyperbaric Welding.

5 Experimental Equipment

This project took place in the Hyperbaric Laboratory of the Welding Engineering Research Centre at Cranfield University. The lab is equipped to simulate dry hyperbaric welding conditions for a maximum depth of 2,490 m [250 Atm]. A short description of the equipment is provided below.

5.1 Hyperweld 250

The Hyperweld 250 is the name of the pressure vessel that is used in order to simulate hyperbaric conditions. The main characteristics of the Hyperbaric Facilities in Cranfield have been described shortly in 1.1. The vessel has a capacity of 1,200 litres and can simulate pressures up to 250 Atm [2,490 m] and is equipped with all the necessary instrumentation systems for the monitoring and control of the experiments. The instrumentation is wired through special penetrators that provide the necessary electrical contacts and at the same time they can withstand the pressure from the gas inside the vessel. Through these penetrators are passed all the necessary electrical and control signals for the instrumentation, the welding process and the operation of the manipulators. If necessary, these penetrators can be removed and rewired. This gives the vessel the flexibility to be upgraded with new equipment easily so as to be adjusted to new needs.

Cartesian Manipulator

The Cartesian manipulator allows the vessel to be used for performing experiments like bead on plates or sleeve-on-pipe specimens [for example sections from large diameter pipes]. One great advantage of the system is that the manipulator can be rotated to any angle. This is very important because that way there is the possibility for initial parameter development and testing in any position without the need for use of the orbital manipulator which requires the use of more expensive specimens. Also, the torch's angle can be adjusted at the desired position.

Orbital Manipulator

The orbital manipulator can be used to perform experiments on complete pipe specimens and not only in parts of them like the linear manipulator. It is limited however to pipe diameters of 16 inches.

Specimen Temperature Control

In order to control the temperature of the specimens so as to perform experiments close to the real conditions there is the capability of heating up the specimen inside the vessel to a temperature of 200 °C or more, through the use of heating mats placed underneath the specimen. Also, the vessel is equipped with a water circulating system which can be used to cool the specimens down to around 15 °C-to-20 °C if necessary.

Vessel Instrumentation

The vessel instrumentation includes five “K” type thermocouples for temperature measurement, fume extraction through gas recycling and filtering, a Michell dew point meter and voltage feedback leads. The current measurement is done externally using ampere clamps with Hall Effect sensors. Also, the vessel is equipped with a camera housed in a suitable case for monitoring of the welding process. The camera includes a polarizer which gives the ability for monitoring of the welding arc in operation. All the camera parameters like iris opening, polarizer use, and others, can be controlled remotely from outside the vessel during the experiments. The camera is supported by two 12 V / 50 W Halogen bulbs in order to provide the adequate light for the inspection of the welds inside the vessel between the welding passes.

Support Systems

For the vessel operation, a number of support systems are required. These include:

- 1) De-ionised water cooling system capable of cooling water down to 10 °C –or even less if necessary- for specimen temperature regulation,
- 2) Heating mats and power source which can be placed underneath the specimen, again for temperature regulation,

- 3) Two gas banks for storage of the gas used for pressurization. The gas that is used is pureshield argon from BOC. The total capacity of the banks is 2,800 litres plus an additional 1,400 litres,
- 4) Vessel pressurization and depressurization system which handles the gas between the gas banks and the vessel,
- 5) A control panel which incorporates a Mitsubishi Programmable Logic Controller [PLC] programmed to monitor the operating status and to control the Hyperweld 250 facility. The control panel is also used for the control of pressurization and depressurization processes,
- 6) Network of pressurized air for the operation of the pneumatic systems, mainly two-way valves,
- 7) Hydraulics network for the operation of the hydraulic systems like the safety systems used when the vessel is under pressurization, or for opening and closing the vessel,
- 8) Finally, the controls include the control of the lights for the camera inside the vessel and the control of the fume extraction system.

5.2 Data Acquisition System

The DAQ system used is the Personal Computer [PC] based Arc Watch DAQ system which was developed many years ago between Medcen and Cranfield University. Before the start of this project, the Arc Watch system was used for data acquisition in Cranfield University's Hyperbaric Program. A number of references exist to describe the fundamental characteristics of the hardware and software initially developed, the 'CRANMON' [65, 67, 68, 72] that was used as well as the software's refinement, Arc Watch [63, 64]. For the work in the RPRS program Arc Watch was used for acquisition and storage of the welding current and voltage at 1,024 kHz sampling rate per channel with 12-bit [4,096 discrete points] scale resolution. It gives the ability for off-line analysis of the stored signals. The signal conditioning used was custom built for the work in Cranfield University. From the above it can be concluded that the equipment is suitable in order for the experiments to be performed and the data to be collected. Nevertheless, its capabilities are basic and there is no easy way to expand them, especially as far as it concerns the data analysis part.

For this project, a new DAQ system was developed for the following reasons. Firstly, the Arc Watch system had to be used on a permanent basis for the work in the hyperbaric lab and its operation should not be disturbed or compromised. Secondly, the Arc Watch system had a fundamental limitation because of the technique it is using. Computer capabilities were limited when Arc Watch was developed, so fast data acquisition rates were difficult to be achieved [68, 72] and data storage was limited because of technology and cost limitations, hence limited amount of data could be acquired during each run [68, 72]. CRANMON and Arc Watch solved these limitations by developing the technique of windowing [67, 72]. Based on this technique, the desired welding parameters were sampled at high sampling rates [up to 200 kHz [72]] but only a 'window' of 512 points was stored [67, 68, 72]; then a waiting period of 0.25 ms allowed the computer system to perform other operations before the next 'window' was captured [67, 72]. This technique allowed detailed chunks of 512 points to be used to examine details of metal transfer [72] and long term variations [between windows] to be examined [67, 72].—Thirdly, Arc Watch

cannot be used as part of a control system since it is mainly designed to acquire and store the data. These limitations created the need for a different system was required in order to perform real time data acquisition, analysis and control.

The data acquisition systems in the Hyperbaric laboratory also include the Michell Dew-Point meter that does not have the ability for automatic logging of the dew point value and a PC based thermocouple measuring system for monitoring and logging of the specimen and the vessel temperature. Finally, the system includes a setup for the observation of the welding process through the camera and a setup for the recording of the video information.

5.3 Welding Process Equipment and Control

Control of the welding process is performed remotely through a set of computer programs specially developed for this purpose, the initial version of which is described by Alfaro *et al.* [64] and Woodward [66]; some of the computer programs are hosted in specially built computers as described in [64, 66].

Welding Power Sources

The hyperbaric setup in Cranfield includes three identical Fronius TPS 450 inverter Direct Current [DC] power sources connected in series in order to provide up to 200 V and 450 A maximum ratings. The power sources are made by Fronius and are fully flexible to be controlled externally from the power source controller.

Power Source Controller

The power source controller was build by Isotek Electronics and is fully customizable. It is an embedded PC with a Flash drive for the operating system. It is a combination of analogue and digital computer system. The analogue system is generating the output characteristic whilst the digital system provides the user interface and pulse generation capabilities [1]. The system has the ability to sample the voltage and current readings at a rate of 10 kHz and to pass the new current and voltage demands to the power sources at the fixed rate of 10 kHz [1]. The power source controller's parameters for the RPRS have been developed so as to be able to cope with arc's extinctions [78] that commonly take place in the hyperbaric process [69].

Top Station

The top station is a commercial PC that utilizes a version of Linux operating system and a program from Isotek Electronics. Its role is to program the trajectory of the welding torch and the various welding parameters like travel speed, wire feed speed, welding pattern (for example, weaving pass or string pass). In the RPRS system the top station will be on board the shipp.

The top station also hosts the interface program for the power source controller which is used in order to program the power source characteristics and to select the welding process, that is Pulsed or Non-Pulsed welding or the special Clear procedure which is used in order to melt the extension of the wire when the later is stuck in the welding bead.

Bottom Station

The Bottom station is used as the interface between the top station and the process inside the vessel. It is build using an industrial type VME system and in the RPRS system will be submerged within the tooling basket. Its main purpose is to control the stepper motors of the manipulators and synchronise all motion, wire-feed and power source events.

6 Determination of CTWD via Dip Resistance for the RPRS

In order to determine the CTWD via the dip resistance method for the purpose of this project, knowledge of the welding voltage and the welding current at the exact moment that the filler wire dips into the weld pool and the arc is completely extinct is needed. In order for that to be achieved accurate knowledge that a short-circuit event occurs is needed. Thus, a detection algorithm -like the ones that have been used for 1 Atm described in 2.5- should be designed and implemented in software. There were two algorithm designs that could be used.

First Algorithm Design

The first one is to measure the resistance constantly and to examine when that resistance is at its minimum value and below a threshold level which must only be happening in a short circuit occurrence. This is the method that Philpott used in [13] and is described in 2.5.5. In the bottom part of Figure 2-82 is shown the output of such a system. The output is saturated during arcing time and when the short circuit is initiated the output resistance value falls below the saturation value. The minimum resistance value is considered to correspond to the CTWD. Even better results could be obtained if the algorithm examines if the resistance stays at its minimum value for a period of time, which would be dependent on the actual process and would be different for different materials and/or welding parameters, as it is analysed in 2.5.

Second Algorithm Design

The second method is to detect the short circuits from the welding voltage or welding current instantaneous values, or both of them. The initiation of a short circuit could be detected from the crossing of the signals from predetermined thresholds. The resistance could then be measured when the voltage is at its minimum, or, both the welding voltage and the welding current are at the minimum and maximum levels respectively.

Assumptions and Requirements

Both algorithm designs will assume that the welding arc's length is either zero, or its length is so small so as to be considered negligible as far as concerns the value of its

electrical impedance. In addition, the data acquisition rate, or sampling rate, must be high enough to enable sufficient resolution of the short-circuit events so as the minimum value to be measured with satisfactory accuracy, especially if more than one measuring points are required during the actual short-circuit when the wire dips in the weld pool which means that the sampling rate must be even higher. Consequently, as it has been shown in 2.5, when different welding parameters and consumables are used the short-circuit duration and resistance value(s) can be different hence the algorithms must be adjusted to match the new welding requirements.

Short-Circuit Event Detection and Welding Current Measurement

Due to the time lag in the delivery of the welding current that occurs because of the overall inductances of the welding setups as well as due to the time that the power source controller needs in order to react to changes in the process parameters, there are three different tactics that can be used for the detection of the short circuit event and the measurement of the true welding current value during the short circuit when the molten metal bridge is approximately equal in diameter to the welding wire's diameter. For this report, the three tactics are titled as: 'I@short', 'I@short+1', and 'Constant I'.

'I@short', examines the value of the welding current exactly at the moment that the welding voltage is at its minimum. If the welding current is not at its peak, then the event is not considered to be a short circuit.

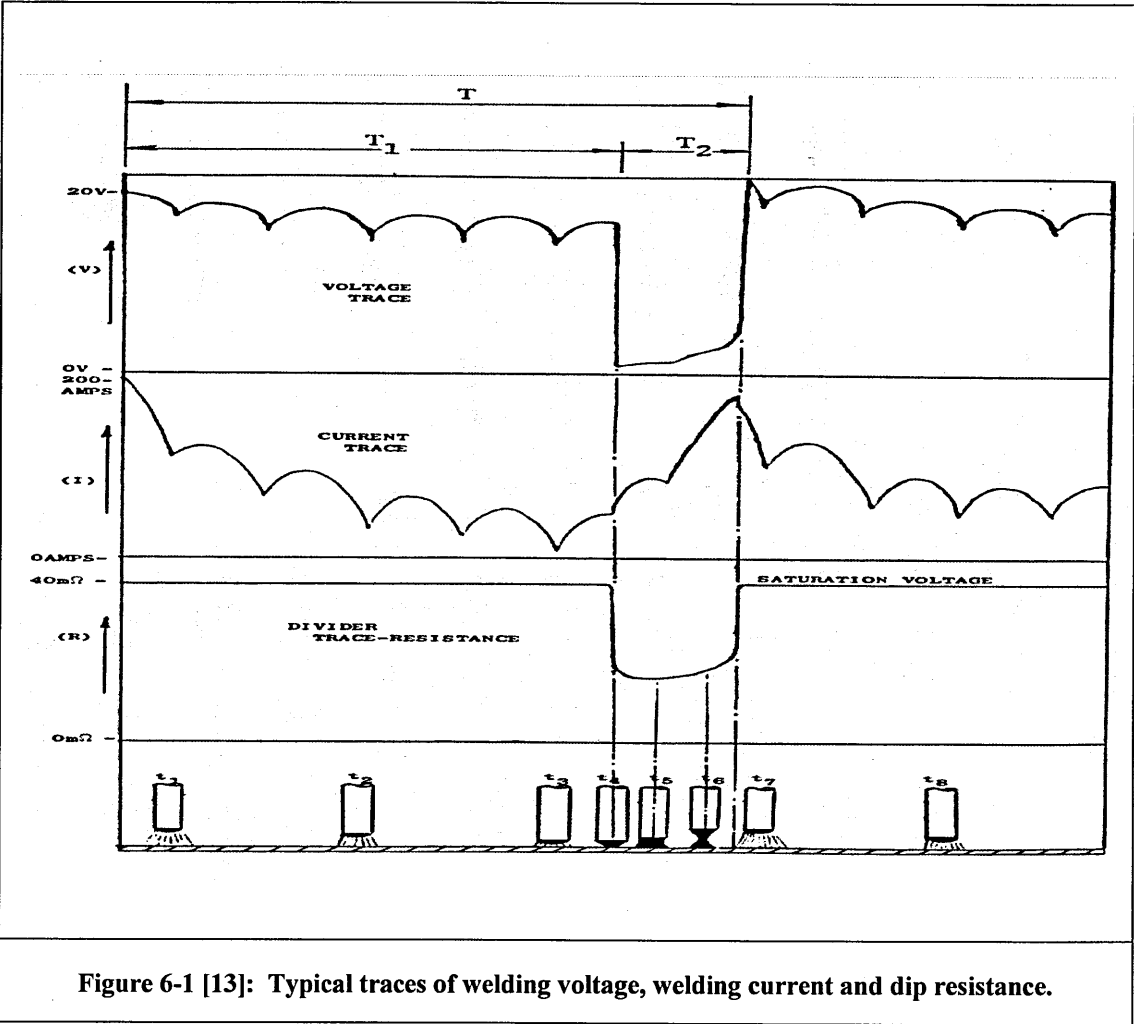
'I@short+1', examines the welding current for a peak at the next sample point [1 ms later in the case of this project] from the one that the welding voltage was detected at its minimum; this method assumes that the welding current's time lag is constant [1 ms for this project's work].

'Constant I', looks at the welding voltage's lowest peak and considers that the welding current has to have its maximum peak value at that time, which should be equal to the pre-determined settings of the power source controller. This tactic is based on the fact that the power sources are nothing else than a machine that tries to pass the voltage dependent welding current demand through the load, in this case the welding circuit. The correct value of the welding current could be assumed to be the

pre-determined one at some point in time near [and after] the voltage lowest peak. The ‘Constant I’ tactic eliminates the need for zero or very small time lag compensation between welding voltage and welding current due to the welding circuit’s inductance.

Further analysis and Justification of Detection Strategy’s Validity

Looking at Figure 6-1 [which is Figure 2-59 and is repeated here for clarity], can help understand the difference between the three tactics and justify their validity.



If the welding voltage’s fall and welding current’s rise have no time lag between them, measuring the value of the welding current when the welding voltage reaches its minimum value [the ‘I@short’ tactic] should result in a correct resistance estimation. This is the time t_4 in Figure 6-1.

However, the resistance is at its minimum when spreading has occurred which is at time t_5 but the welding current's rise can be gradual and not instantaneous like in the case of Figure 6-1 where the welding current reaches a maximum between the times t_6 and t_7 , when the welding voltage is not at its minimum and necking has occurred. The tactic 'I@short+1' will detect this value of the welding current assuming that the time lag between the welding voltage and welding current is constant and equal to the time between two samples.

The tactic of 'Constant I' manages to avoid the difficult to measure time lag and assumes that the peak welding current's value [between t_6 and t_7] is the welding current value that should be taken into account.

Implications of Using a Software Based System Instead of a Hardware Based One

In the case of Philpott's work in [13] all these were not a problem since his method is not dependent on sampling for dip-resistance determination; instead, he used a hardware based analogue divider system which continuously correlates the welding voltage and welding current values and uses the lowest output values to determine the CTWD, as shown in the middle trace of Figure 2-82. Philpott's approach in [13] results in a resistance waveform with almost constant dip-resistance value which makes it possible to use as control.

In the case of a digital system that samples the welding voltage and welding current value things are not the same. In a case like the one in Figure 6-1 it is easy to implement a current detection strategy since the resistance value during the short-circuit is almost constant as the minimum welding voltage and maximum welding current values occur during the short-circuit event, and as we know from the work of Di Pietro *et al.* [12] presented in 2.5.3 the CTWD should not be adjusted with every dip-resistance measurement. However, if the sampling rate is not high enough and/or the welding current has its peak value [due to high welding circuit inductance] when the welding voltage has risen again, for example between t_6 and t_7 of Figure 6-1, it is necessary to implement the 'I@short+X' tactic to sample the welding current ['I@short+1' assumes a time lag 'X' equal to one sampling interval].—Alternatively, if the sampling rate is not high enough, a pre-determined value for current, as the

'Constant I' tactic uses, resolves the difficulty in measuring the welding current at the correct moment but it has to be made certain that the detected short-circuit event is not erroneous and that the welding voltage measurement has been taken at the correct instance.

Extracting the Dip Resistance Value

Having the welding voltage and welding current values, Ohm's law described by Equation 2-5 [pp. 100], can be used, as mentioned earlier in Measuring the Dip Resistance Value [pp. 110] to calculate the electrical resistance of the welding wire which would correspond to the length of the welding wire from the tip of the welding torch to the top of the weld pool, the CTWD. The value of the electrical resistance 'R' however is not easy to be measured in practice unless suitable instrumentation is used, since it is in the area of a few mOhms/mm. The exact value depends on the welding wire's physical properties.

It should be noted that the actual distance that is measured using the Dip Resistance method, is the distance between the contact tip and the surface of the weld pool and as it has been shown in 2.5.2 this should be taken into account. In the case of bead on plates this distance is almost the same as the distance of the CTWD. In the case of welds with V-butt geometry though, the CTWD is usually referenced as being between the centre of the groove and the contact tip, but during welding, this distance would change as the torch deviates from its centre position, or, if sideways weaving is used. For this project, the CTWD is considered to be the distance between the tip of the welding torch and the weld pool in the direction of the welding wire's extension. In other words, if the welding torch is positioned in an angle, the CTWD is not considered to be the vertical distance between the welding torch and the parent metal but the actual stick-out during the short-circuit event as mentioned in CTWD and Reasons for the Project's Work [pp. 26].

6.1 Factors That Can Induce Errors – Unexpected Results

The method of measuring the electrical resistance of the wire during the short-circuit event to determine the CTWD might seem easy and straightforward, but there are a number of factors that can induce errors in the measurements. If these factors are not considered and treated properly, then the method might not produce valuable results.

Sampling

The first and most important problem regards the exact moment of sampling the values of the welding voltage and welding current used for the determination of the dip resistance. For valid results there are a number of factors that must occur at the same time. First of all, the arc must be completely extinct, or so small in length so as to be considered negligible. If not, then Ohm's law [Equation 2-5 [pp. 100]] cannot be applied, since the impedance of the welding arc cannot be calculated using Ohm's law, thus there will be an error in the measurement. In addition, the welding voltage and the welding current must be at their minimum and maximum values respectively that best correspond to the value of the welding wire's resistance which reflects the length of the welding wire's stick-out during a short circuit consequently the CTWD. This means that the power sources must be able to provide the welding current that corresponds to the welding voltage feedback value ideally with zero time lag; since nothing is ideal and a delay in the response of control will exist and due to the large inductance of the system and the process' behaviour, at least a small time lag will exist. Besides the time lag, the power source's current slope characteristic will control the rising of the current according to the pre-determined behaviour. This is shown in Figure 2-59 and Figure 2-83 where the minimum welding voltage peak occurs before the maximum welding current value. So, investigation is needed in order to establish if the welding current value needs to be measured exactly when the welding voltage value is at its lowest level, or, a time period after the measurement of the welding voltage must elapse before measuring the welding current and to establish how long this period must be.

Measurement Accuracy

Furthermore, another problem has to do with the measurement of the welding voltage and the welding current. Assuming that ideal conditions exist with no welding current leaks, all the welding current that enters the welding circuit flows through the arc. Therefore, there is no problem there, as long as the assumption is true. The welding voltage though is another matter. The exact point in the geometry of the welding system at which the measurement of the welding voltage is made can influence the process in a negative way by introducing errors. Ideally, the measurement should be made between the tip of the welding torch and exactly at the point that the welding wire touches the parent metal and the welding wire should touch at the very edge of the welding torch's tipp. It is obvious though that due to practical limitations, the measurement cannot be made at exactly the points mentioned above. For the experimental work at Cranfield University, the welding voltage was measured between the upper end of the welding torch and the edge of the welding table on which the parent metal was placed on with such a way so as to have good electrical contact. Like every point of contact though, it will induce some impedance.

Due to the practical limitations above, the actual resistance that is measured is not the resistance of the welding wire alone, but includes the resistive path of the welding current through the parent metal and the welding table and the resistance of any point of contact in the above configuration. It also includes the resistive path of the welding torch from the point of contact of the welding wire with the welding torch until the point that the voltage feedback is measured. As reported in [9, 74, 76, 77], the path of the welding current through the workpiece can lead to process disturbances due to the magnetic fields generated [69]; it follows that as the welding current has to flow through large pieces of metal, the Ohmic resistance of these metals can become significant and variable with magnetic fields or temperature. Lythall and Gibson [69] reported that their experimental work was influenced from the length of the welding cables they used to emulate a hyperbaric process due to the increased Ohmic resistance of the cables [69]. On this must be added the resistance of the wire length inside the welding torch when the point of contact is not at the tip of the torch something that is very likely to happen, especially at the RPRS where the wire diameter is 1.0 mm and the tips used are 1.2 mm to prevent the wire to stack in the tip

when operating underwater. This means that although the dimensions of the welding torch are constant and its actual resistance can be accurately calculated, in practice this value might not be the one that is measured, since the point of contact of the welding wire might vary, so this value cannot be directly subtracted from the resistance value that is measured.

Inherent Process Instabilities

One more issue has to do with the metal transfer. As mentioned earlier in The Shape of the Molten Droplet and its Influence on the Dip Resistance's Waveform [pp. 102], if the part of the welding wire that melts is forming a molten drop which when it touches the weld pool or the contact area has diameter different than the actual diameter of the wire, errors might occur but the treatment by Di Pietro *et al.* [12] should help eliminate their influence. In addition to the process' behaviour, inherent instabilities occur from the weld pool's dynamic characteristics during operation, for example as mentioned in Influence of Weld's Bead Characteristics [pp. 118] for the uphill and downhill runs and in 2.5.3. Finally, instabilities due to surface 'dirt' or surface defects of the parent metals could occur and surface cleaning and grinding like the one performed by Silva and Hazlett [75] and Lawson and Kerr [76] is required to limit the influence of surface dirt and make the specimens "mill scale" free [75] and improve arc stability [76]. The use of bead-on-plates, where appropriate, should enable the elimination of any confusion arising from multiple passes and groove [or other] size variations as the welding conditions and/or parts of the experimental apparatus were replaced/altered [75] [for example the welding torch's tip diameter].

The Welding Wire's Physical Properties

Another reason for concern is that the wire used in the RPRS is not a solid steel wire, but a metal fluxed core wire. This effectively means that the electrically conductive cross-sectional area ' s ' in Equation 2-3 [pp. 100] is less than the welding wire's geometrical value, since the materials that constitute the core of the wire are not necessarily electrically conductive in the same way that the steel is. Generally steel wires are having a large resistance value and are better for use with this method of sensing since the magnitude of Ohmic resistance per unit length is higher than other materials which results in better SNR and makes it easier to be measured. The use of

a fluxed core wire means that it might be proven harder to implement the method of dip resistance measurement for CTWD estimation if the fluxed core results in a resistance per unit length lower than a non-cored steel wire. Nonetheless, experimental evaluation shall be enough to overcome this potential difficulty.

Temperature

One other factor is the influence of the temperature to the change of the resistance on the metals that form the electric current path of the process. It is well established that temperature influences the resistivity ' ρ ' of an electrical conductor, therefore its electrical resistance ' R ', as described by Equation 2-7 [pp. 139], Equation 2-8 [pp. 139], and from Equation 2-3 [pp. 100] which connects the previous two equations together. Most important are the temperature, therefore electrical resistance, changes on the welding torch, the welding wire and the parent metal. Philpott [13] examined the influence of the welding wire's electrical resistance from temperature during welding and therefore their influence on CTWD estimation using a through-the-wire sensor as presented earlier in Resistivity ' ρ ' Vs. Temperature [pp. 139] Average Resistivity ' ρ_{avg} ' and Average Temperature ' t_{avg} ' Vs. CTWD [pp. 140]. These might be the source of errors, but it might be proven to be safe to assume that since after the first few seconds the temperature of the components will be at the maximum working levels, then with the exception of the first measurements, all the rest of the results will have the same error included, so a direct comparison between them should not have any problems.

Ground Location

The ground location is something that can cause turbulence in the weld pool and influence the weld bead shape hence the CTWD estimation as has been reported earlier in Influence of Weld's Bead Characteristics [pp. 118] and in 2.5.3. Nonetheless, the small dimensions of the specimens might result in this effect to be so small that does not influence the results. This will be part of the experimental investigation. What needs to be kept in mind is that for the RPRS the welding wire is connected to the negative pole of the welding power source and the parent metal is connected to the positive pole of the welding power source. This should not have any influence on the Ohmic resistance but it might influence the weld pool's behaviour

and the results might not be what have been described earlier in Influence of Weld's Bead Characteristics [pp. 118] and in 2.5.3.

These factors seem to indicate that the method cannot be directly employed for the RPRS, unless a way can be found such that by applying the correct data treatment these errors can be reduced to a level that they will not make a significant change in the results. This is one of the most important tasks of this research project.

7 Initial 1 Atm Evaluation

As far as the initial data analysis for the project is concerned, the only tools available were Arc Watch for data acquisition and off line analysis and MS Excel® or a similar program for a more flexible off line analysis. MS Excel® provides the ability to update its data through a network of computers, but still cannot be considered as a real time tool. It seemed sensible at the beginning of the project that a few trials could be performed at 1 Atm in order to evaluate the flexibility and the effectiveness of MS Excel® as an offline analysis tool. If it was good enough, then a pre-programmed control system based on the results of this research project could be constructed in the future.

7.1 1 Atm experiments

A series of experiments were performed under 1 Atm conditions in order to gather a data set which then could be used for off line analysis with MS Excel® for evaluation purposes.

Experimental Strategy

The proposed experimental strategy was that the experiments should involve producing “*bead-on-plates*” at various standoffs with different welding voltage target values. The Wire Feed Speed [WFS] and the Travel Speed [TS] should to be such so as to maintain a constant metal deposition rate.

1 Atm Experimental Procedure

The experiments were done using “*bead-on-plates*” as described by the Experimental Strategy above. The welding voltage range was between 19 Volts to 27 Volts and the stand-off range was between 10 mm to 16 mm. The wire feed speed was kept at 7 m/min and the travel speed was 344.3 mm/min. The voltage and current traces were acquired using a Yokogawa digital oscilloscope at 10 kHz sampling rate. The CTWD and the rest of the welding parameters were kept constant for the duration of the run.

1 Atm Analysis and Results

The voltage and data acquired from these experiments were imported to MS Excel® for analysis. Because of the fact that MS Excel® has a limitation of 65,536 lines, and each pair sample of voltage and current requires one line, the values from each run were not able to be fitted in a single spreadsheet. This was because with the original sampling rate there would be 10,000 values per second, hence the maximum length of data that could be imported into MS Excel® would be approximately 6.55 seconds. For that reason, a file was re-sampled at 1 kHz and 2 kHz using DL Wave, a PC based software package for waveform viewing from Yokogawa. That way it was feasible to import all the data from each run to one sheet. A small part of the 10 kHz data and 1 kHz and 2 kHz data were then graphically compared and the values of welding voltage and welding current were averaged and compared, so as to show if any significant loss of information occurred by the re-sampling process. The conclusion was that no significant loss of information occurred. Thus, it was decided that all the data files will be re-sampled and processed at 1 kHz and then imported into MS Excel®.

A series of formulas was then written in order to make some basic calculations concerning dip resistance like detection algorithms, dip resistance values, shot-circuit events frequency, mean values and others. The detection algorithm designed and employed was making use of the welding voltage and welding current values at their minimum and maximum values respectively, after both of them had passed the thresholds, the values of which were set to be the same as the ones that the power source controller uses to detect a short circuit and to deliver the short circuit current ; for the 1 Atm experiments the threshold values were: welding voltage less than 10 Volts and welding current [to be delivered] 250 Amperes. At that point, the resistance was calculated. However, it was noticed that the maximum value of the current occurred a few milliseconds after the minimum voltage value was reached, as expected based on the descriptions of Figure 2-58, Figure 2-59, Figure 2-63. Thus, the tactic used for the algorithm to determine the welding current, was to examine what the value of the welding current was and if it was at its maximum on the next sample point from the one that the welding voltage had been detected to be at its

minimum value. This method of algorithm was preferred over the method to follow the resistance continuously and to try to find its minimum value in the small duration of a short circuit. The reason was that the sampling of consecutive resistance values at their minimum value during the same short circuit occurrence may not have been able to be satisfied, mainly because of the fact that the re-sampling of the data at 1 kHz could limit the number of the short circuit events that satisfy this requirement since with this sampling rate the short circuit event duration should be quite extended, thus valuable information points could be lost/rejected due to insufficient data. The reason is that with 1 kHz sampling rate the time between two consecutive samples is 1 ms and if the detection algorithm requires more than one samples to be taken during each short circuit event, then each short circuit should last for more than 1 ms. This would not be a problem with high sampling rate, but with 1 kHz, and no guarantee that the first sampling point will be taken exactly at the initiation of the short circuit, then the second sampling point might have be taken too late [after the short circuit event if it was short in duration] so the short circuit event might have to be rejected due to insufficient data.

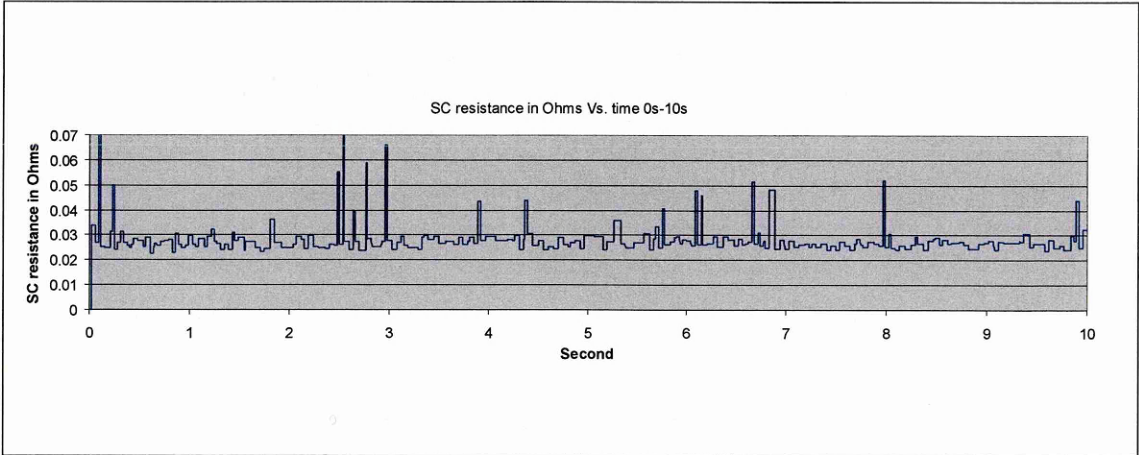


Figure 7-1: Typical resistance trace from the 1Atm analysis for 25 V target value and 12 mm CTWD.

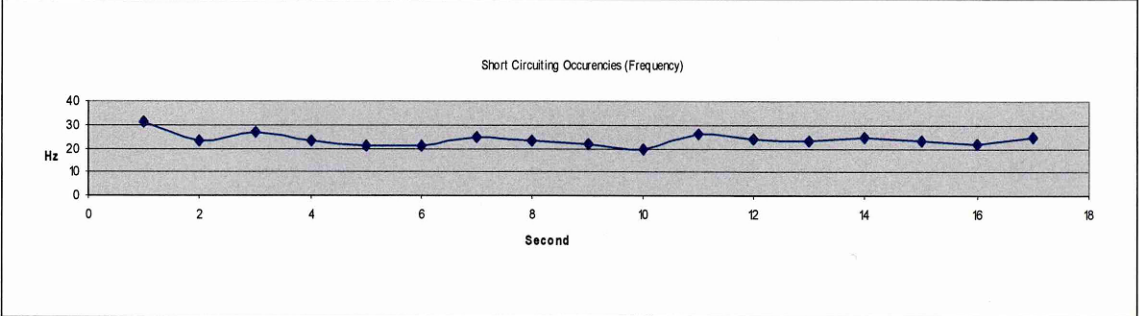


Figure 7-2: The variation in short circuit frequency over time for 1 Atm process with 25 V target value and 12 mm CTWD.

1 Atm Results Discussion and Conclusions

Although it was feasible to import the data into MS Excel[®] and analyse it then, the process proved to be very time consuming. The situation became better due to the fact that once the spreadsheet has been set-up, the only thing needed was for the original data to be replaced. The conclusion is that continuous use of MS Excel[®] for such a process is possible but it is better to be avoided, since there are other ways that could give the same results in much less time and with less effort. This involves the use of an advanced programming language with the use of which an adaptable program could be built.

However, this first approach did support some of the remarks that previous researchers had made, like the fact that although the CTWD was kept constant during a run, subsequent resistance values seemed to fluctuate [12] as shown in Figure 7-1 and Figure 7-2. Di Pietro *et al.* [12] had noticed this issue in their work and it was the reason that the CTWD should not be readjusted each time a resistance value is measured. One reason for that could be the threshold values that were used in order to detect the initiation of a short circuit. This suggested that further investigation for the ideal threshold values should be made. Nevertheless, the algorithm seemed to work satisfactorily and was able to detect the short circuit events successfully.

8 DAQ System Development

The results from the initial 1 Atm experiments suggested that it would be wise to develop a new DAQ system completely independent from the old instrumentation not only in hardware but also in software terms. This would enable the new system to be built in parallel with the old one without interfering with the operation of the Hyperweld 250 and the work that was currently carried out. It was considered to be a good choice to utilise a PC based DAQ system in order to be able to meet the hyperbaric welding needs and to provide greater flexibility for future use and expansion. In order for that to happen, there were two main decisions to be taken. The first was concerning the programming language that was going to be used to build the GUI and the second one was about the hardware that was going to be utilized.

8.1 Selection of the Programming Interface

Nowadays, there is a lot of advanced higher level programming languages that could be used in order to build a data analysis program. Even better, these could also offer the ability to build DAQ software to be used with one of the available DAQ hardware systems. There are two main categories. The text based programming languages and the graphical ones.

The text-based ones have been around since the beginning of the computer age. Although they have evolved a lot and now offer the flexibility of building an advanced GUI in order for the end user to be able to operate the program, they are almost as difficult to work with them as they used to be in the beginning. The main reason is that everything has to be typed and, most importantly, to be typed correctly. This practise can be proven to be a very time consuming process not only during the initial development. In addition, editing an existing program is not an easy task, especially for a program that has been written some time ago and is not exactly “fresh” in the programmer’s memory.

The graphical programming languages on the other hand have been around only for a much shorter period of time. Nevertheless, they offer a great advantage. They are, as their name implies, graphical, which means that they use symbols in order to represent functions and operations, which are of the drag-and-drop form, but also support the combination of use of text base programming and import of modules from text based programming languages in combination with the graphical programming. Thus, it is a much better choice for new programs. For that reason, it was decided that a graphical programming language would be the best option. One of the most well known graphical programming languages today is LabVIEW.

LabVIEW is a platform created by National Instruments [NI] and is based on the same principles and theorems like MATLAB. Therefore, it has the ability to act as an excellent tool for data analysis. This, in combination with the fact that LabVIEW and the hardware DAQ systems that NI builds are structured so as to be used together makes LabVIEW [version 7.1] the optimum choice for being the programming interface that should be used for the development of the data acquisition and analysis software. In addition, the use of a graphical programming language will expand the future possibilities of adapting the same system to a number of different applications welding projects, since everything will be much easier to be done.

8.2 Selection of the DAQ hardware

The DAQ hardware is an important part of the system. It is the interface between the physical process and the system that is controlled by the operator. Like programming languages, DAQ hardware comes in a lot of forms and specifications. Some of them are fairly basic and are designed for low-end systems where the requirements are not very demanding. On the other hand, there are the high-end systems which are designed for demanding applications. However, there are various factors associated with the selection of a DAQ system. For this project, in order for a system to be chosen must comply with all of them. These are:

- 1) Economical factors,
- 2) Off-the-self availability for spare parts/modules,
- 3) Current availability of the required instrumentation,
- 4) Flexibility and further expansion,
- 5) Accuracy required.

The economical factors are different for each project. It is clearly a variable that changes according to the needs. These needs are the rest of the above factors. Firstly, it is very important that there will be spares available off the self. This is very critical since it is certain that at some point repairs will be required. It is much easier to buy a spare part than to build one. The instrumentation that is required for the project is another very important reason. Not every DAQ system can make use of every sensor. For this research project but also for the RPRS program development, the parameters that currently need to be taken into account are the following:

- 1) Voltage,
- 2) Current.

In addition to the voltage and current values for determining the electrical resistance of the welding wire during the short-circuit events, the work in the hyperbaric program would be benefited by measuring and logging the following:

- 1) Temperature,
- 2) Dew point.

The temperature values can also be used to evaluate its importance, or not, in determining the CTWD using the dip-resistance values.

The above can cover the current needs, but the flexibility of the system and possibility of further expansion must be taken into account. Finally, the accuracy required from the system is a very critical factor that can play an important role in the hardware selection process. For the welding processes and for the development of the RPRS, the accuracy is not an extremely demanding factor. However, the accuracy must be fairly reasonable but most important repeatable and realistic. The latter means that the DAQ system must be able to be calibrated easily and to be able to maintain the calibration accuracy if valuable results are to be obtained.

For this research project, it was selected that the hardware that should be obtained would be a NI DAQ M-6259 PCI card in combination with an SC-2345 SCC type signal-conditioning carrier and a SCB-68 break-out box. The M-6259 implements the latest technology available. It employs the method of using a single PGIA and an ADC with a MUX in order to scan all the channels. The SCC carrier provides the ability for easy interfacing of the DAQ card with sensors. NI offers a wide range of SCC signal conditioning modules that can be used in order to adopt the system to the needs of the project. Each module is a complete signal conditioning unit. With the use of these modules, the majority of the DAQ components can be off the self, meaning that there is no special dependency from specific people/skills or special components. For this research project, the SCC modules utilized are listed in Table 8-1.

Quantity	Type	Description
1	SCC-A10	2 channel, x10 attenuator module, analogue input module
5	SCC-TC02	One channel thermocouple input module, 10 Hz LPF, with CJC [Cold Junction Compensation]
2	SCC-LP04	2 channel, 1kHz LPF, analogue input module
Table 8-1: List of the SCC type signal conditioning that was used in order to monitor the required signals.		

The SCC-A10 module was selected so as to monitor the welding voltage parameter. The fact that attenuates the input signal by a factor of 10 makes it ideal for that task. For extra safety though, an external differential attenuator was designed built and implemented as described in 8.3. This module is used in cascade configuration with an SCC-LP04 module used to filter out the electrical noise.

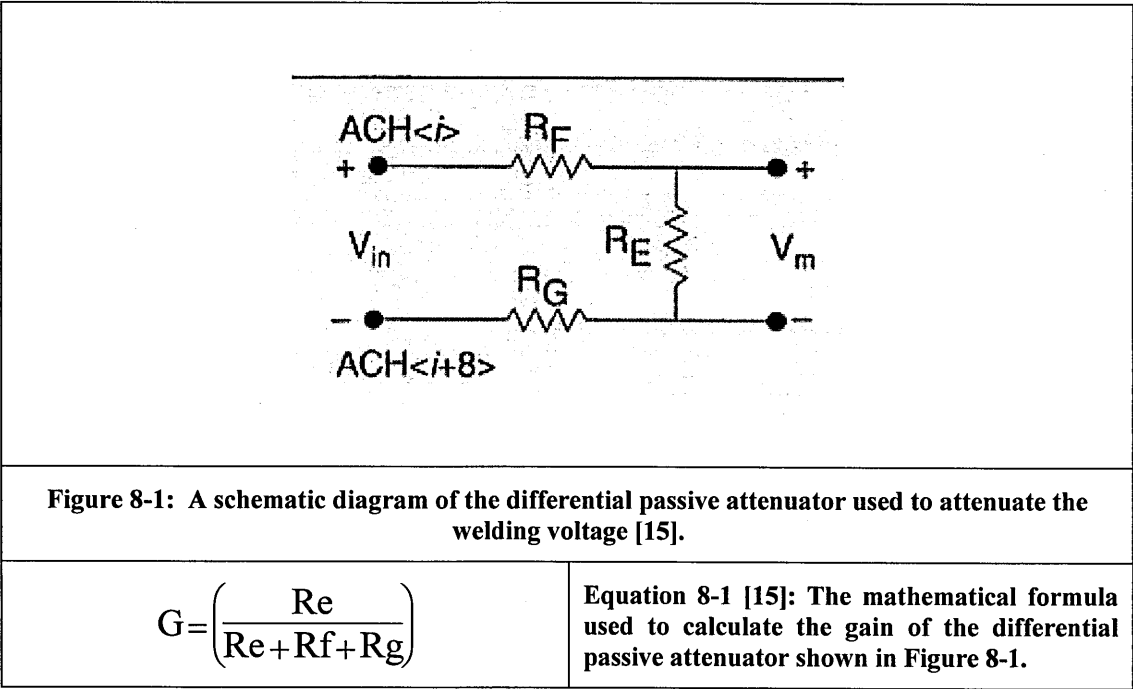
The SCC-TC02 modules were used to monitor the temperature of the specimen. Four of them are dedicated to that task and the fifth one is used to monitor the vessel's temperature, although, if required it can be used as a fifth monitoring temperature sensor as well. The second SCC-LP04 is used to filter the welding current signal.

The SCB-68 break-out box is a general purpose unit which gives great flexibility to the system since it can be used for the connection of a wide range of sensors directly on to the DAQ card without the need for any additional hardware, with the provision that the output signals of the sensors have been conditioned before.

The DAQ card needs to be used in combination with a suitable PC based computer system. Since the later should have hi-end specifications in order to provide real time DAQ and data analysis with the possibility for the future to be required to provide real time control, it should provide the flexibility for future expansion without an increased cost, or without the need for changes in the DAQ hardware and software. The system that was selected and used was the Dell Precision 670 series PC series.

8.3 Custom Built Signal Conditioning

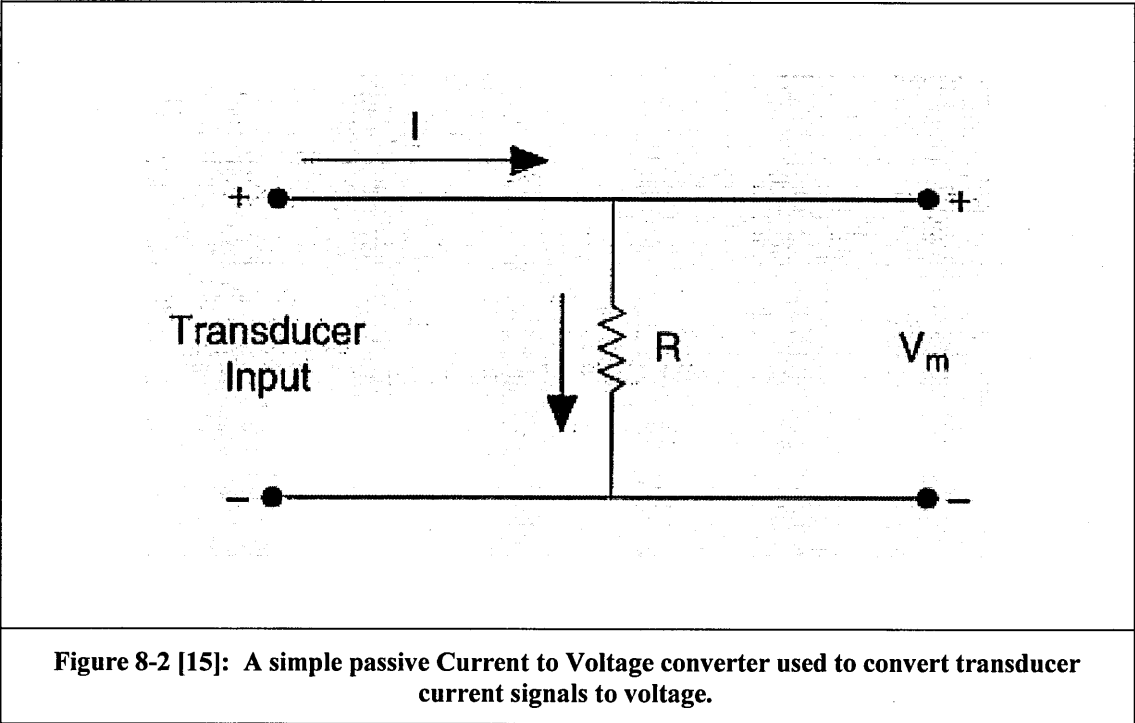
The project required two custom built signal conditioning circuits to be built. The first one was a differential attenuator for use with the welding voltage signal, a general schematic of which is shown at Figure 8-1. The desired attenuation was 10:1, that is a gain, G , of 0.1. This value in combination with the attenuation from the SCC-A10 [10:1] module would give a total attenuation of 100. This allows values of up to 1,000 Volt to appear at the input of the signal conditioning unit and still to be safe for the equipment. Equation 8-1 below is used to calculate the component values for the attenuation. According to Equation 8-1 below, the required values were 4.5 MOhm for R_F and R_G and 1 MOhm for R_E . The values of the components were selected to be a 3 MOhm $\pm 1\%$ resistor in series with a 2 MOhm potentiometer for R_F and R_G and 1 MOhm $\pm 1\%$ resistor in series with a 100 kOhm potentiometer for R_E . The selection for use of such large values resistors is unusual, but it was taken with safety in mind since, the maximum isolation possible was required. For that reason, the resistors used are capable of handling 7.5 kVolts [manufacturer's specifications – Tyco Electronics HB1 series]. The use of the potentiometers allowed the exact values to be achieved, since the calculated values are not of the standard range.



Even in the case of overvoltage which could damage the potentiometers, the resistors can ‘survive’ and provide adequate protection for the rest of the equipment; to that

contributes their relatively large size needed for achieving 2 W power dissipation rating which helps maintaining their value constant [negligible temperature drift in this application and the large distance between the component's leads minimised the possibility of high voltage arcing which could bypass them and damage the rest of the equipment.

The second circuit is a simple passive Current to Voltage converter. It is nothing more than a 1 k Ω potentiometer connected at the current output (4-20 mA) of the Michell Dew Point measurement system. The potentiometer was set at 232 Ohms as NI specifications suggest [15]. Also, two ceramic decoupling capacitors each one with a value of 10 nF were used to reject any high frequency noise induced on the signal cable connecting the output of the Michell instrument with the input at the break-out box. This circuit was built in order to convert the current output to a voltage, which can be directly sensed from the DAQ card. The theoretical circuit without the decoupling capacitors is shown at Figure 8-2.



According to Ohm's law [Equation 2-5 [pp. 100]], the value of 232 Ohm for the potentiometer will give a voltage across it from 0.928 V [at 4 mA] to 4.64 V [at 20 mA].

8.4 Sensors Used

For a DAQ system in order to be able to sense physical quantities like voltage and temperature, it is necessary to use some transducers that will actually convert the information from a physical quantity in another form of signal. Usually, the output that is required is a voltage signal. For the DAQ system used in this research project, the welding voltage signal did not need a special sensor since the nominal values were not expected to exceed the equipment’s handling capabilities after they had been passed through the differential welding voltage attenuator described in 8.3. The welding current was sensed using an ampere-clamp transducer based on the Hall Effect, providing electrical isolation from the power sources. The ampere clamps provide a linear voltage output which is dependent on the strength of the magnetic field that passes through the sensor. For the temperature, K-type thermocouples were used in order to convert the temperature to voltage. Finally, a Michell dew point sensor was used. Table 7-2 shows the sensor types and their make and model used for this project.

SENSOR	MANUFACTURER	MODEL
Current Clamp Meter	LEM	PR 1030
Dew point sensor	Michell	Cermet II Hygrometer
Temperature	RS	Type K Washer (290-4982)
Table 8-2: Sensors used, their manufacturer and their model.		

9 DAQ Software

As mentioned earlier, the programming language that was selected for the DAQ software was LabVIEW 7.1. A short description of the main software areas and features is given below.

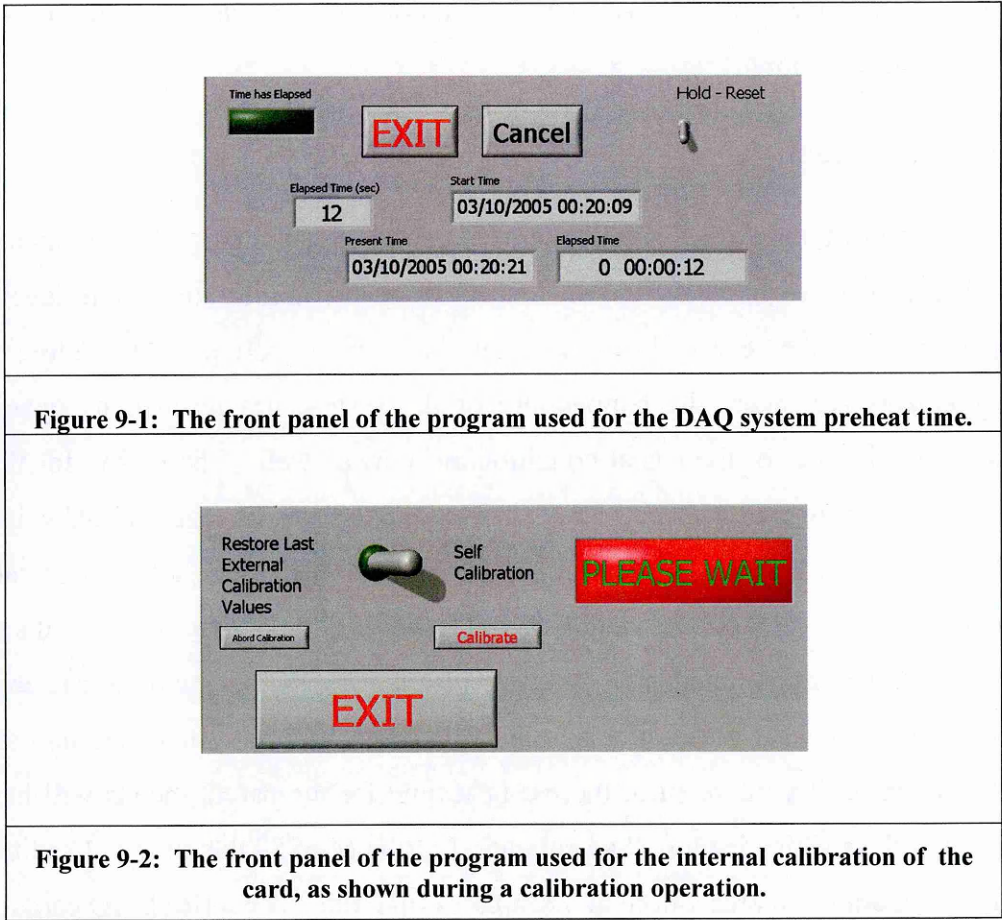
DAQ Preheat Time

The first part of the software is the timer that counts the time that NI recommends as the time that is required so as the card can reach normal operation levels of temperature. Like every instrument, it is very important that before any measurements are taken, the temperature of the system has reached its operation levels. This is true for the signal conditioning units as well. The reason for that is that as the components get heated up, their characteristics change. Usually it is a slight change, but because of the number of the components, the total effect can be great. Thus, the equipment should be allowed the time that the manufacturer recommends before commencing operation, in order for the results to be as accurate as possible. This is not going to be a problem in practise if the system is to part of the RPRS system in the future since the pre-heat time for the parent metals will have a duration of days which is more than enough. For the M-6259 this time is 15 minutes, but the program has a preset time of 30 minutes [like the older series DAQ cards] just to be on the safe side. Figure 9-1 shows the panel of the program that is used for the equipment preheat. This part of the program intentionally “stresses” the CPU usage so as in the same time to raise the temperature inside the PC case, which can affect the final temperature value of the DAQ card.

DAQ Calibration

The second step is to perform a calibration of the DAQ card. The M series range supports two types of calibration, internal and external. The external one needs to be performed every two years and requires specialized and calibrated external equipment. The internal calibration has to be performed every time the DAQ card is going to be used, or even between periods of its use. What the internal calibration does is that it compares the temperature that the card on board sensor was reading at the last external calibration. Then, it reads the current temperature reading and scales

the calibration values accordingly in order for the card to be accurately calibrated under all conditions. That is why it is important that the calibration will be performed after the preheat time has been elapsed. This step is performed with the aid of the simple panel shown at Figure 9-2.



Sensors Calibration

The third part of the program is the calibration of the sensor values. These values need to be set only when a system calibration is performed. What the controls of this panel do is to scale and offset the readings of the sensors as necessary in order for them to be accurate. Thus, in order for that to be done, the best way is to compare the readings with a known calibrated instrument and to make the two readings match. Figure 9-3 shows the panel that is used for this procedure. With the aid of this panel a full system calibration can be performed in minutes, including all the sensors used, which is a strong advantage of this program in case sensors or other parts need to be changed.

The top left corner of the panel is used to monitor the welding voltage and welding current waveforms and values in order to perform the calibration. The bottom left corner of the panel allows to monitor graphically various other user selectable parameters, for example temperature. The right half of the panel has the knobs used to alter/adjust the shift levels for each sensing signal input and the gain for the welding voltage and welding current. It also includes a graphical monitor for the dew point sensor.

Welding Parameters Initialization Values

This panel is used to set the welding parameter's values that are going to be used during welding, for example the travel speed [TS] amongst others. It is very important for the correct operation of the program that these values will be set correctly. Once they have been set they only need to be changed if the parameters change. Figure 8-4 shows the panel used for that operation to be performed. This front panel is also used to import the time stamps for the truncated data log. What this means is that the program can be preset to log not only all the data but also to log separately a part of that data. This way it is possible to automatically cut the parts at the beginning and the end that should not be included in the real time parameter observation or the later off-line analysis. This panel is also used to set the process target values for the welding voltage and the welding current and their threshold values for the short circuit detection algorithms.

Alarms Control Panel

This control panel is used so as to set the preferences for the visual alarms for the welding voltage, current and the temperature. The program can inform the operator when the temperature of the selected sensors has passed the limits by changing the colour of the numbers that display the temperature, or by blinking the indicator on the DAQ panel. The program also informs the operator if the welding voltage or current pass the target values by a percentage which is predetermined here, by changing the background colour of the indicators on the front panel. There are three colour codes for that. The green, which should be used when the values are inside reasonable limits, the yellow which should be used when the values tend to deviate a lot from the target values and the red which effectively means that the process is performed with

parameters that are very much different from the targets. These settings are applicable for all three sets of captured data. Below is shown the front panel used for the alarms configuration.

Data Acquisition

This part of the program is obviously the most important one. This is the panel where the operator can monitor all the welding parameters involved except the travel speed which currently is not linked to a sensor but they are set as constants through the initialization values. Figure 8-6 shows the panel used for the data acquisition.

The left half of the panel hosts the welding current [up] and welding voltage transient waveforms with the view meters for the mean values below them. Below the mean welding current view meter is a user pre-select waveform that is used to display graphically a measured quantity, for example temperature. Next to it is a graphical representation of the various locations of the thermocouples depending on the type of specimen used, with the “sleeve-on-pipe” currently active, as well as graphical and digital representation of the temperature for each thermocouple. The right part of the panel hosts the graph used for the dip resistance experiments [trial] and exactly below it is a mean dip resistance view meter and switches used to evaluate various dip resistance measurement techniques. Finally, the right part of the panel hosts the dew point level measurement.

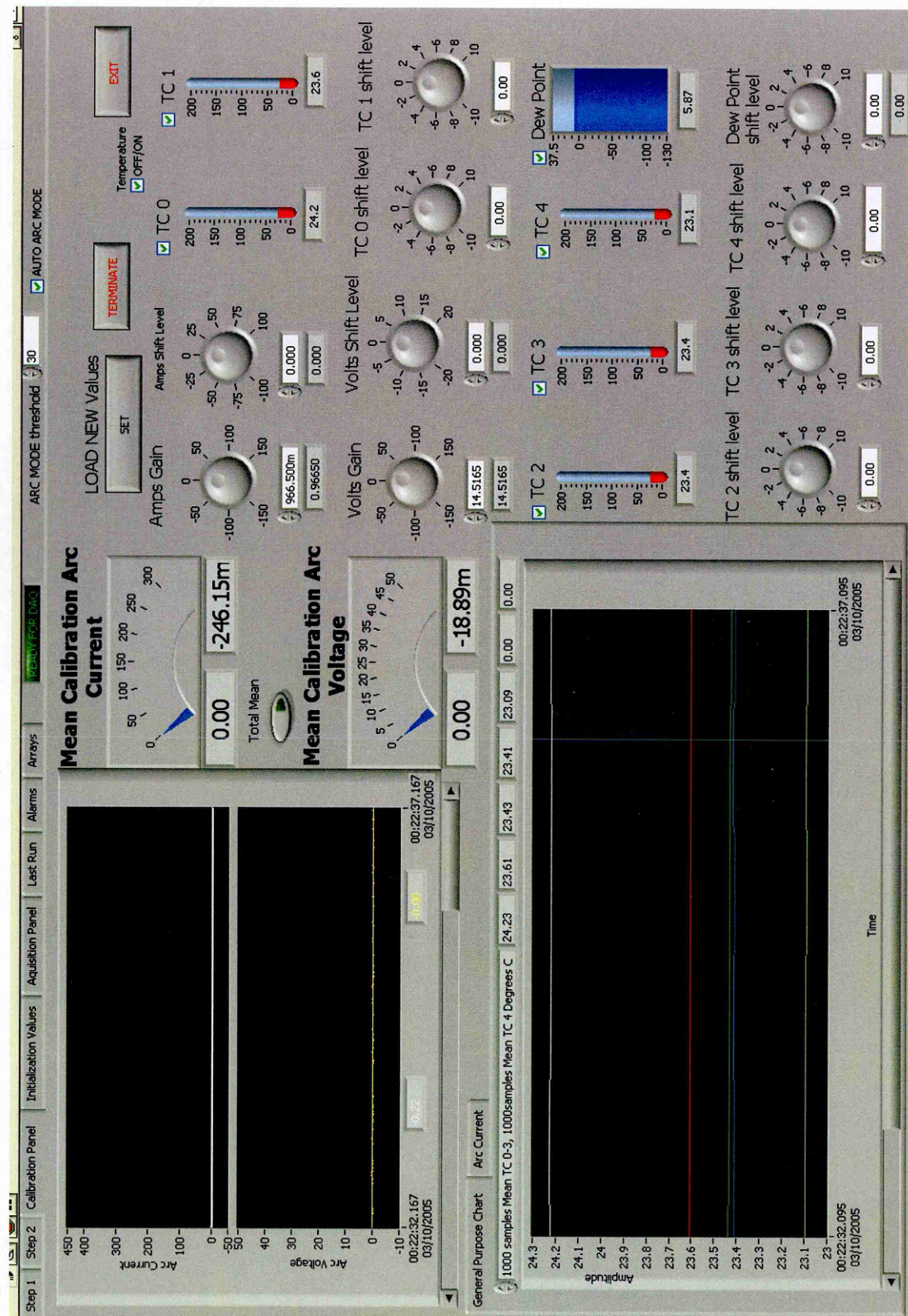


Figure 9-3: The front panel of the sensors calibration section.

Figure 9-4: This panel is used to import to the program the welding parameter values.

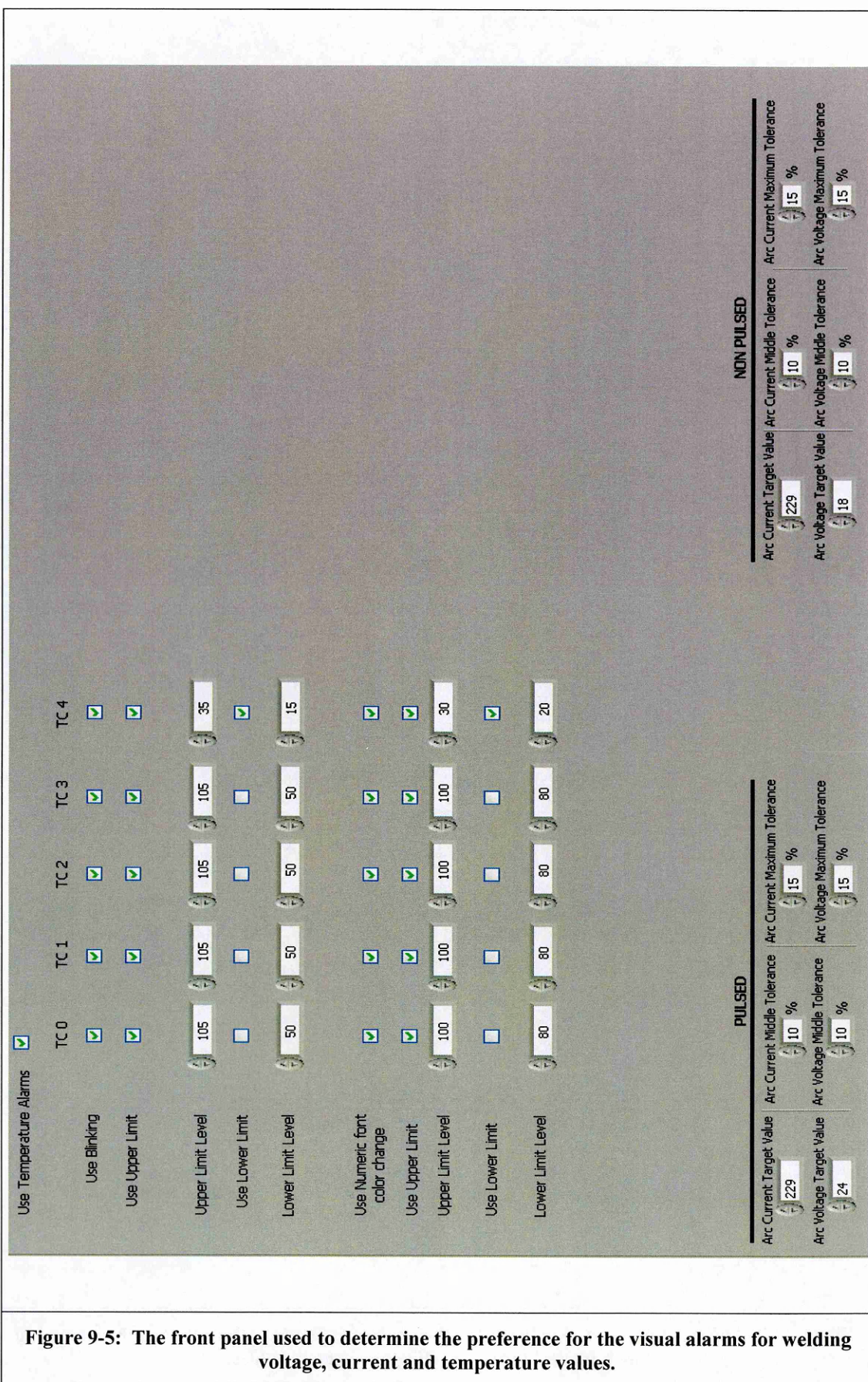
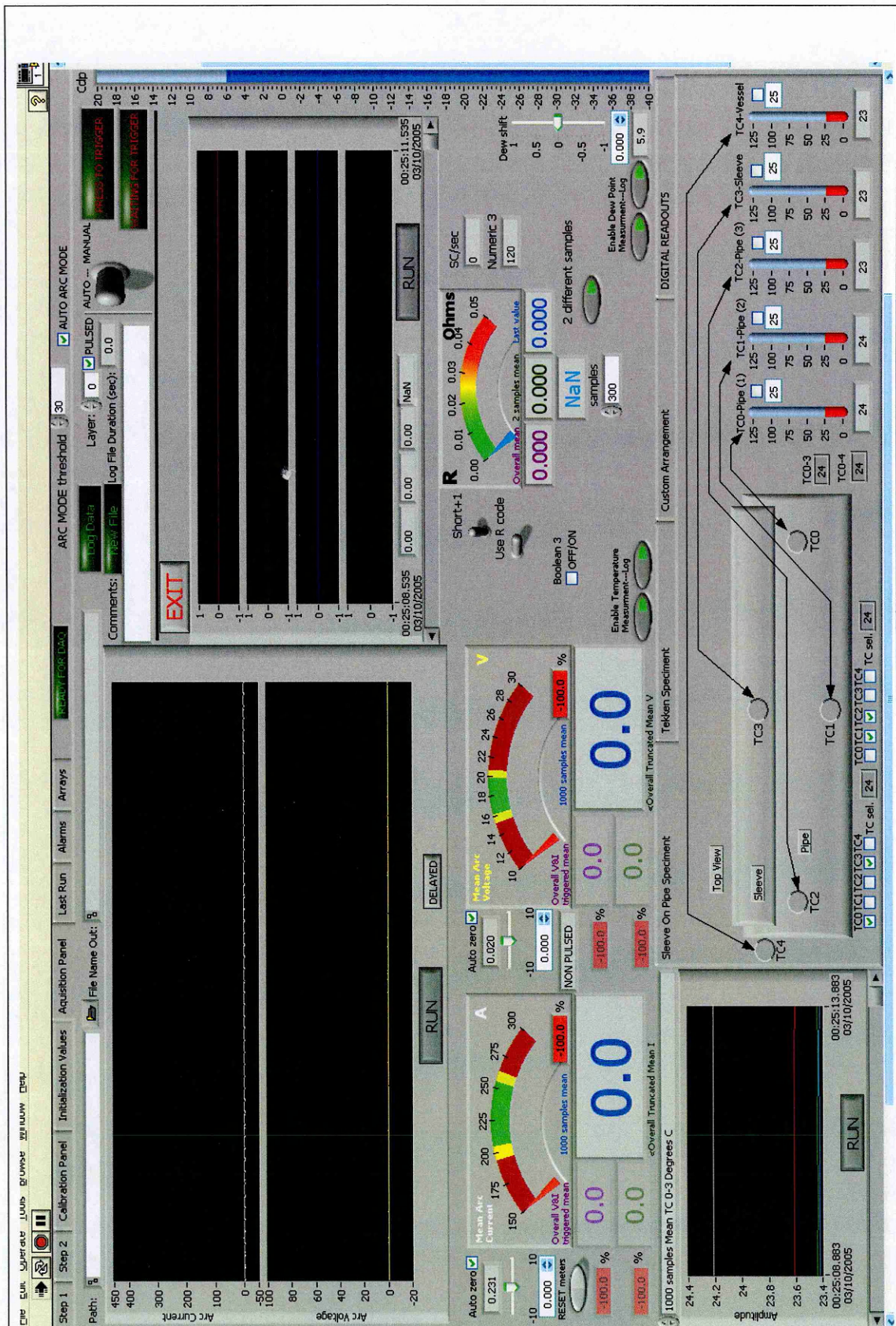


Figure 9-5: The front panel used to determine the preference for the visual alarms for welding voltage, current and temperature values.



9.1 Main DAQ System's Characteristics

The main characteristics of the DAQ system are:

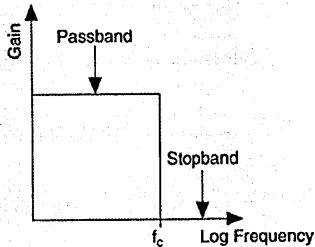
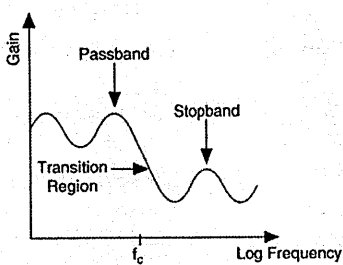
- 1) 1 welding voltage channel low pass filtered at 1 kHz,
- 2) 1 welding current channel low pass filtered at 1 kHz,
- 3) 5 temperature channels,
- 4) 1 dew point channel,
- 5) Sampling rate 1 kHz per channel,
- 6) Real time data acquisition processing and display,
- 7) Minimum real time delay 100 ms.

The welding voltage and current values are acquired and displayed in raw form and in averages of 1 sec [1,000 samples for process monitoring]. For the temperature readings of the four thermocouples used for measuring the specimen temperature, the averaging is 1,000 samples, equal to 1 sec. The fifth thermocouple and the dew point sensors, which monitor the vessel's environmental conditions, the averaging is every 10,000 samples, equal to 10 seconds. This averaging for the temperature and the dew point is done in order to minimize the effect of the noise on the lines that carry the signals from inside the vessel to the DAQ system. The averaging of the voltage and the current is used so as to have a better appreciation of the real welding parameters, since the instantaneous values are changing all the time due to the nature of the process. The program gives the ability to capture data in three ways at the same time. The first way is to capture the overall run. The second way is to capture a truncated part of the run, with the truncated part limits to be predetermined from the initialization panel. The third way is to capture the data when the welding voltage and current have passed the thresholds that have been predetermined in the initialization panel. Except from the above, the data acquisition panel gives the operator visual information using graphs about the raw welding voltage and current signals. It also has a multi-purpose panel that can display graphically every parameter that the system monitors either alone or in combination with the others of the same group. It also gives an update every second for the percentage deviation of the welding voltage and current for all three ways of data acquisition, and more specifically, full, truncated or

voltage and current triggered. Finally it offers the ability to assign a name to every acquired file based on the pattern that the operator has set. In general terms, the program makes use of colour changes in order to inform the operator that important parameters have exceeded the predetermined tolerance limits.

9.1.1 Aliasing and Counteraction

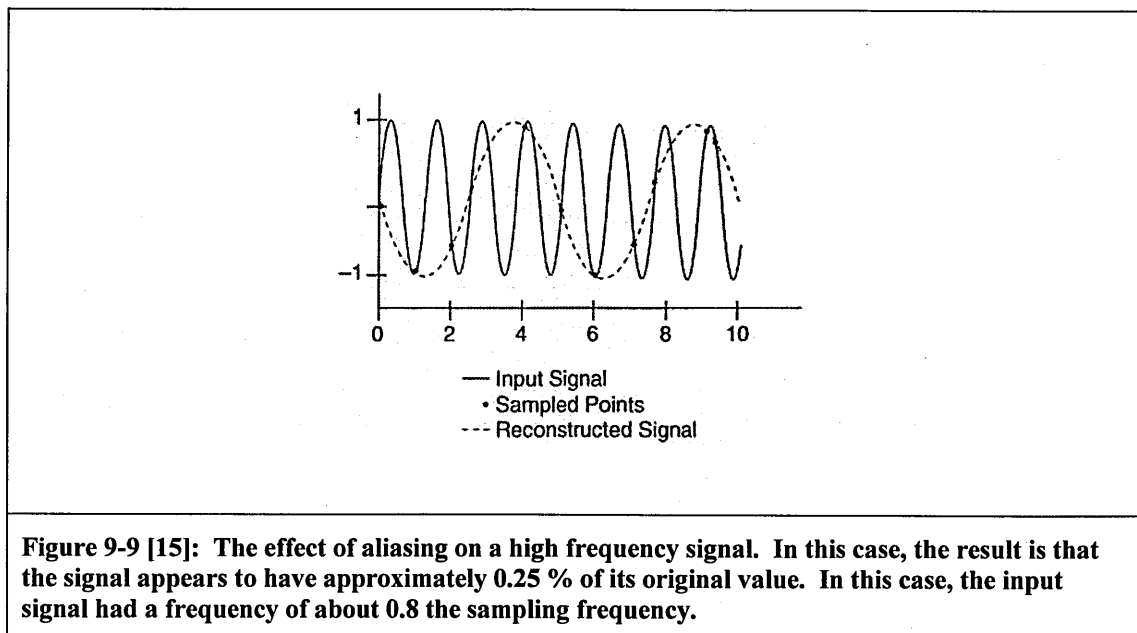
At this point, it should be noted that from the above characteristics it is shown that the sampling rate has the same value as the low pass filters cut-off frequency. Normally, the sampling rate should be at least double than the highest frequency component of the signal according to Nyquist theorem [49] [also known as the Shannon theorem], otherwise aliasing may occur. In this case, with the sampling rate of 1 kHz, any signal should not exceed the 500 Hz, which is the Nyquist or folding frequency [49]. That is the normal frequency cut off value for the filter, considering ideal filter frequency response as shown in Figure 9-7.

	
Figure 9-7 [15]: An ideal frequency response of a low pass filter.	Figure 9-8 [15]: A more realistic response of a low pass filter.

Real filters however, have a frequency response like the one shown in Figure 9-8. It is evident that signals with frequencies above but near the cut-off frequency f_c of the filter will go through, even though they will be attenuated.

For the SCC-LA04 filters with a cut-off of 1 kHz, NI suggests that the sampling rate should be at least 20 kHz, otherwise aliasing could occur. Aliasing is the phenomenon which causes the high frequency signal components above the folding frequency to appear as low frequency signal components below the folding frequency

[15, 49] as shown in Figure 9-9. Aliasing can be a result of either sampling or sampling rate conversion and the finite attenuation of any filter means that cannot be eliminated, it can only be attenuated/reduced [49].



The problem with aliasing is that it distorts a signal before it is being digitised. Since the moment that the signal will be digitised, the information is permanently lost [49]. The alias frequency, in other words, the frequency that the original signal will appear to have is the absolute value of the difference between the frequency of the input signal and the closest integer multiple of the sampling rate [17]. Figure 9-10 shows a graphical example of the relationship between the original frequency components, the sampling frequency, the Nyquist frequency and the alias frequencies.

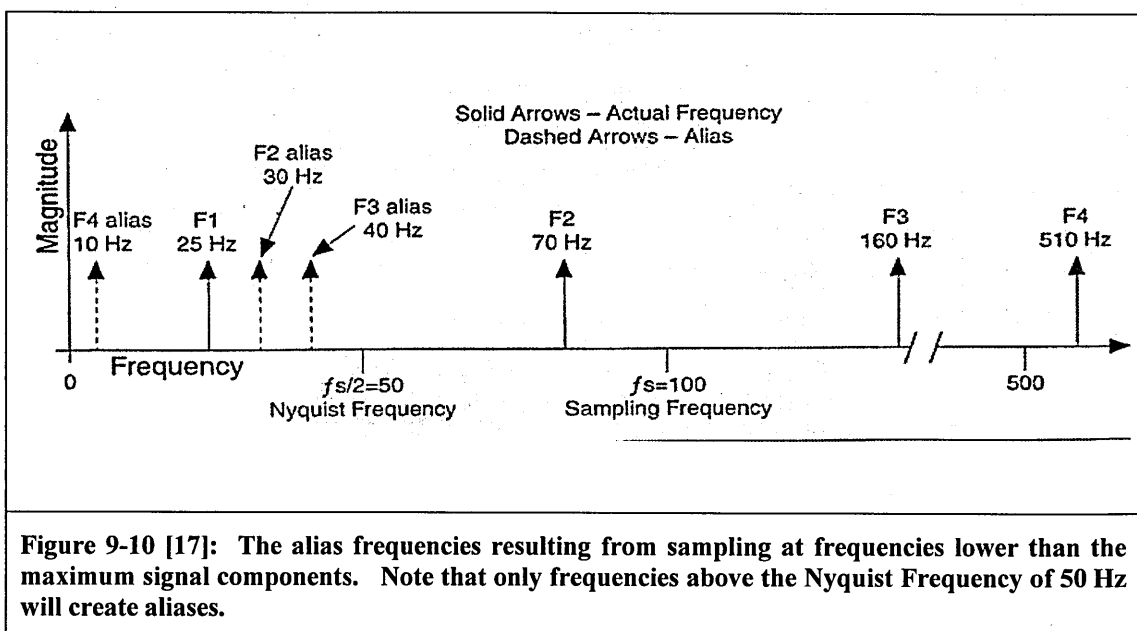


Table 9-1 explains how the alias frequencies can be calculated and how to calculate the alias frequency for the power sources’ inverter.

Original Signal Frequency in Hz	Sampling Frequency in Hz	Multiplied By	Result	Difference or Alias Frequency in Hz
25	100	N/A	N/A	N/A
70		1	100	30
160		2	200	40
510		5	500	10
Power Sources Inverter [operating frequency of 160 kHz]				
160,000	1,000	160	160,000	0

Table 9-1: Calculation of the alias frequencies for the example of Figure 9-10 and for the case of the power sources’ inverter operating frequency used for the project.

Theoretical Investigation of the Effect of Aliasing for RPRS DAQ

For this project, the frequency that could cause a problem is the frequency that the inverters of the power sources are operating, in this case, the frequency of 160 kHz. This signal is much higher than the SCC-LP04 filter cut-off frequency and it should normally be completely attenuated. Also, in our case, the closest integer multiple of 160 kHz is itself. Thus, the absolute difference, as shown in Table 9-1 is 0 Hz so, the alias signal –if any- will be a DC voltage [0 Hz]. This means that the moment the power sources are switched on, the DC alias from the power sources’ inverter will swift the open welding voltage measured by the DAQ system. This is easy to compensate for by calibrating the equipment using another calibrated and independent voltmeter, so no further action was necessary. Finally, even though the frequencies from 500 Hz to 1 kHz will be affected from aliasing, it is not considered to be a significant problem, since the signals from the process that are of interest have frequencies that are much lower in value than the limiting Nyquist frequency of 500 Hz.

9.1.2 DAQ operation

The internal operation of this part of the program is much more complex than that of the other parts and is subdivided in three main states. This part of the program can be operated in any one of the three main states. In which state the program operates is determined from the operating condition. The operation of these states is briefly described below.

Idle State

In this mode, the program waits for a trigger to occur either from the process or from the operator. Until this trigger occurs, the program reads 100 data samples for each signal for every loop iteration and updates the front panel accordingly.

Triggered State

When triggering occurs, the program collects the data continuously in chunks of 100 samples [100 msec] for every loop iteration. It then buffers the values in the PC memory and updates the front panel. This is continuous until the trigger conditions cease to be valid.

Data Formatting and Data Logging State

The program enters this mode when the trigger conditions cease being true and only if valid data have been collected; if not, the program returns to the idle mode. If however valid data have been collected, the program formats the data and stores them into a LabVIEW measurement file type and assigns a name for each file automatically based on the initial name that the operator has selected. The selection for use of this type of file was made since it is very easy to load and manipulate stored files into LabVIEW for off-line analysis and they are accessible using a spreadsheet or even a simple text editor. After this operation finishes, the program returns to idle state.

9.2 DAQ Program Experimental Evaluation

The DAQ program was tested experimentally for its stability and easy of use. Through this evaluation the key parts of the software were improved as much as possible so as to serve in the best possible way the needs of the operator for fast and accurate information of the welding parameters. In order for that to be done, the first step was to calibrate the system as described next.

Equipment Calibration

The first and most important part is to calibrate the new DAQ system so as to be able to produce the most accurate results. The DAQ card is shipped with a valid two year calibration period from NI. So, the calibration is required just for the signal conditioning, the sensors and the losses from the system's components electrical resistance, for example the wiring or the penetrators. The calibration was done against calibrated reference equipment and it was done for all the DAQ systems in the Hyperbaric Lab, and it was verified that all the systems have the same indications for the same reference input. The Voltage was calibrated by applying a voltage signal at the tip of the torch. That voltage was measured using a calibrated FLUKE voltmeter and the gain and offset of the DAQ program were adjusted so as to achieve the best fit from a range from 0 V to 30 V. The Current was calibrated originally at the Isotek Top Station and the DAQ program was calibrated against it, from all the range up to 380 Amps. The temperature was calibrated by attaching the thermocouples on a steel plate with the heating mattress underneath it and by applying a heat input through the mattress. The values were cross-checked by using a calibrated non-contact Infrared thermometer by heating the steel plate and measuring the temperature multiple times at different temperature values next or on the thermocouple's measuring ends [on a non-shiny surface area so as to enable proper operation of the Infrared thermometer since too much reflection of the original Infrared beam could saturate the receiver and make it impossible to measure the temperature value].

Summarizing, the accuracy of the setup was perfect at the first decimal digit for both the voltage and the current and almost perfect at the second decimal digit. This meant

that according to Ohm's law, the system could detect with accuracy resistance values in the range of hundreds of mOhms, for example, from Ohm's law shown earlier in

Equation 2-5 [pp. 100], $\frac{3.3 \text{ Volts}}{387.7 \text{ Amperes}} = 0.00851174 \text{ Ohms, or, } \approx 851 \text{ mOhms.}$

9.3 Commissioning of the DAQ System

The next step was to commission the system for use. This would be the most significant set of experiments of the system since it would perform under “real” conditions. The implemented system in the Control Room of the Hyperbaric Lab is shown in Figure 9-11.

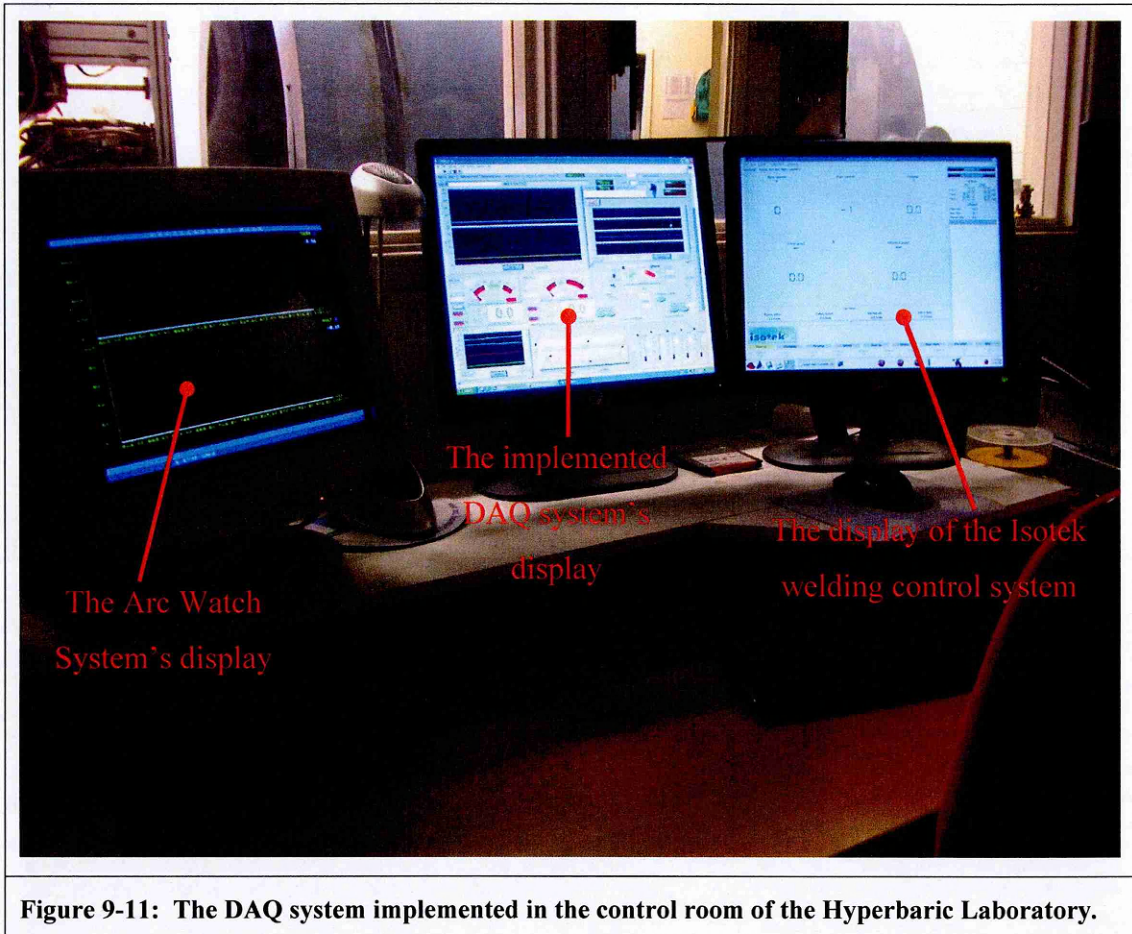


Figure 9-11: The DAQ system implemented in the control room of the Hyperbaric Laboratory.

The system was implemented in such a way so as not to affect the operation of the already installed systems so as the later to be able to work in parallel if necessary.

System's Operation Experimental Evaluation Results

The system's operation was evaluated experimentally during welding experiments by operating in parallel with the ArcWatch system and the Isotek system [which also displays to the operator a 1 sec rolling average of the welding current and welding voltage]. From the experimental evaluation of the system the results were highly satisfactory. The hardware's operation was accurate with no further improvements to be needed. It seemed that the system had only minor software glitches that had to be

trimmed. These glitches could affect its real time operation by introducing time lags in displaying the data on the front panel which may be quite long in duration; however, the data acquisition and storage functions were always successful.

Discussion

As mentioned, the system was commissioned and evaluated experimentally. The problems that arose were from some wrong implementation 'directions' that were followed during the initial design of the system. The most important was that during that period, the software was built in such a way so as to store on the hard drive the acquired data immediately after the end of the acquisition. This was not a problem with small files, but with larger files the result was that a large part of the system memory was occupied for that purpose and there was a degradation of the systems performance. The solution was to exit the program after a few hours of operation and to restart the program. This action was giving good results, since it was freeing up the memory for use by the system.

Conclusions

The overall conclusions from the design, build and use of the system are that LabVIEW 7.1 offers a good alternative solution to the text programming languages. It is not free-of-errors though. Nevertheless, there are always ways to work around them like in every programming interface. As far as it concerns the DAQ system design, the conclusions are that a good system was designed and built which operates satisfactorily and to provide what it was designed to do. However there are some parts of the program that need to be improved.

Suggestions for Further Improvement

The suggestions for further work mainly concern the reprogramming of the DAQ software. There are some key areas that could offer great improvement with little or more work. One of these has to do with the treatment of the acquired samples. During the initial program design it seemed a good idea to import the values as waveforms. However, as the program development was evolved, this became a problem since it adds more processing load during execution. A good solution would be to substitute the representation of the acquired data to plain numbers with double

precision. Another suggestion has to do with the ease of editing the program. Originally the program was not expected to need all the features that currently has. Thus, it was not structured with use of sub-vi [sub-routines which are called individually on demand, thus providing a more structured way of memory mapping]. It would be a great benefit to convert the program into a modular sub-vi structured program that can offer more flexibility for future expansions. Finally, the third suggestion has to do with the time lag and a way to avoid it. It is suggested that the program should be converted to save only the raw data after each acquisition has ended and not their statistical analysis as well. That way the memory use will be minimized. After the completion of the welding runs, a complementary program could be used so as to read the files with the raw data files, to analyse them statistically and to store them this time with the statistical analysis included.

10 Data Analysis Software

The data analysis software was structured and implemented in such a way so as to provide a means of analysing the acquired data off-line with the ultimate goal of the investigation of the feasibility of using the Dip Resistance as the method to estimate the CTWD under hyperbaric welding conditions. Figure 10-2 and Figure 10-1 show the front panel of the program that is used by the operator to analyse a data set.

The operation of the program is very simple. A stored file is selected and is loaded. From that file, the acquired signals of voltage, current temperature and dew point -either the complete set or a part of it- are used so as to recreate the waveforms of the signals. That way, even if part of a file with the analysed data is corrupted, as long as the raw data are intact, the signals can be recreated. The next step is the statistical analysis of the signals. The analysis includes averages, standard deviation of the means, variance and median values. The program focuses upon the way that the dip resistance information is extracted analyzed and treated with statistical ways or with digital implementations of filters. The method used is again the detection of a short circuit based on the voltage and current values and the extraction of the resistance when these are at the minimum and maximum respectively and have pass the threshold values specified as indication of initiation of a short circuit event, like the 1 Atm algorithms described in 2.5 and the way the controller for the welding power sources operates as described in 2.2.4. The program gives the ability to alter these threshold values. It also gives the ability to select which tactic of the ones mentioned previously in chapter 6 for the current measurement will be selected in order to calculate the resistance. This information can also be filtered by a series of digital filters. Currently the Butterworth type of filters was used, but other types can be easily implemented. The parameters of the filters like the cut-off frequency and the order are adjustable through the front panel giving flexibility of the program for quick parameter adjustment and repeated analysis.

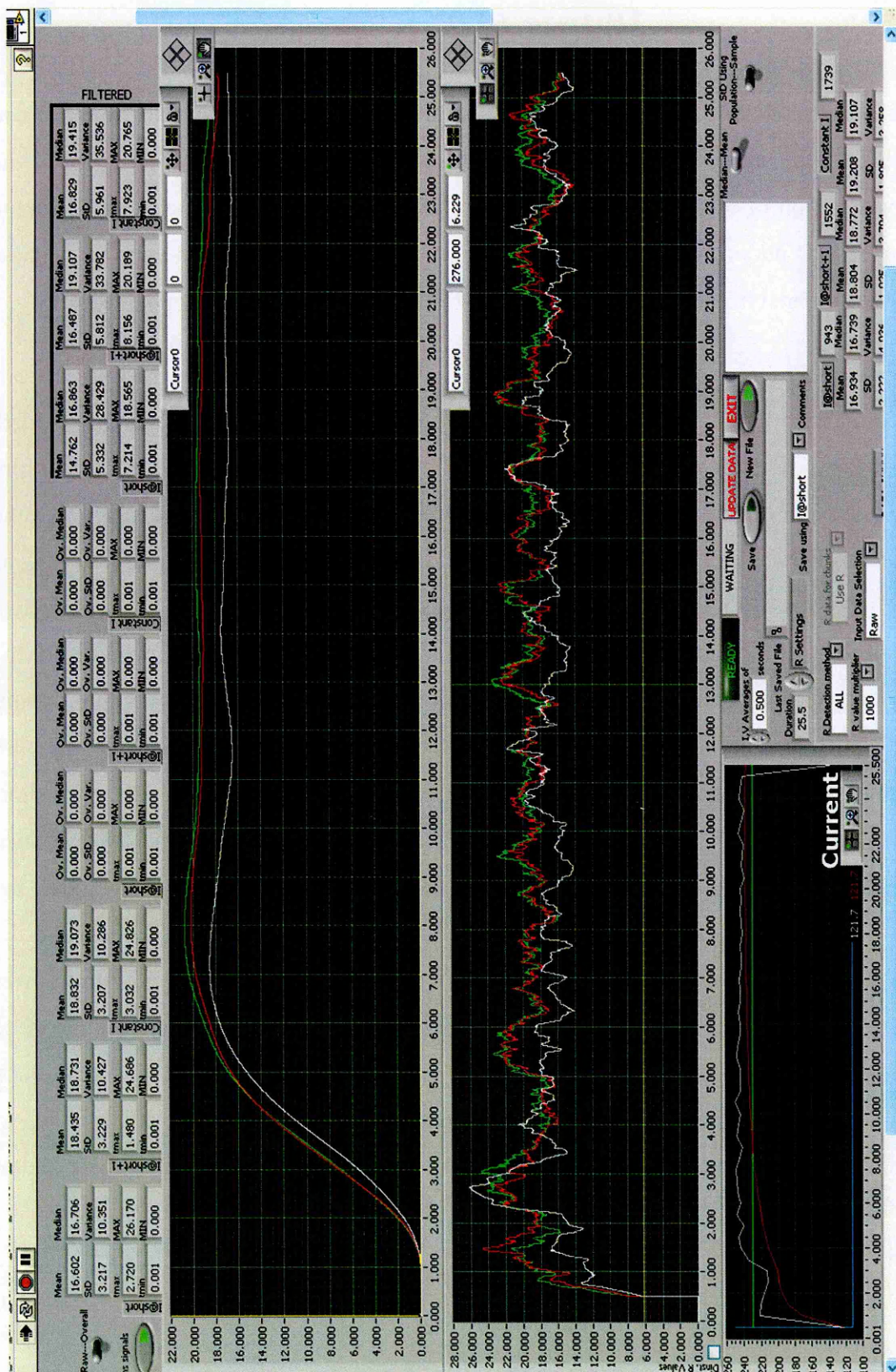


Figure 10-1: The part of the program that is used for analyzing the data through the filters.

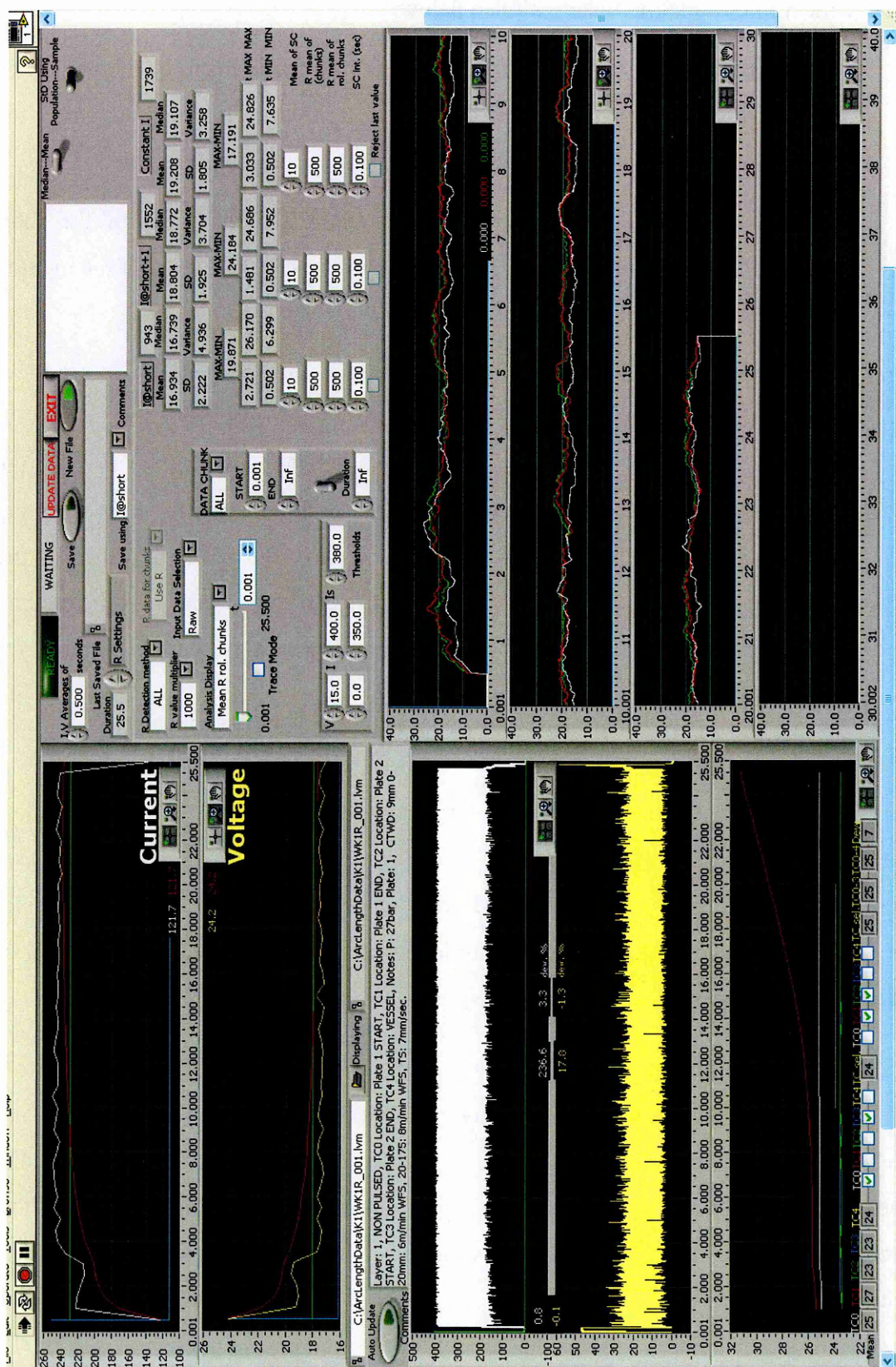


Figure 10-2: The main part of the program front panel used for the off-line data analysis.

The treatment of the dip resistance information includes a number of ways, but three are the most important ones as mentioned below:

- 1) Mean of shorts: This method produces the arithmetic mean of the resistance over a predetermined number of shorts. It is a useful method when the welding process manages to keep the number of short circuits stable,
- 2) Mean R chunks: This method produces the arithmetic mean of the short circuit resistance values every fixed amount of time. The output of the method appears to have step changes,
- 3) Mean R_{rol} chunks: This is the most important method of the three. It produces the arithmetic mean of a rolling number of samples, in other words, it calculates a rolling average. If, for example, the value is set to 500, the method will produce the first output result after 500 ms [with 1 kHz sampling rate] including the samples 1 to 500. The second result will be at 501 ms in the welding run and will include the samples 2 to 501 and so on. It is the method that produces the results with the smoothest output which is desirable for CTWD control.

In Figure 10-1 the control panel of the data analysis program for the application of filters is shown. The top boxes display statistical results, the top waveform displays the filtered output and the middle waveform displays the unfiltered but statistically treated dip resistance values. The bottom left waveform is explained with the aid of Figure 10-2 below.

In Figure 10-2 on the top left is the waveform viewers for the welding current and welding voltage. The red lines are showing the overall average, which means that each sample of the waveform is the average of all the samples acquired so far. The second waveform in each of the two windows is a moving average 'N' samples, where 'N' is a number determined from the operator through the control panel. With green colour are the target values that are set for the welding parameters.

11 Experimental Results and Analysis

Initial Experimental Strategy

The initial experimental strategy was to investigate the relationship between the changes of the dip resistance with the change in CTWD. Other parameters like the relationship between the short circuit frequency and the CTWD, or the welding voltage, welding current and their percentage deviation from the target values with the CTWD could also be investigated. Additionally, initial evaluation of which is the best tactic to use in order to extract the dip resistance value could be investigated.

11.1 First Set of Experiments

The experiments were made by using bead on plates at different levels of stand-off. The use of bead-on-plates approach aids elimination due to influence on the results of multiple passes and geometrical variations in size [where applicable] as the welding parameters and consumables are changing [75]. As in the cases of [75] and [76] machining free of “mill scale” and degreasing with alcohol before welding aids to achieve reliable results [75, 76] by improving arc stability [76]. For this reason, the plates were surface cleaned with a grinder and cleaned with acetone and the welding torch was at vertical position. The specimens were checked that they were horizontal and parallel compared to the torch x-axis, so no errors would occur on the results from unwanted CTWD change as the torch moves around. The welding involved non-pulsed welding at WFS: 6 m/min and TS: 7 mm/sec for the first 20 mm and then the parameters were WFS: 8 m/min and TS: 7 mm/sec for the rest of the run. The low WFS for the first 20 mm serves the purpose of avoiding a large build up of weld metal due to the low temperature of the parent metal. The target values are 229 A for the welding current and 18 V for the welding voltage. These parameters are the same as those used in the RPRS program. The ambient pressure used was 27 bar corresponding to a depth of 260 msw, the middle of the range for which RPRS is developed as mentioned earlier in 2.3. At these experiments, three beads were made on each stand-off covering a range between 7 mm to 13 mm.

11.1.1 Results Obtained and Initial Analysis

The results obtained were analyzed using the analysis program described earlier in chapter 10. The threshold limits for the short circuit detection were the same like the ones that the power source controller uses, more explicitly, the welding voltage should be between 0 V and 15 V and the welding current should be between 350 A and 400 A. If a sample had voltage value below 0 V or the current was above 400 A, then the sample was discarded since it was assumed that at that case the inductance of the welding circuit and the power sources played a significant role by trying to react to the current changes and consequently altered the real voltage and current values. Although the short circuit welding current should be 380 A, in practise it is only possible to have a value around it mainly because of the influence of the welding circuit inductance, resistance and the power sources(s) power slope characteristic of which can induce a controlled time shift of the welding current which, in some cases where the short circuit duration is very short, might result in the maximum welding current for the specific dip resistance value never to be delivered. This means that the dip resistance estimation from Ohm's law, Equation 2-5 [pp. 100], would be wrong. Thus, these welding current margins were introduced.

Graphical Analysis

All three tactics, the 'I@short', 'I@short+1' and 'Constant I' presented in chapter 6 of analysing the raw untreated data for the detection of the short circuit events were tested. The analysis results are shown in Figure 11-2 to Figure 11-13. For each Y data point that is graphed, the value is the average of the overall average of the three passes. This was done so as to minimize the effect of random local instabilities. Also, the data were treated in two different ways. The first one was to use the whole data from each run, while the second one was to truncate the data and to use the truncated part. Table 11-1 has the data points that the graphs represent for the results from the analysis using the whole data, whilst Table 11-2 shows the results from the truncated data set. These truncated parts were missing the first 4 seconds of data and the last 0.5 second. This was done in order to have clear analysis results with only the normal welding parameters without having the effect of the initial and last parameters, which are different in order to help the initiation of the welding arc and the extinction of it. As Silva and Hazlett [75] report, the influence of starting and stopping

phenomena can be eliminated if the data segment to be analysed is taken from the middle of the trial [75]. The aim here was to reveal if there is any significant loss of information by the use of the truncated data.

Raw Dip Resistance Values

Figure 11-1 shows the raw resistance values for the first pass at 7 mm CTWD with welding voltage threshold of 6 V. The values are all over the scale, something that is expected due to the inherent instabilities [2], false detections which include the presence of the arc, dip resistance calculations based on wrong welding voltage and welding current values, welding voltage and welding current high and low peaks due to the inductance of the welding circuit and the slope-based power source characteristics which induce a delay. In addition, weld bead characteristics and weld pool characteristics presented in pp. 118 and pp. 120 respectively also played a role. The work of Di Pietro *et al.* [12] presented in 2.5.4 which proposes to use thresholds and to not use every dip resistance value for CTWD control and their data shown in Figure 2-71 agree with the acquired data in Figure 11-1. Also the work from Orzagh *et al.* [52] and Orzagh *et al.* [54] presented in 2.5.2 and specifically their data presented in Figure 2-68 once more verify the suggestions from Di Pietro *et al.* [12] and that the acquired data shown in Figure 11-1 are to be expected. Clearly some statistical treatment like the one presented in chapter 10 is necessary since the rate of fluctuation of these data prohibit their use in CTWD control.

Selection of Short Circuit Event Detection Tactic

The graphical results in Figure 11-2 and Figure 11-3 show a good agreement between the 'I@short+1' and 'Constant I' methods, but not with the results from the 'I@short' method. Also, as Table 11-1 and Table 11-2 shows, the dip resistance value for the 'I@short+1' tactic is close to the one obtained using the 'Constant I' where the maximum welding current is assumed. This indicates that the 'I@short+1' detects the welding current value more accurately than the 'I@short' [assuming that during the short-circuit event the welding current reaches the maximum value prescribed from the power source's slope characteristic]. This can be explained by looking at Figure 2-58 and Figure 2-59 which indicate that the welding current's peak value has a time lag with respect to the welding voltage's lowest value due to the welding circuit's inductance and the power source's slope characteristic and response time of the

control system. The reason for the selection of the 'I@short' method is, as mentioned above, the agreement of the results with the theoretical approach that the dip resistance value should vary with CTWD in a linear fashion, as expected from the theory described by Equation 2-3 [pp. 100], and has been reported by numerous works in 2.5, clear graphical examples being shown in Figure 2-68, Figure 2-70, Figure 2-73 and Figure 2-82, and less clear but indicative results shown graphically in Figure 2-85, Figure 2-86 and Figure 2-87.

Another reason for selecting the 'I@short' method as the valid method for this project is the similarity of the traces from the results of the other two methods with the traces in the upper part of Figure 2-71; Figure 2-71 presents the results of the investigation from the authors of [52] and [54] regarding the influence of the power source current delivery characteristic, 'K', on the short circuit duration and short circuit frequency. The results from the work in [52] and [54] presented in Influence of Power Source Characteristic on Short-Circuit Parameters [pp. 117], substantiate even further that the 'I@short+1' and 'Constant I' methods should not be used. From the work in [52] and [54] it can be seen that different power source slope characteristics alter the short circuit's parameters, since the heat input to the process is altered and the molten droplet's and bridge's formation process and geometry changes as the left part of Figure 2-64 shows and is analysed in The Short-Circuit's Event Duration and Influencing Factors [pp. 105]. Therefore, the weld pool's and molten droplet's behaviour are altered as presented earlier in Influence of the Welding Current's Characteristics on the Weld Pool [pp. 121] and The Shape of the Molten Droplet and its Influence on the Dip Resistance's Waveform [pp. 102] respectively. The 'I@short+1' and 'Constant I' methods effectively manipulate the welding current's value either directly ['Constant I'] or indirectly ['I@short+1'] by altering the welding current's time of detection; then, the welding current's manipulated value is used in combination with the detected welding voltage's value to extract the dip resistance value.

The inability of the 'I@short+1' and 'Constant I' methods to produce a linear response of dip resistance to CTWD variation in the experiments could be the result

of the fact that it is the values of the welding current that are erroneous since all three tactics use the same welding voltage values. The effect of using these erroneous welding current values is equivalent to virtually changing the power source's slope characteristic(s). If the algorithm of dip resistance estimation uses a welding current value which is 'artificially constricted' due to the slope characteristic employed, then this will result in the dip resistance values to appear higher than what they really are.

Another way to explain it is that 'I@short+1' and 'Constant I' methods detect the current when necking occurs, at the left stage '4' in the case of Figure 2-62, when the liquid bridge breaks, which means that the instantaneous welding voltage and welding current values at that moment in time will be different, according to Equation 2-3 [pp. 100], since the cross-sectional area is less. Finally, although the results from [52] and [54] presented in Influence of Power Source Characteristic on Short-Circuit Parameters [pp. 117] reassure us that a constant trend exists even though the short circuiting behaviour of the process is different, it has to be kept in mind that this work was done in 1 Atm and not under hyperbaric conditions, in other words, the hyperbaric results might be different.

Welding Voltage and Welding Current

As Figure 11-6 to Figure 11-13 show, the overall average welding voltage and welding current values show very good correlation of their value with the CTWD value and could be used as control parameters. Nonetheless, to rely solely on these is not sufficient for two reasons. Firstly, under hyperbaric conditions the welding arc might extinct [41, 69, 78] during operation which means that the welding voltage will equal the open circuit welding voltage and the welding current will drop to zero; Figure 2-18 shows the form of the transient welding voltage waveform when welding arc extinction occurs. Nonetheless, the welding circuit's inductance might cause a peak in the welding current before it drops to zero as well as a peak in the welding voltage. Depending on the values and relative timing between these transients, they might be mistakenly interpreted as a short-circuit event which might result in abrupt adjustment of the CTWD. However, proper control like the one Di Pietro *et al.* suggested in [12] where thresholds are utilised and not every short-circuit event is utilised in CTWD control, can help minimise the influence of any such events

however they are still a source of errors. Secondly, although the overall average values of the welding voltage and the welding current do correlate nicely with CTWD, their transient values are far from ideal. As mentioned earlier, in Process Stability Vs. Electrical Stability [pp. 107], process stability does not mean electrical stability [6] and each process is different [6, 13]. Looking at Figure 2-65 it is clear that the transients of voltage and current can have large fluctuations, so if averaging is used, the acquired information might be indicating a different CTWD than the actual one.

Combining Short Circuit Event Detection Tactics

A last point is that the almost linear variation in short-circuit frequency with CTWD for the 'Constant I' method, which almost eliminates the 'step' between the 8 mm and 9 mm CTWD in Figure 11-4 triggers the suggestion to use a combination of short-circuit event detection tactics. The 'Constant I' could be used for detecting the event(s) and the 'I@short' could be used to detect the correct welding current value and extract the dip resistance information. However, care must be taken since, once more, only the 'I@short' tactic was consistent between both, the whole and the truncated data sets as Figure 11-4 and Figure 11-5 demonstrate. Summarising, based on the graphical analysis the following observations were made:

- 1) The best method to detect and extract the dip resistance information is clearly the 'I@short' since it appears to be proportional with CTWD,
- 2) There are clear trends for the CTWD estimation via the dip resistance change using this method,
- 3) Some of the other variables such as dip resistance short-circuit frequency, welding voltage and welding current also have a similar trend in their variation with CTWD,
- 4) There was a 'step' appearing in all graphs between the 8 mm and 9 mm CTWD - this needed further investigation,
- 5) Although the trend is evident for the overall averages, the estimation of the CTWD from raw dip resistance data without any statistical treatment is not feasible due to the large fluctuations in its values –Figure 11-1- as this may impose a limitation for real time analysis,

- 6) There is no significant loss of information between the analysis of the whole data and the truncated data. Thus, the data set selected for further analysis is the truncated set.

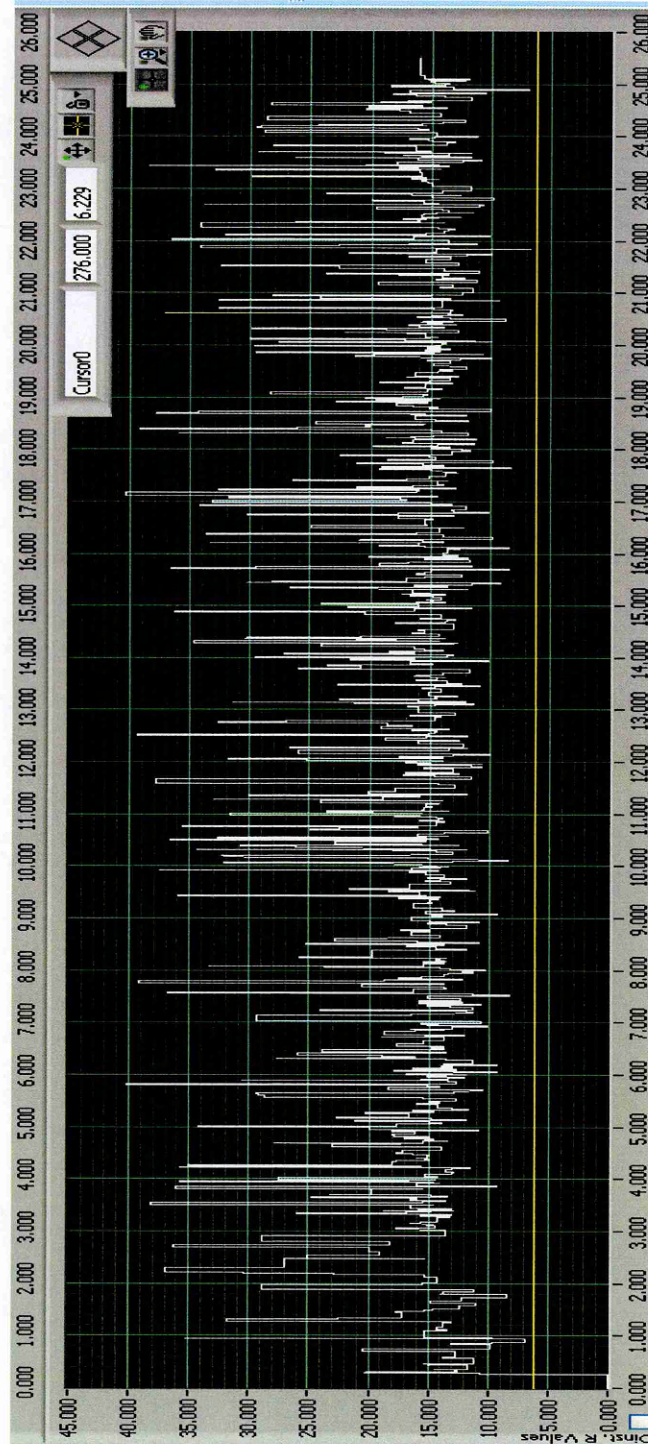


Figure 11-1: Raw resistance values against time for 9 mm CTWD at 27 Atm with 15 V threshold using the 'I@short' tactic. The results are all over the scale and a statistical treatment is needed.

					'I@short'		'I@short+1'		'Constant I'	
CTWD	I	I [%]	V	V [%]	R	f _{sc}	R	f _{sc}	R	f _{sc}
7	252.7	10.3	17	-5.7	16.7	44.1	19.4	72.9	20.1	85.1
8	241.6	5.5	17.4	-3.1	16.9	35.5	19	62.7	19.3	71.9
9	234.7	2.5	17.8	-1	16.8	35.6	18.4	41.1	18.8	64.7
10	224.7	-1.8	18.4	2.2	17.7	30.8	18.5	49.8	18.8	55.5
11	215.3	-6	19.1	5.9	18.8	27.3	19.2	43.1	19.5	47.9
12	207.8	-9.3	19.6	8.8	20.2	22.5	20.3	36.6	20.6	40.7
13	199.9	-12.7	20.3	12.9	21	18.5	20.9	32.2	21	35.8
Table 11-1: The results from the analysis of the whole data.										

					'I@short'		'I@short+1'		'Constant I'	
CTWD	I	I [%]	V	V [%]	R	f _{sc}	R	f _{sc}	R	f _{sc}
7	261.1	14	16.5	-8.2	16.6	48.1	19.2	78.4	19.7	31.5
8	248.8	8.6	17.1	-4.8	16.8	38.8	18.3	62.3	19	77.2
9	242.1	5.7	17.6	-2.6	16.8	38.6	18.3	53.9	18.6	69.4
10	231.8	1.2	18.1	0.6	17.8	33.9	19.1	47.1	18.6	60.1
11	221.7	-3.2	18.8	4.5	18.9	30.5	20.5	40	19.4	52.2
12	214.6	-6.3	19.3	7.3	20.2	25	20.8	35.4	20.7	31
13	206.9	-9.7	19.9	10.6	20.9	20.3	18.7	67.6	21	39.4
Table 11-2: The results obtained from the analysis of the truncated data, used to draw the graphs.										

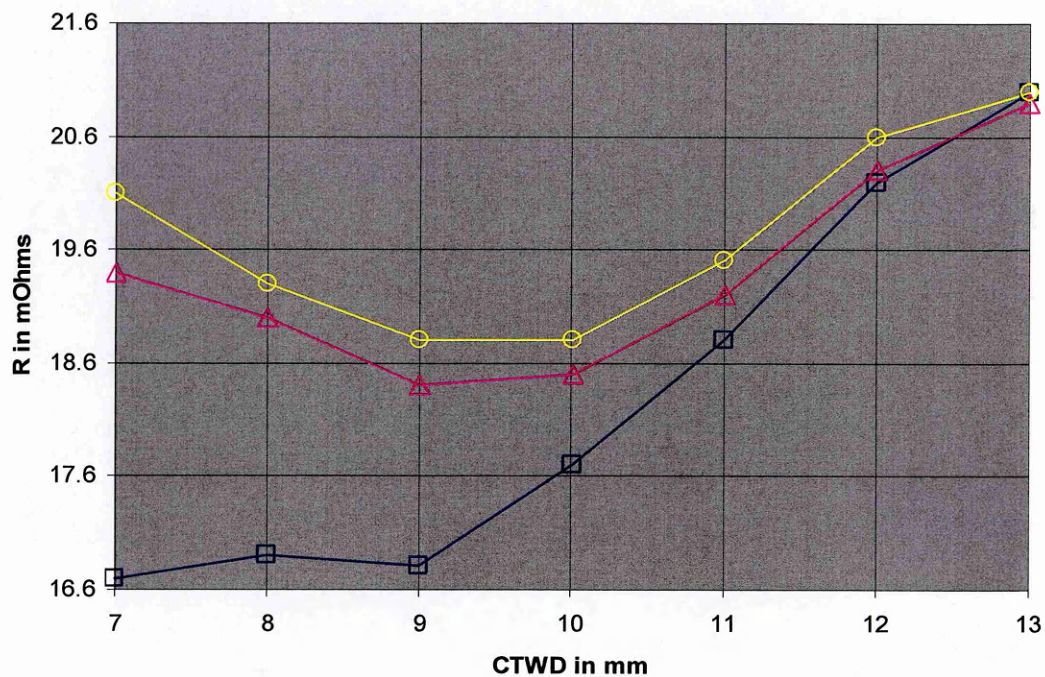


Figure 11-2: The variation of Dip Resistance with CTWD for each one of the shorts detection tactics. The blue line corresponds to 'I@short', the purple at 'I@short+1' and the Yellow at 'Constant I'. The graphs were made using the whole data sets of the runs.

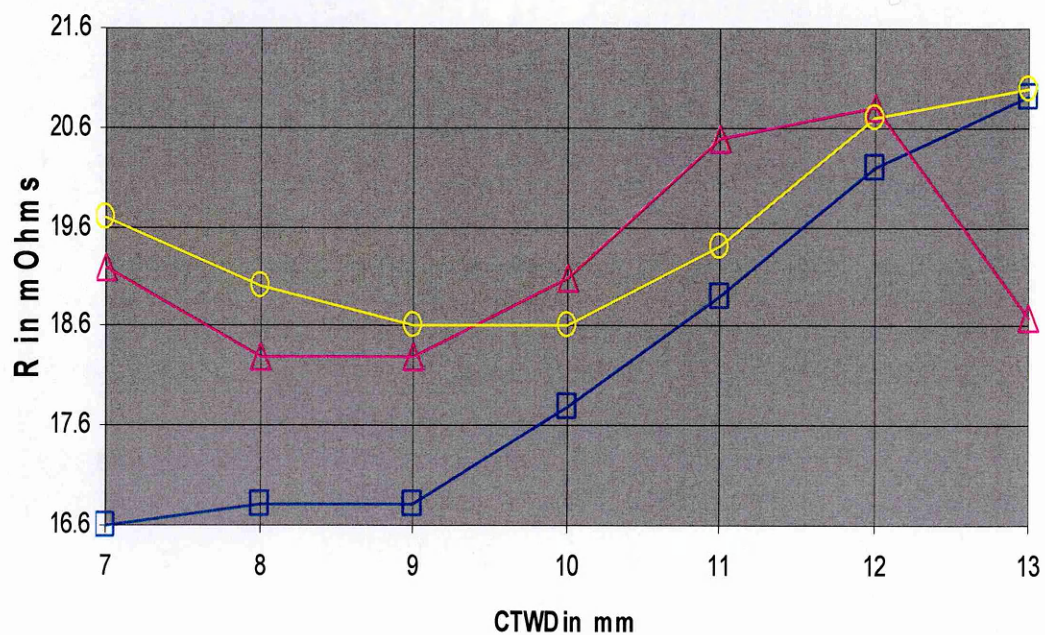


Figure 11-3: The variation of Dip Resistance with CTWD for each one of the shorts detection tactics. The blue line corresponds to 'I@short', the purple at 'I@short+1' and the Yellow at 'Constant I', but this time the graphs were made using the truncated data sets of the runs.

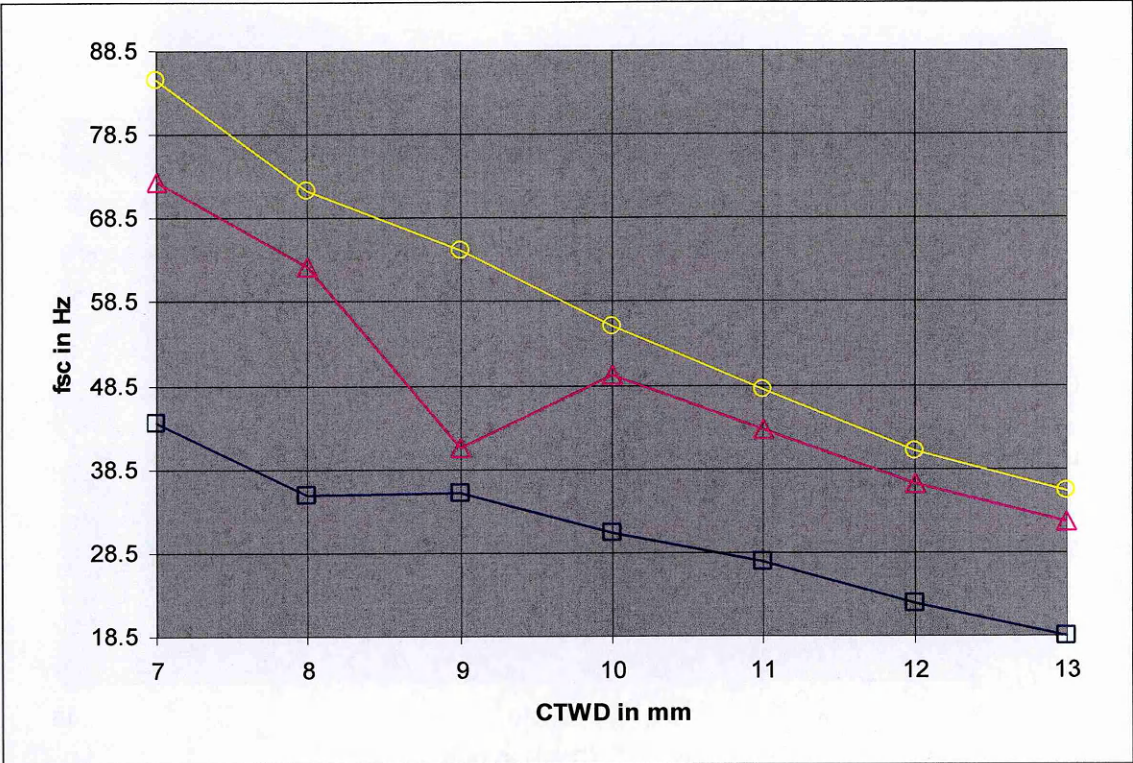


Figure 11-4: The variation of Short Circuit Frequency with CTWD for each one of the shorts detection tactics. The blue line corresponds to 'I@short', the purple at 'I@short+1' and the yellow line at 'Constant I'. The graphs were made using the whole data sets of the runs.

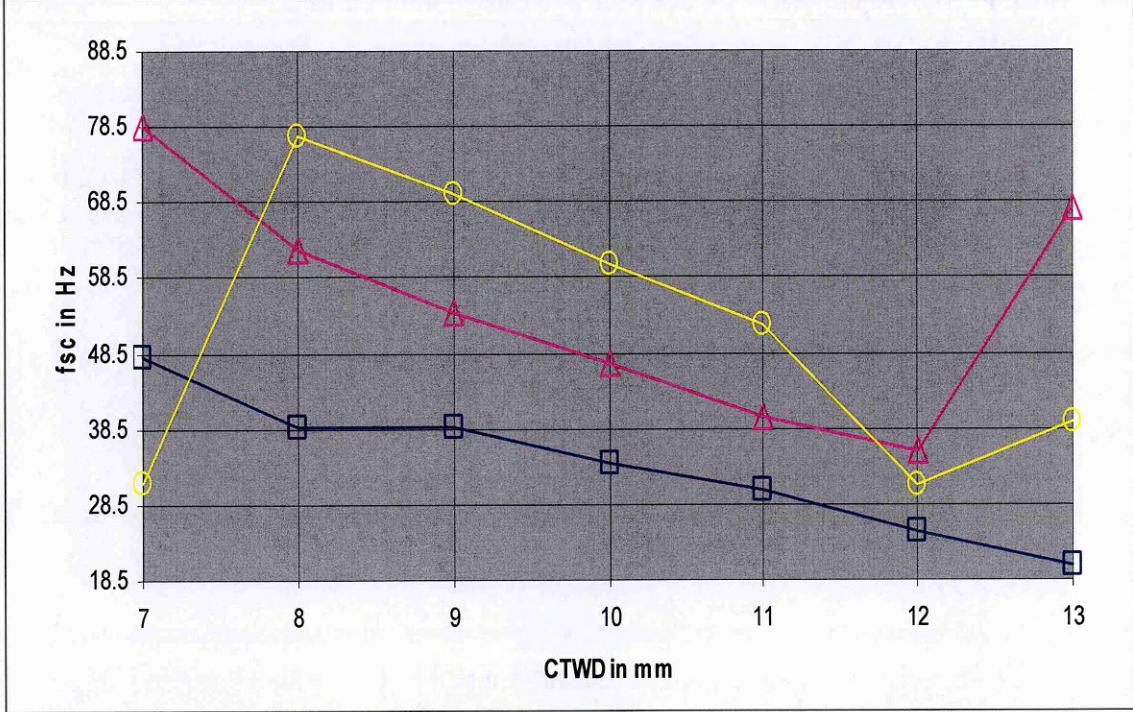


Figure 11-5: The variation of Short Circuit Frequency with CTWD for each one of the shorts detection tactics. The blue line corresponds to 'I@short', the purple at 'I@short+1' and the yellow line at 'Constant I', but this time the graphs were made using the truncated data sets of the runs.

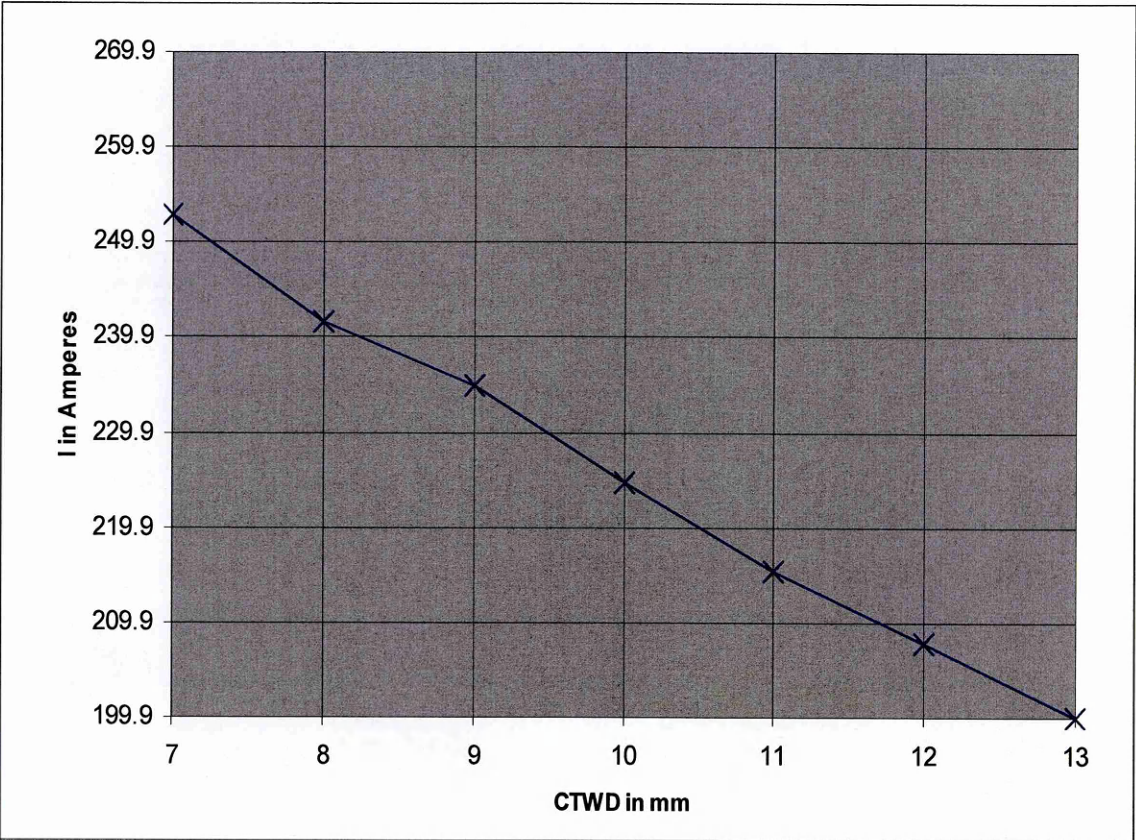


Figure 11-6: Overall average welding current variation with CTWD using the whole data sets.

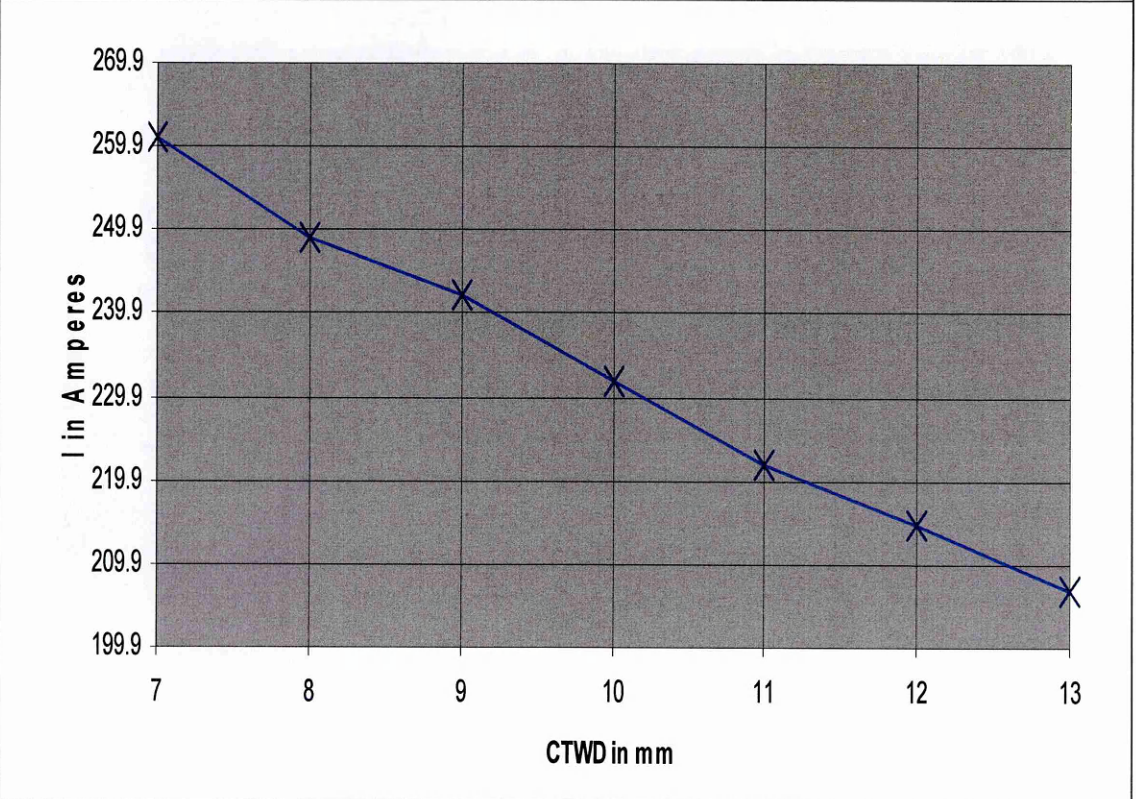


Figure 11-7: Overall average welding current variation with CTWD using the truncated data sets.

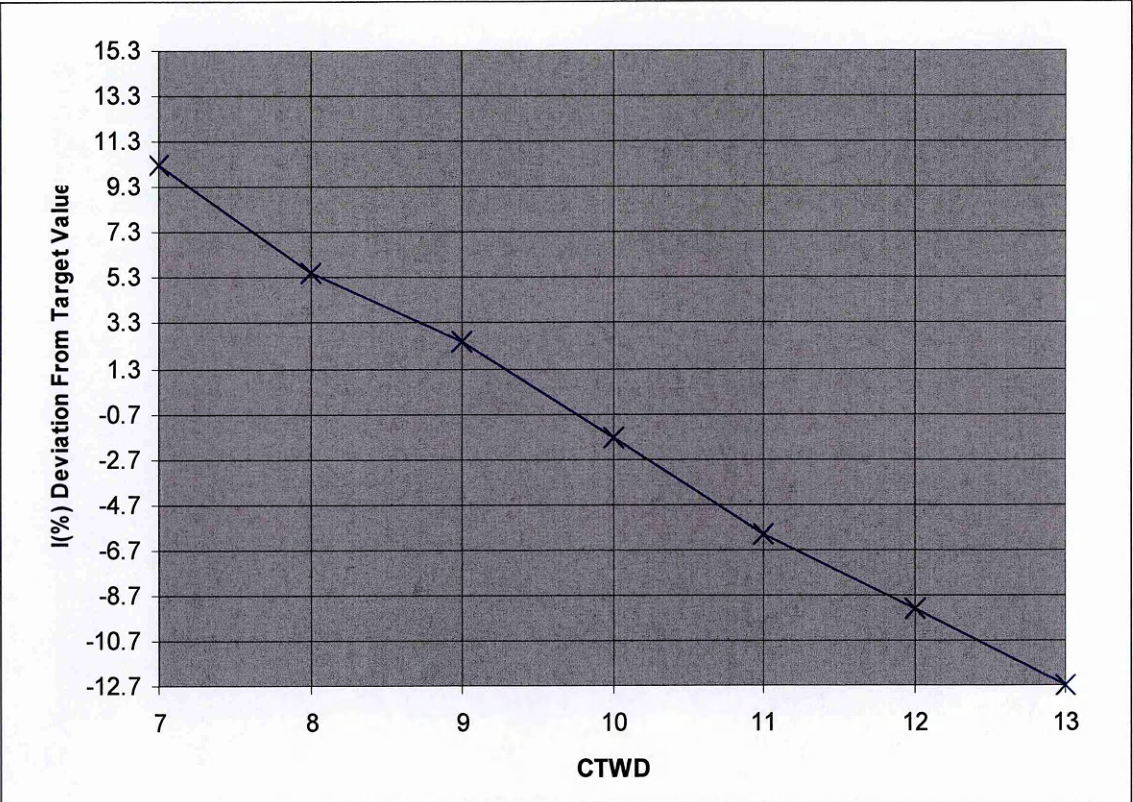


Figure 11-8: Variation of the overall average welding current deviation from the target values with CTWD using the whole data sets.

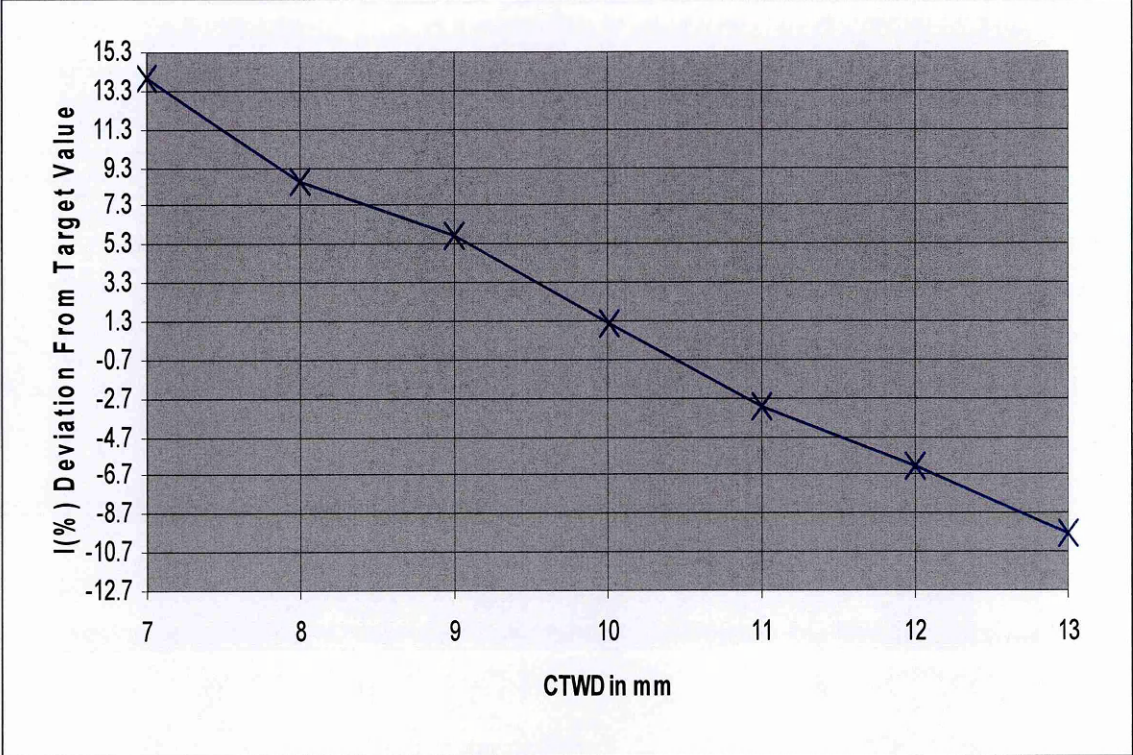


Figure 11-9: Variation of the overall average welding current deviation from the target values with CTWD using the truncated data sets.

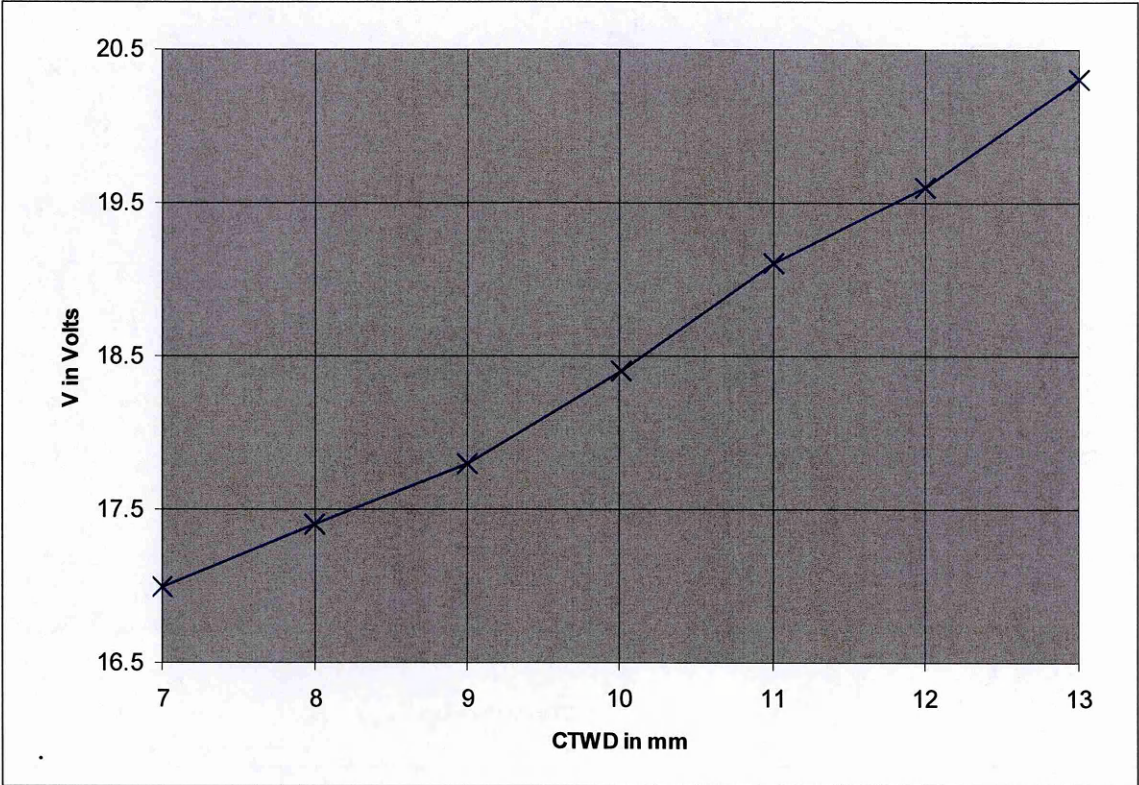


Figure 11-10: Variation of the overall average welding voltage with CTWD using the whole data sets.

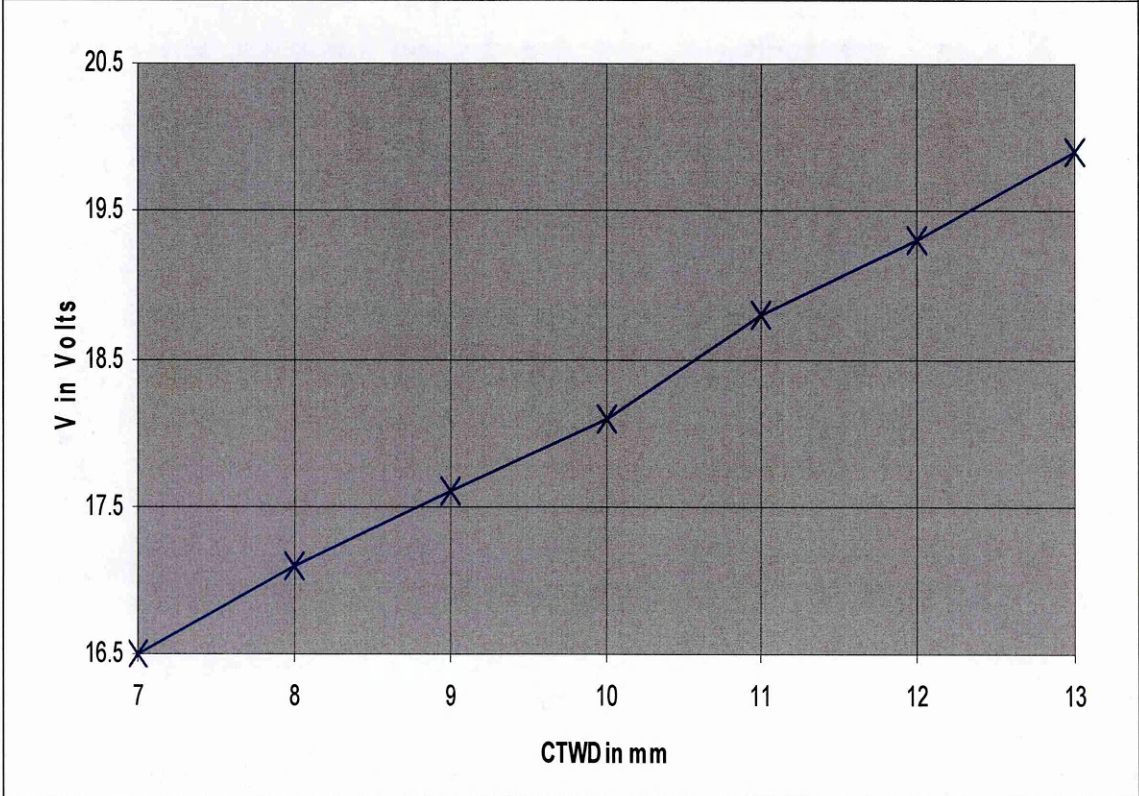


Figure 11-11: Variation of the overall average welding voltage with CTWD using the truncated data sets.

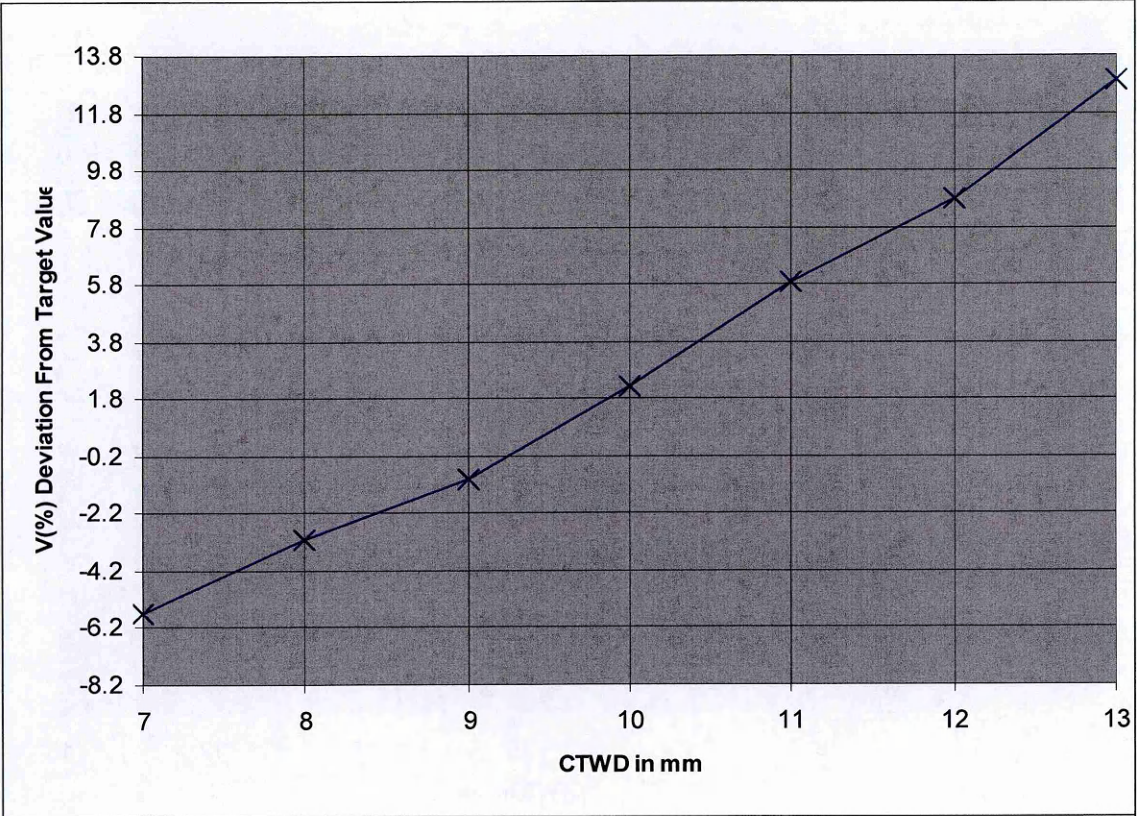


Figure 11-12: Variation of the overall average welding voltage deviation with CTWD using the whole data sets.

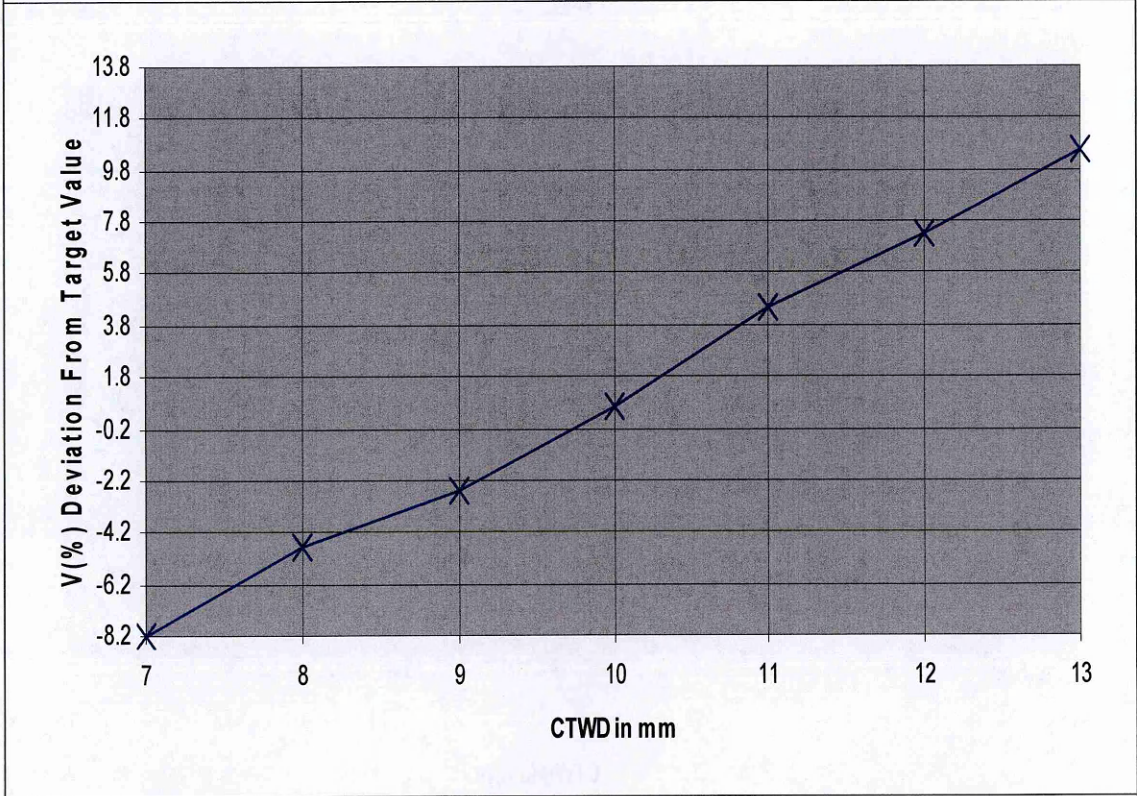


Figure 11-13: Variation of the overall average welding voltage deviation with CTWD using the truncated data sets.

11.1.2 Further Analysis

From the previous results, it was evident that further analysis on the same data was necessary in order to find a statistical treatment that could give suitable dip resistance information with respect to the current CTWD value, in other words, a linear trend like the one shown in Figure 2-69, Figure 2-70, Figure 2-73. Another issue that was examined was the effect of the thresholds values for on the results since it was suspected that a threshold of 15 V for the welding voltage might actually be quite high and could cause false short circuit events detections where the arc was actually present. The measurement of the minimum welding voltage and maximum welding current as stated in 6.1 was achieved, however, depending on which detection tactic was employed, the welding current value used might have been different than its maximum value.

The most common statistical treatment is to use the averages of the raw samples. The immediate question was the number of samples that these averages should be performed on. A very large number of samples would give a much smoother signal, but it would also have much slower response to the CTWD fluctuations. A very small number of samples on the other hand would give a much more responsive signal, but with more frequent fluctuations around the mean value. In both cases, if the result is not updated constantly, the outcome would be a signal with step changes and with no information of what is happening between these changes. The solution would be to use a rolling average. After trials on the analysis program, it was decided that a 0.5 second average would be a good trade-off between the two previous issues, since the CTWD changes not only they are not expected to be fast in practise, but they are actually expected to be quite slow due to the design of the sleeve-on-pipe concept presented in Sleeve's Specifications and Features [pp. 13], unless big surface defects exist.

Based on the above, a new analysis was performed on the same data. Each stand-off was analyzed using three different thresholds for the voltage signal, 6 V, 8 V and 10 V; these voltage thresholds are substantially lower than the 15 V threshold

previously used, but still significantly higher from the minimum value of a few volts as indicated in Figure 2-59. The reason these thresholds were again at high levels was the need to investigate the hyperbaric process carefully so as to ensure that a tactic valid for 1 Atm but invalid for hyperbaric operations is not adopted. Unfortunately though, the low sampling rate of 1 kHz adopted for this project does not allow detailed analysis of the hyperbaric process [since this was not the purpose of this project] for direct comparison with the 1 Atm process. In order for a short circuit event to be detected the voltage should be between 0 V and the high threshold level that had been selected. Also, only the ‘I@short’ method was used since it was the most robust method of detection. This has been substantiated earlier in 11.1.1 and can be easily verified by looking at Figure 11-2 to Figure 11-5 where, as shown, only the ‘I@short’ tactic exhibits a trend which is analogous to the CTWD variation with either the whole or the truncated data sets which means the method is robust even in the case of the different starting and stopping parameters. Indicative results for the average [during short circuit] welding voltage, welding current and dip resistance values are shown in Table 11-3; for the reasons above only the ‘I@short’ tactic was used and only three stand-offs were examined at each threshold voltage of 6 V, 8 V and 10 V.

CTWD	Voltage Threshold in Volts	Short Circuit		Resistance in mOhms
		Voltage	Current	
7	6	4.465	358.810	12.520
7	8	4.864	356.942	13.835
7	10	5.329	354.164	15.439
10	6	4.986	343.898	14.687
10	8	5.747	354.658	16.385
10	10	6.031	352.921	17.401
13	6	5.232	295.814	38.700
13	8	6.649	338.545	23.996
13	10	7.224	341.260	24.488

Table 11-3: Indicative average [during short circuit] welding voltage, welding current and dip resistance values for 7 mm, 10 mm and 13 mm CTWD using the ‘I@short’ tactic with 6 V, 8 V and 10 V voltage thresholds.

Dip Resistance and Short Circuit Frequency Analysis

Figure 11-14 to Figure 11-31 below show the results of analysing the data using a rolling average of 0.5 seconds in duration [equivalent to 500 samples for sampling rate of 1 kHz] and its effect on the dip resistance and the frequency of the dip resistance occurrences. Each graph illustrates the result from all three passes for each stand-off. Only three stand-off values are shown here, the 7 mm, the 10 mm and the 13 mm. The stand-off values that are presented here were selected since they are the most representative to illustrate the effect of the threshold on the outcome of the analysis.

As can be seen from the graphs, the higher the CTWD, the higher the threshold value should be. This is easily illustrated by looking at the effect that a very low or very high threshold value has at 7 mm and 13 mm CTWD. At 13 mm, with 6 V threshold value to detect short-circuits, Figure 11-27, the number of short-circuit events detected is very small, in comparison to the number of short-circuit events detected when the threshold was set at 10 V, Figure 11-31. Looking at the corresponding dip resistance waveforms, Figure 11-26 shows that a very low threshold and consequently a low short-circuit frequency results in abrupt output changes; the situation is improved with 10 V threshold as shown in Figure 11-30. However, the best dip resistance results for 13 mm CTWD were obtained when 8 V threshold was used, as shown in Figure 11-28 where the dip resistance waveforms follow smoother fluctuations with fewer extreme values [peaks or dips]. As Figure 11-29 shows the short-circuit frequency was not as smooth as the short-circuit waveforms at 10 V shown in Figure 11-31. This can be attributed to the erroneous short-circuit events that were taken into account. At 7 mm CTWD, the 6 V threshold gave the smoothest dip resistance waveform, as shown in Figure 11-14, and less short-circuit frequency compared to 10 V threshold which gave a more turbulent dip resistance waveform as shown in Figure 11-18, indicating that in smaller CTWD, the lower threshold reduces the number of erroneous short-circuit detections.

The previous are in good agreement with results from 1 Atm work in [52] and [54], shown in Figure 2-68, where the dip resistance values change during a welding run even with constant CTWD and make the tactic used by Di Pietro *et al.* [12] not to use every dip resistance value to control the CTWD but to use thresholds, as shown in Figure 2-80, to be a good suggestion for this project as well. However, at this initial stage, quantification of the threshold limits cannot be accurate; an initial estimate is that the threshold limits for short-circuit detections can vary linearly from 6 V for 7 mm CTWD to 8 V for 13 mm CTWD. From the results, the following observations were made:

- 1) It is clear that although the signals were a lot smoother compared to the raw data shown earlier in Figure 11-1, still the result was not satisfactory to be used as a signal for the estimation and control of the CTWD,
- 2) The welding voltage threshold set point has a great effect on the resultant output,
- 3) In order for valuable results to be obtained, the threshold values should adapt as the CTWD at which the data are collected is changing.

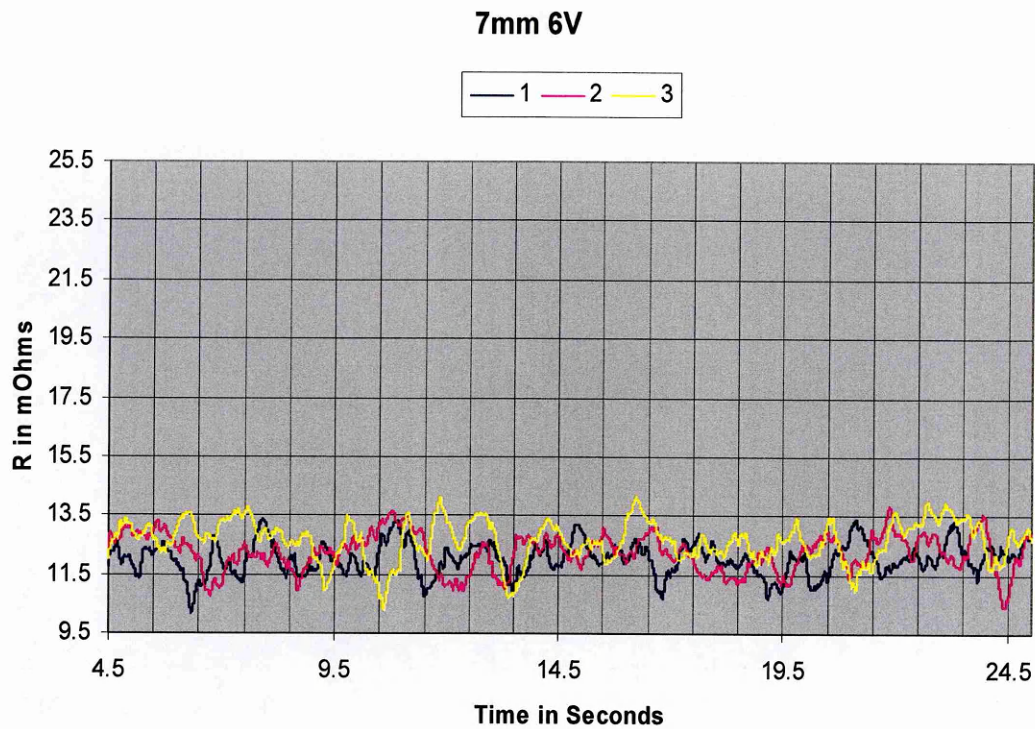


Figure 11-14: The results of the dip resistance evaluation from the analysis of three passes for 7 mm CTWD at 6 V threshold.

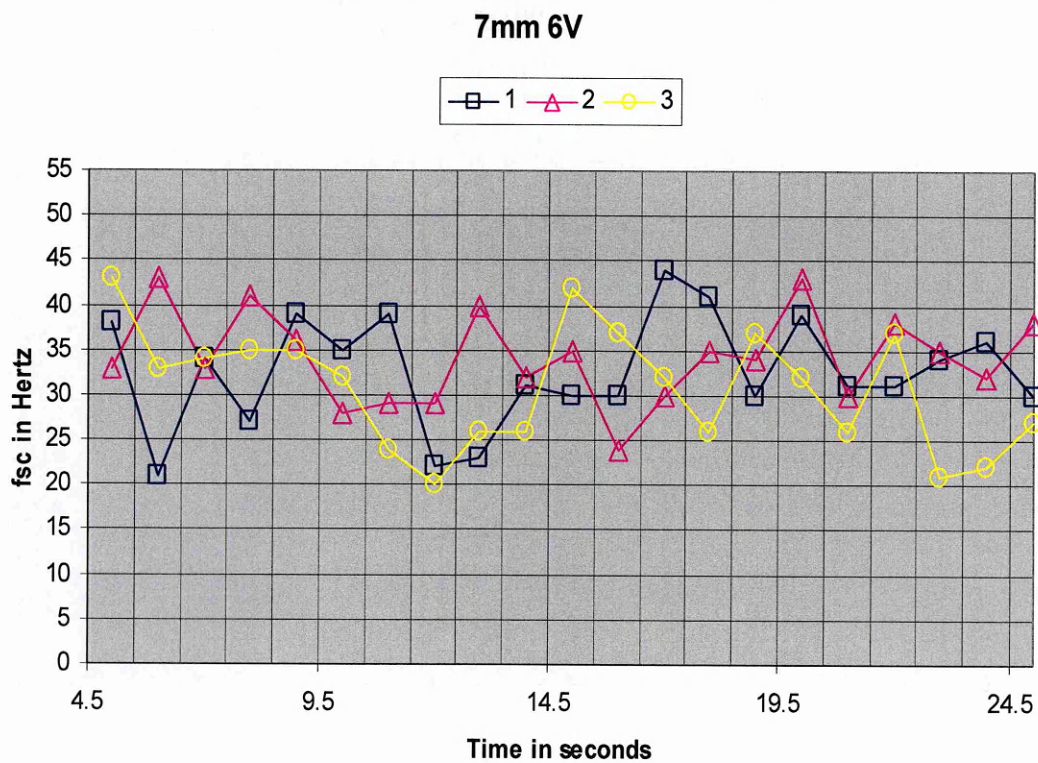


Figure 11-15: The results of the short circuit frequency from the analysis of three passes for 7 mm CTWD at 6 V threshold.

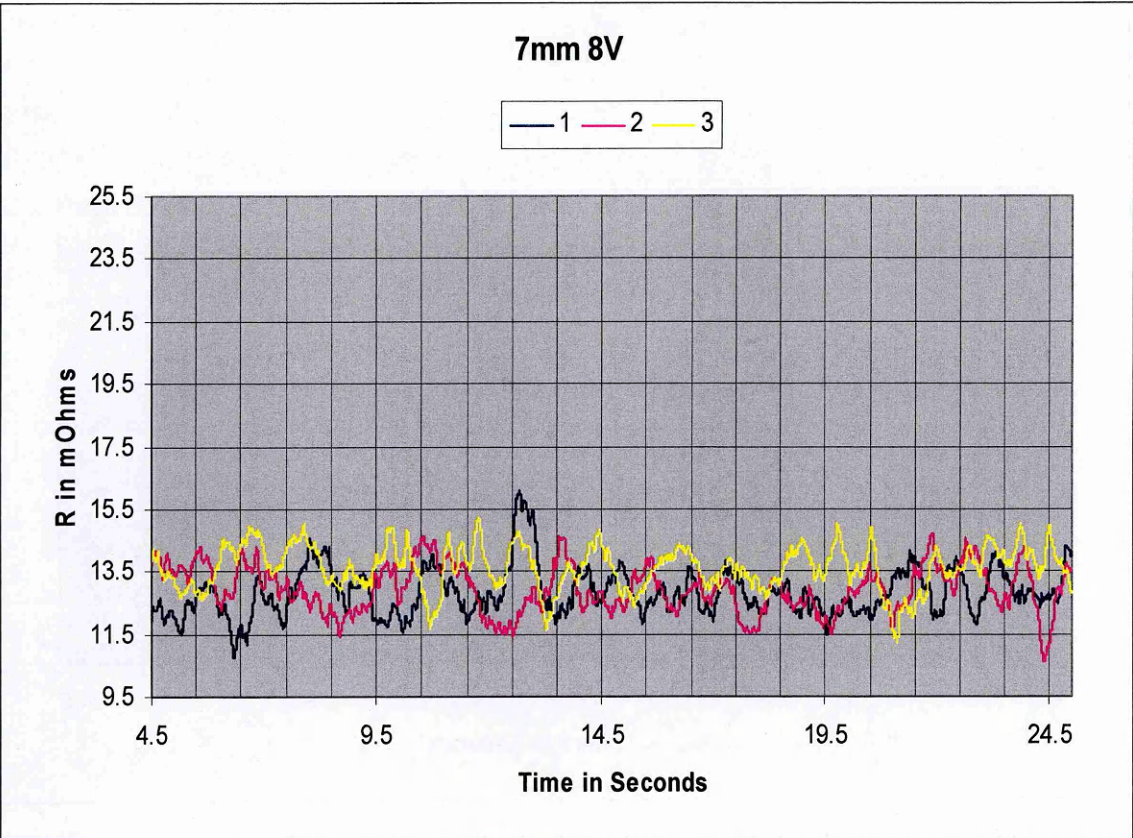


Figure 11-16: The results of the dip resistance from the analysis of three passes for 7 mm CTWD at 8 V threshold.

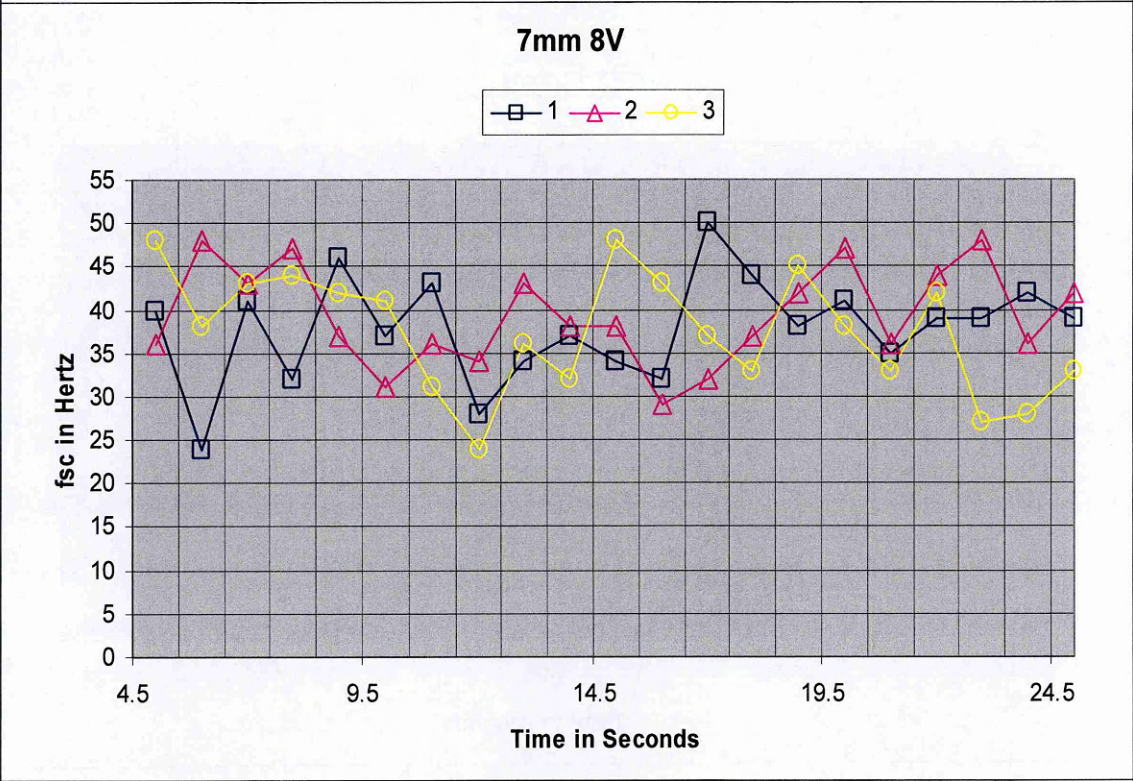


Figure 11-17: The results of the short circuit frequency from the analysis of three passes for 7 mm CTWD at 8 V threshold.

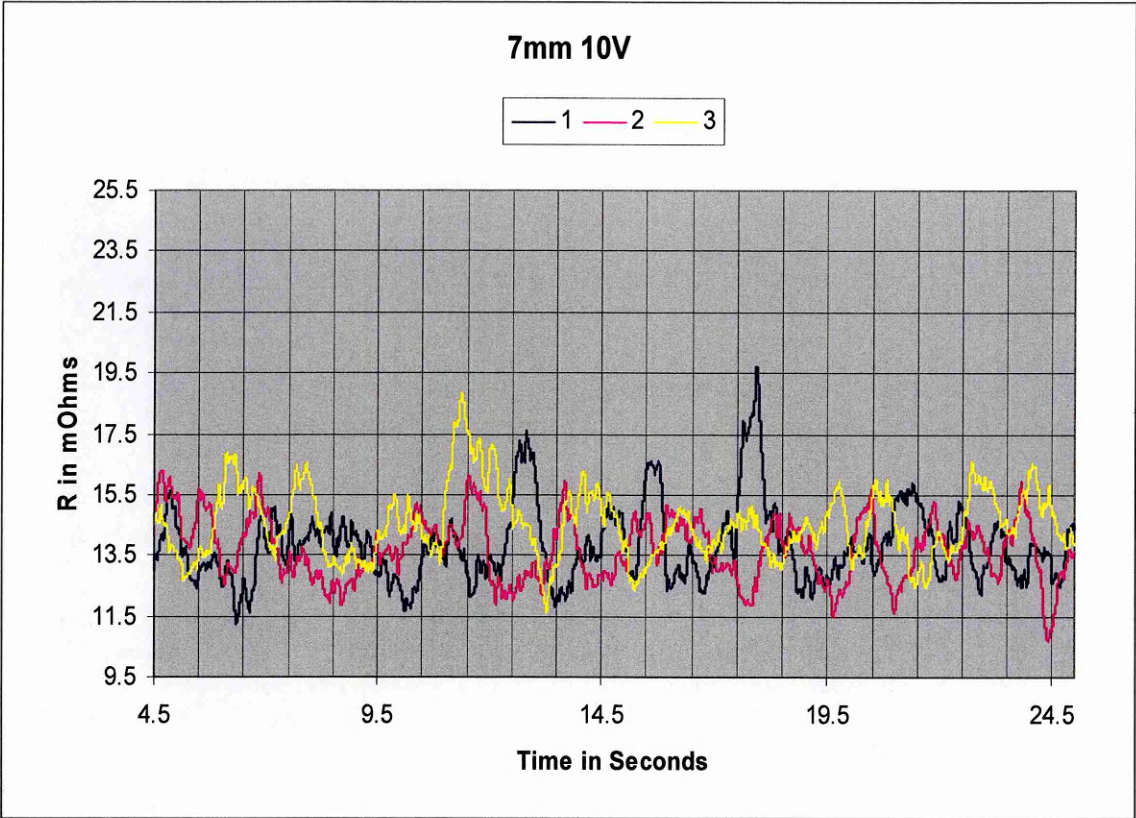


Figure 11-18: The results of the dip resistance from the analysis of three passes for 7 mm CTWD at 10 V threshold.

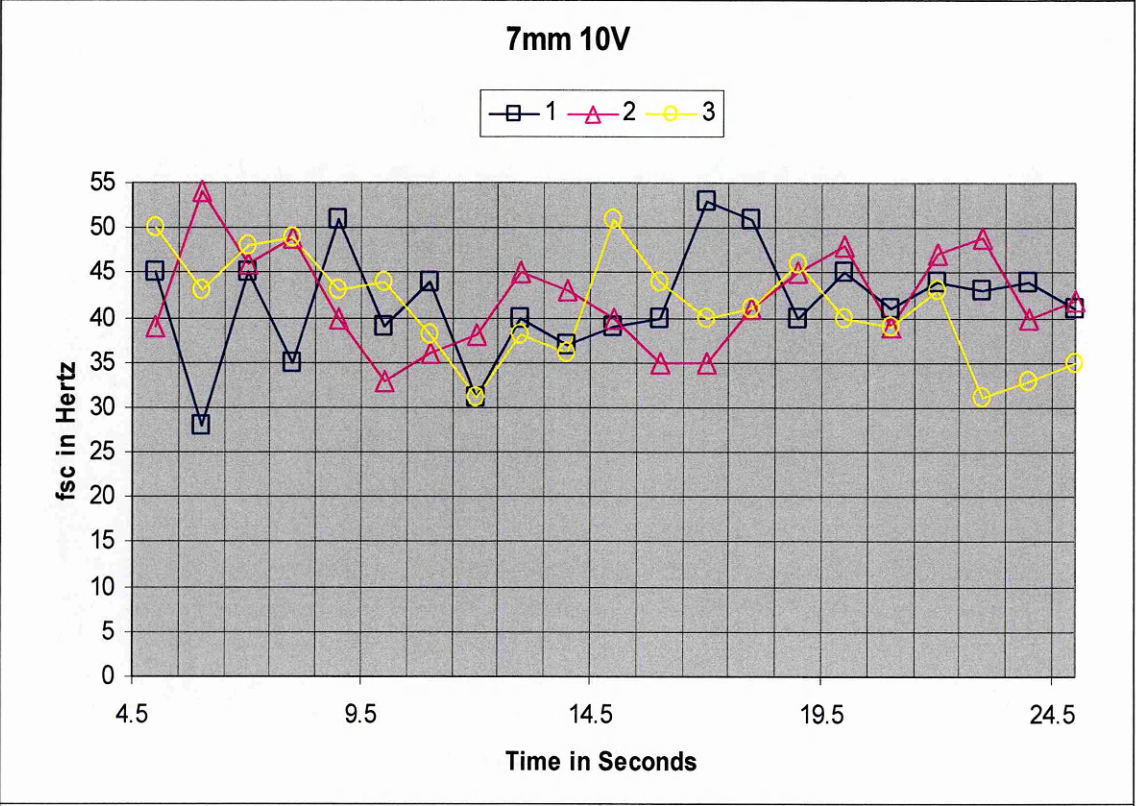


Figure 11-19: The results of the short circuit frequency from the analysis of three passes for 7 mm CTWD at 10 V threshold.

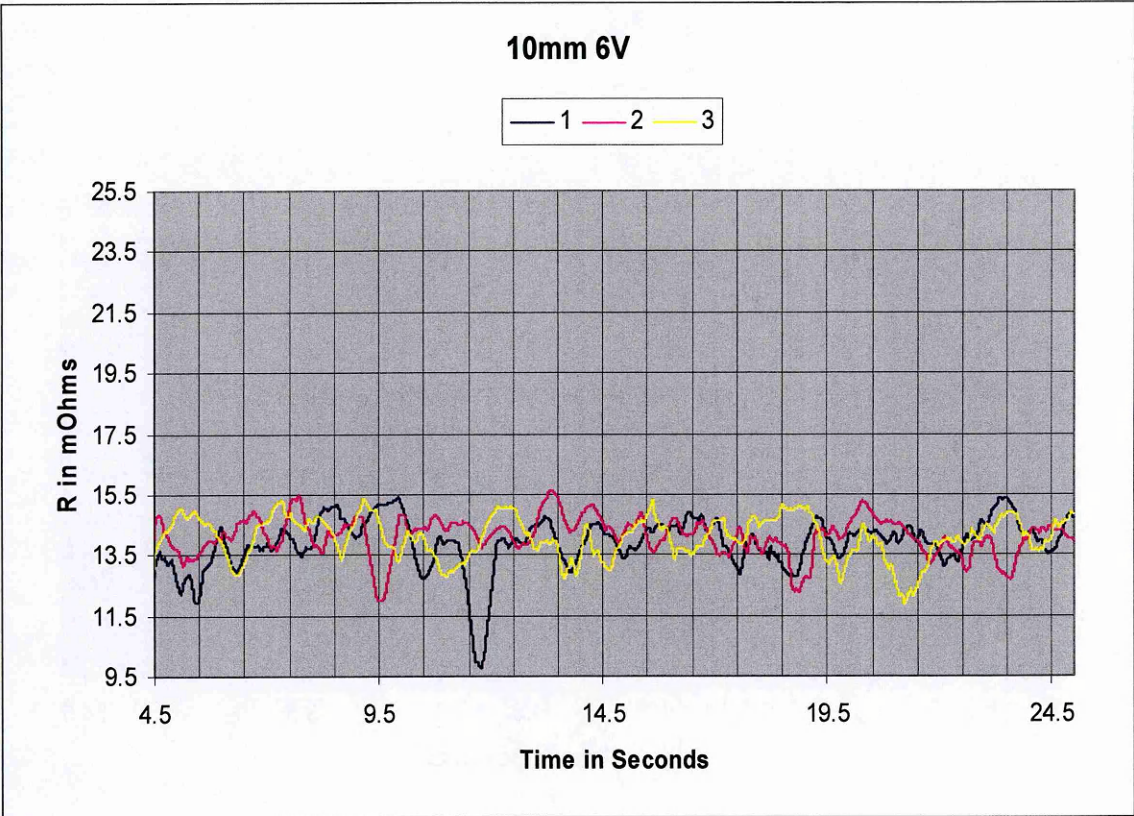


Figure 11-20: The results of the dip resistance from the analysis of three passes for 10 mm CTWD at 6 V threshold.

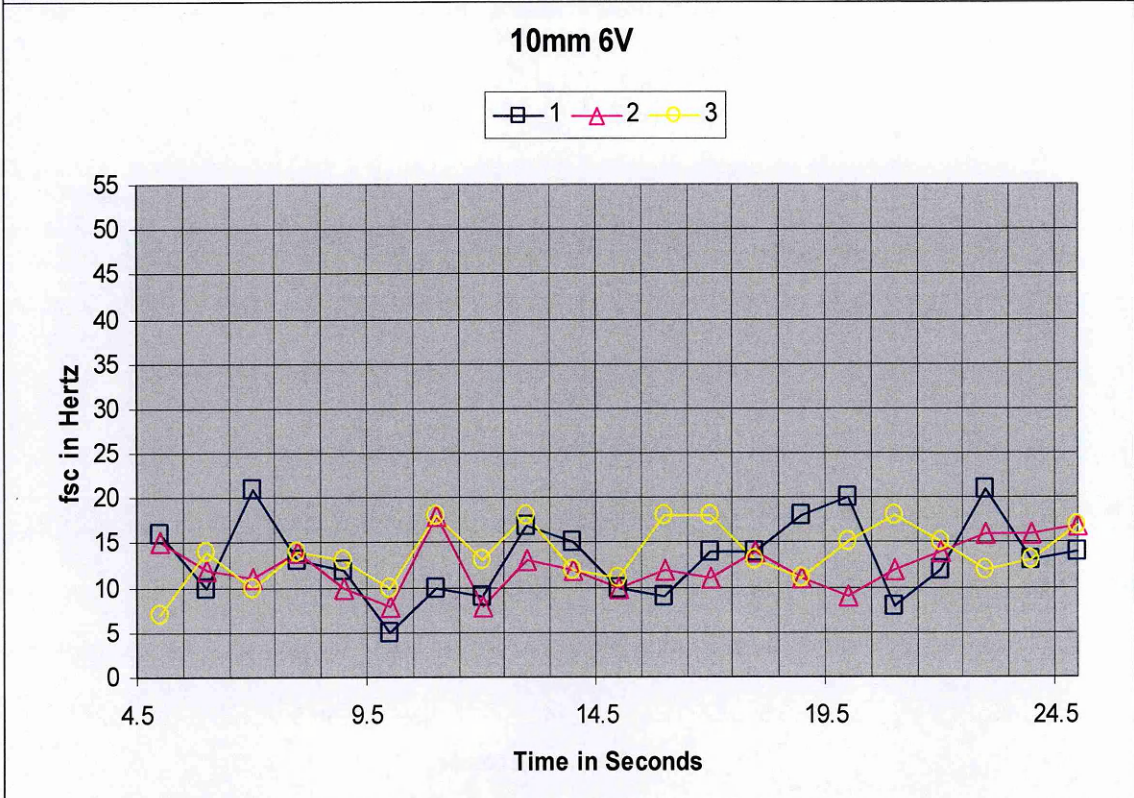


Figure 11-21: The results of the short circuit frequency from the analysis of three passes for 10 mm CTWD at 6 V threshold.

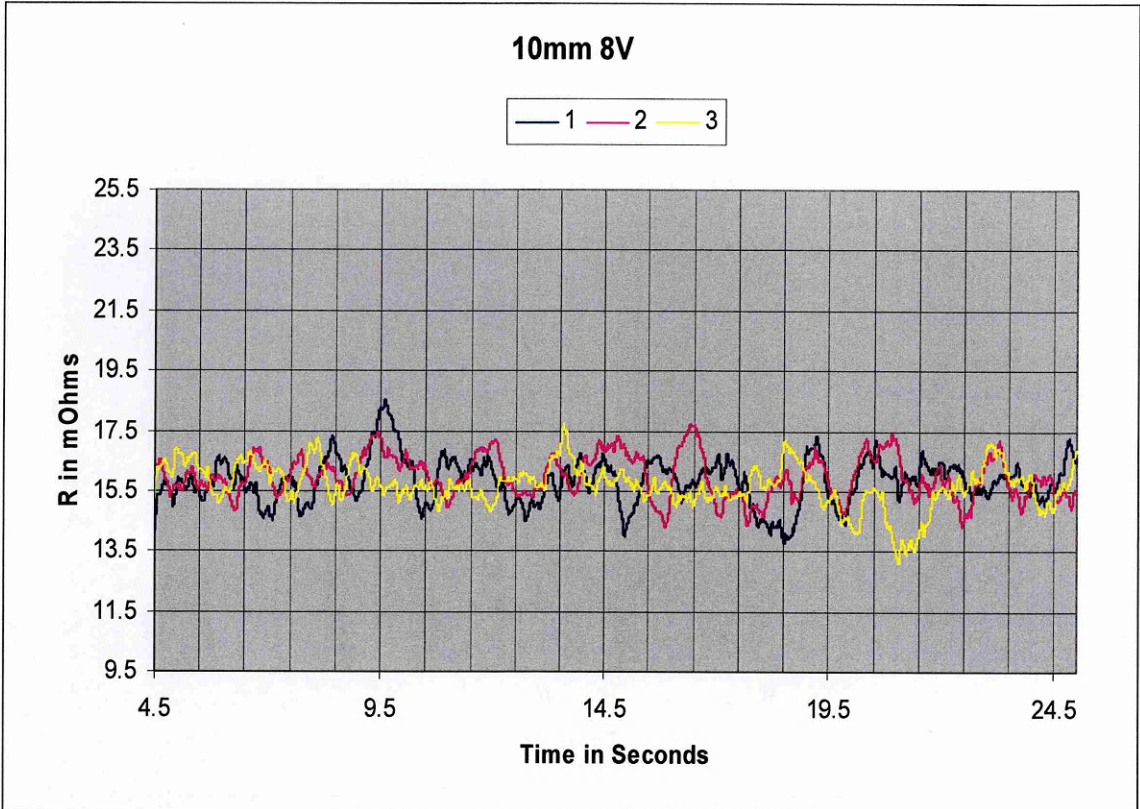


Figure 11-22: The results of the dip resistance from the analysis of three passes for 10 mm CTWD at 8 V threshold.

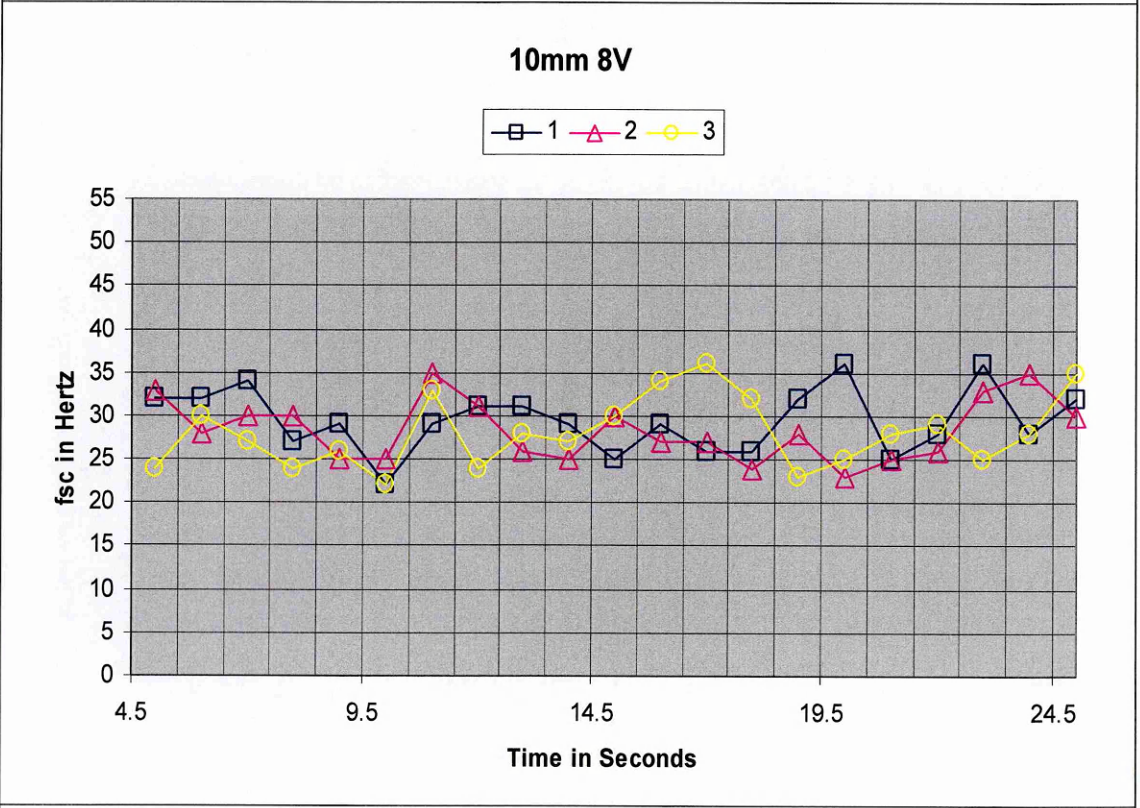


Figure 11-23: The results of the short circuit frequency from the analysis of three passes for 10 mm CTWD at 8 V threshold.

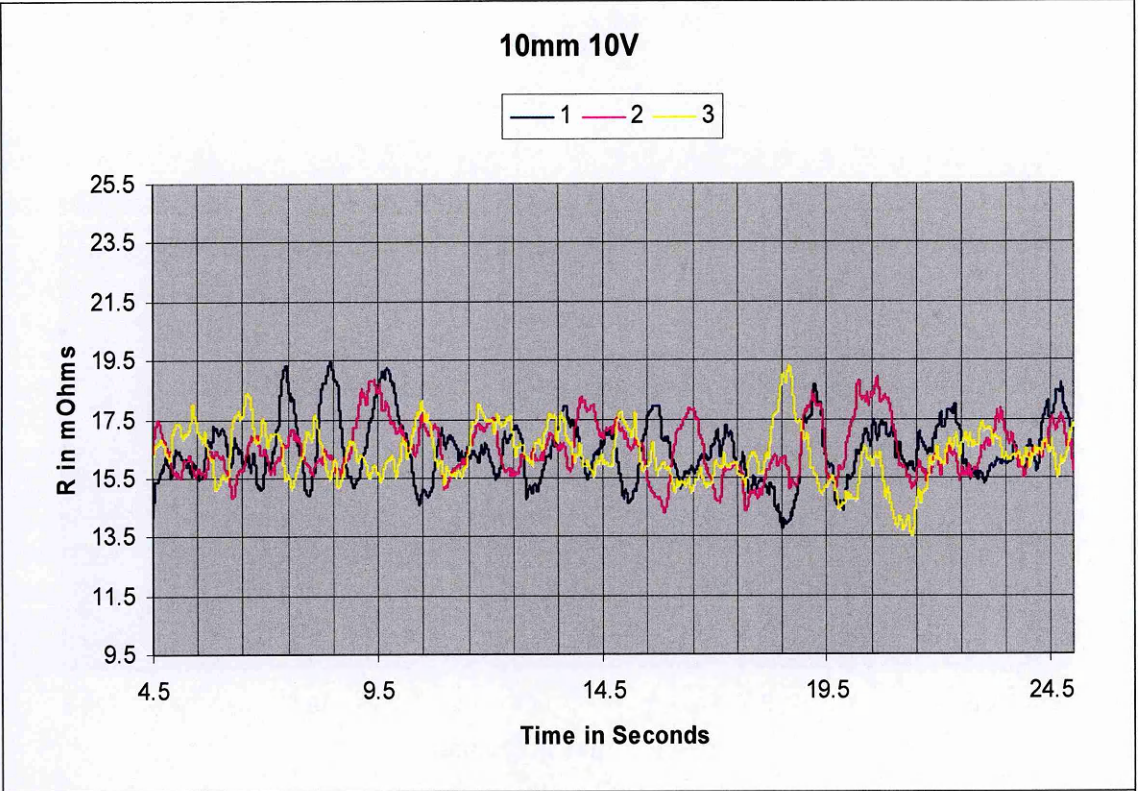


Figure 11-24: The results of the short circuit frequency from the analysis of three passes for 10 mm CTWD at 10 V threshold.

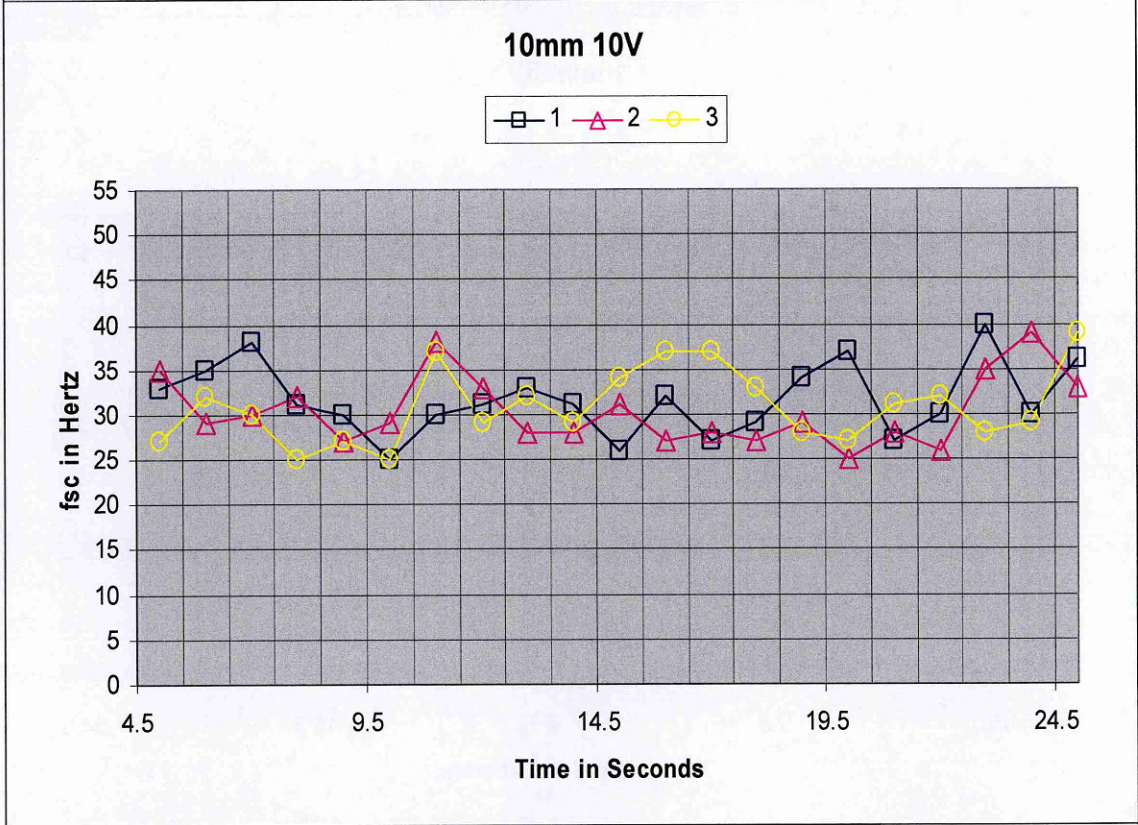


Figure 11-25: The results of the short circuit frequency from the analysis of three passes for 10 mm CTWD at 10 V threshold.

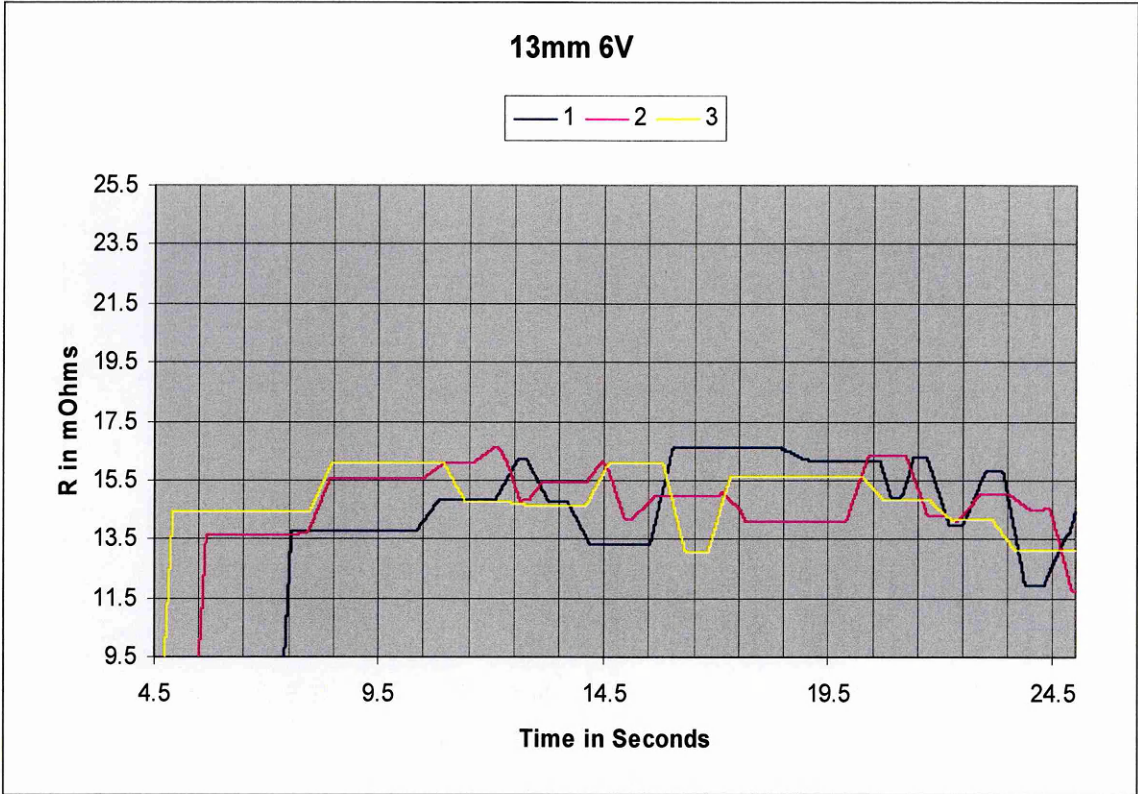


Figure 11-26: The results of the dip resistance from the analysis of three passes for 13 mm CTWD at 6 V threshold.

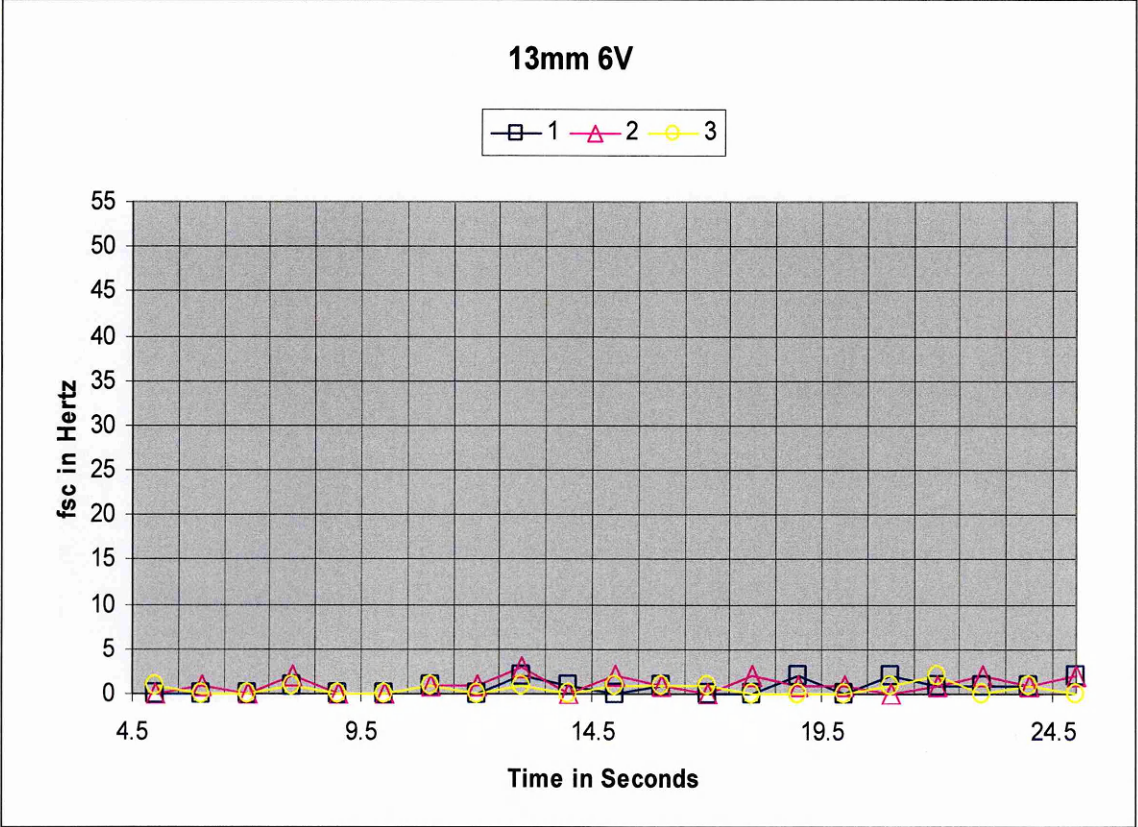


Figure 11-27: The results of the short circuit frequency from the analysis of three passes for 13 mm CTWD at 6 V threshold.

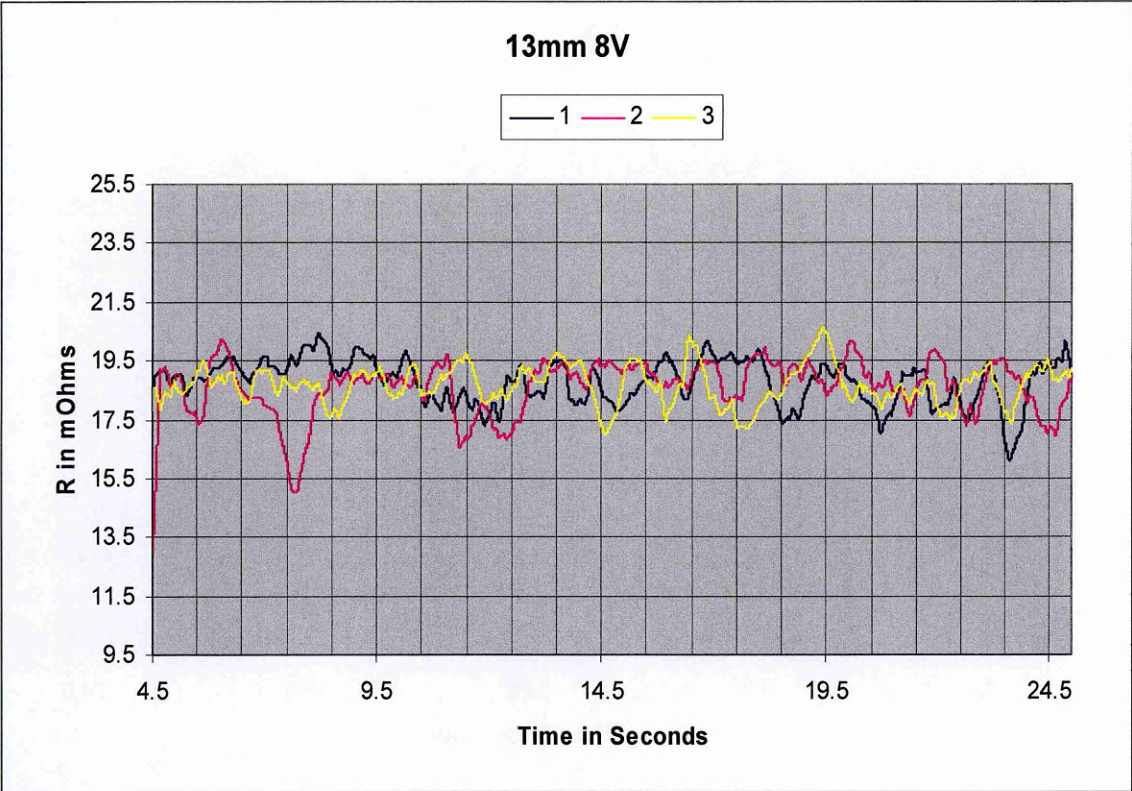


Figure 11-28: The results of the dip resistance from the analysis of three passes for 13 mm CTWD at 8 V threshold.

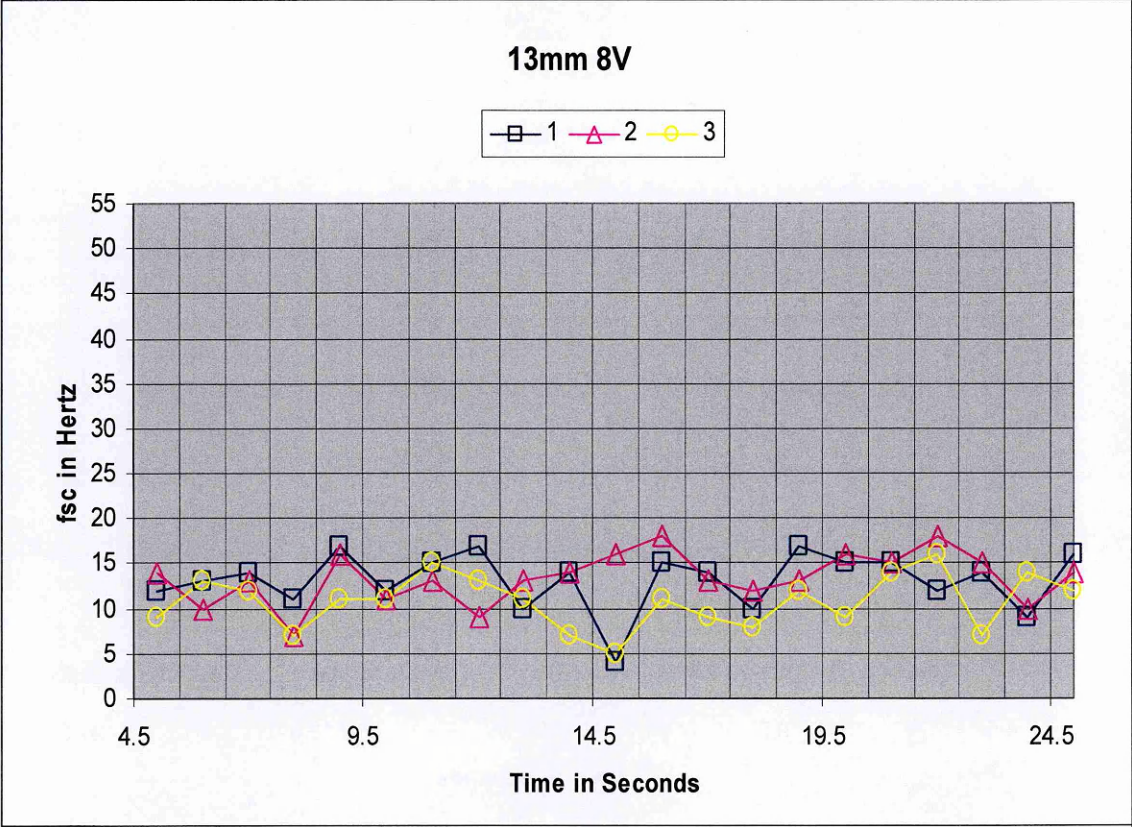


Figure 11-29: The results of the short circuit frequency from the analysis of three passes for 13 mm CTWD at 8 V threshold.

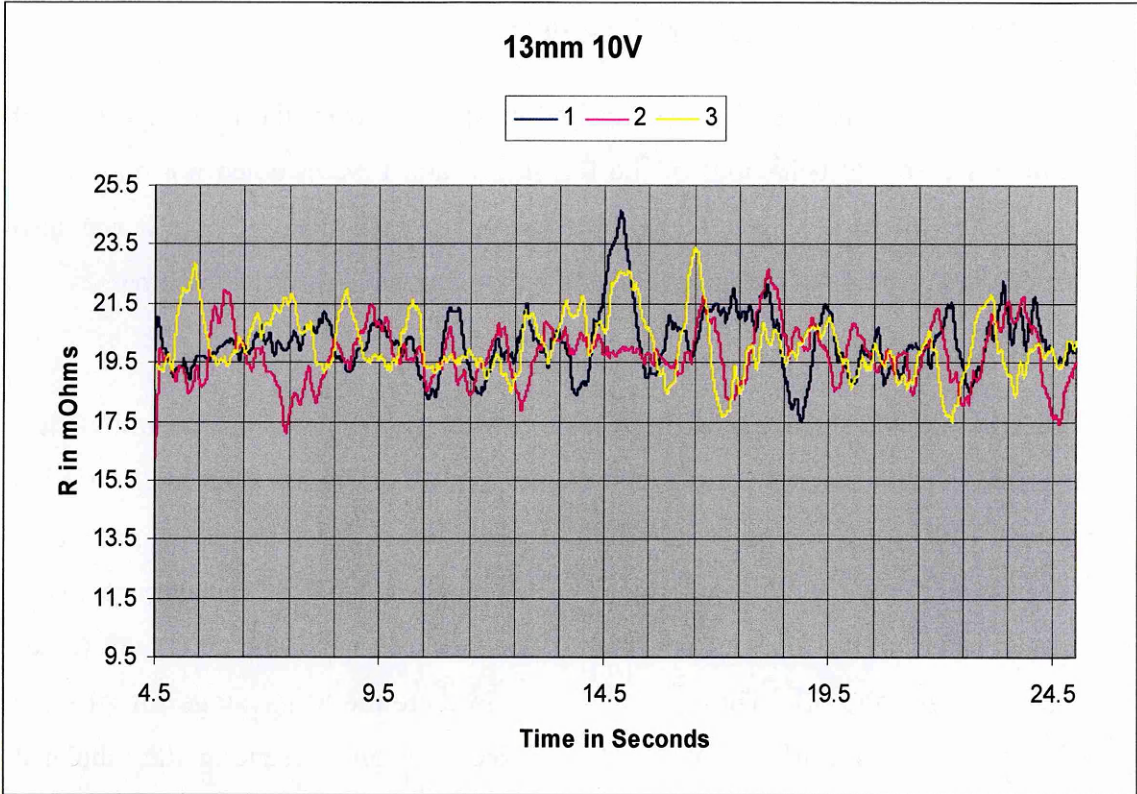


Figure 11-30: The results of the dip resistance from the analysis of three passes for 13 mm CTWD at 10 V threshold.

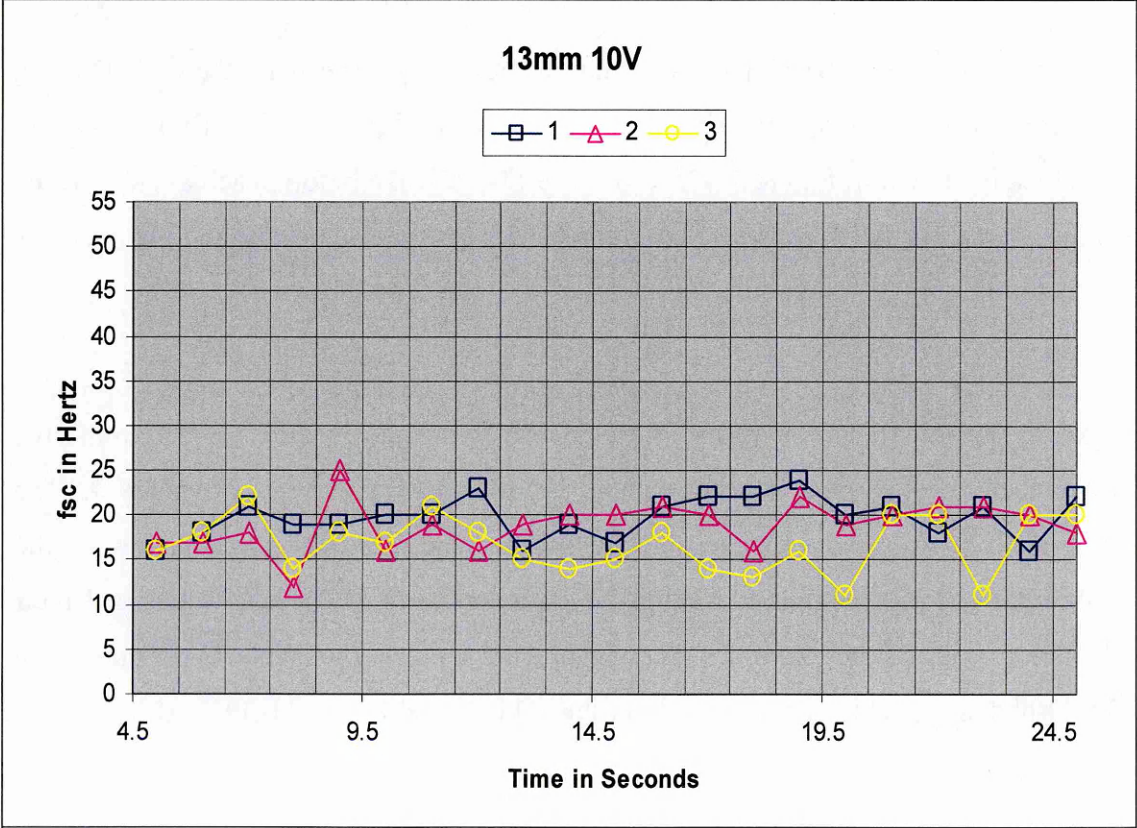


Figure 11-31: The results of the short circuit frequency from the analysis of three passes for 13 mm CTWD at 10 V threshold.

MIN, MAX, and Average statistical treatment

Below is a further analysis that was applied on the data from the first experimental set. In this case, the behaviour of the R_{rol} , f_{sc} , V and I was studied not only as an average value of the averages of the three passes for each stand-off, but it was also considered the average of the minimum and maximum value over the three passes.

In order to be able to compare these results with the results from the initial data analysis earlier, the same type of graphical illustration of the dip resistance variation with the CTWD for each voltage threshold is presented. In each graph there are three waveforms. The average of the averages of R_{rol} for each stand-off, the average on the minimum values of the R_{rol} for each stand-off and the average of the maximum values of R_{rol} for each stand-off. The average values used are the R_{rol} averages of all three passes for each stand-off. Table 11-4 to Table 11-6 are presenting the tabulated results which are graphically presented in Figure 11-32 to Figure 11-34.

The results that describe how the short circuit frequency varies with the CTWD using different welding voltage threshold values, shown in Table 11-7 to Table 11-9, are graphically shown in Figure 11-35 to Figure 11-37. Like before, each average value is the average of the averages of the three passes for each stand-off, and the averages of the minimum, the maximum and the average values are shown.

Like in the initial data analysis, further work was done in order to determine the relationship between the welding voltage and the welding current with CTWD. The data analysis was expanded to include the average from the three passes of the minimum and the maximum welding voltage and welding current values and their deviation from the target values. The results are tabulated in Table 11-10 and Table 11-11 and are graphically presented in Figure 11-38 and Figure 11-39.

From the previous analysis, the observations were the following:

- 1) The trend of the different average R_{rol} with CTWD continuous to exist,
- 2) The trend also exists for the frequency of short circuit occurrences with CTWD,
- 3) As Figure 11-32 shows, the use of the minimum or the maximum averages is not a good idea, since in the extremities of the CTWD variance these values can be extremely unstable,
- 4) The previous point is also possible for the extremes of voltage and current, as Figure 11-38 shows,
- 5) The two previous observations lead to the general conclusion that only the average of the averages is a representative indication of the CTWD for post analysis purposes.

R _{rol} [500]avg. of 3 passes for 6 V threshold			
CTWD	min	max	avg
7	10.279	13.791	12.316
8	11.224	14.876	13.189
9	11.640	14.861	13.513
10	11.186	15.466	14.030
11	10.883	16.279	14.492
12	10.108	16.555	14.705
13	0.905*	16.447	13.941
*[out of scale – not drawn]			

Table 11-4: The R_{rol} variation over the full range of the CTWD for 6 V threshold.

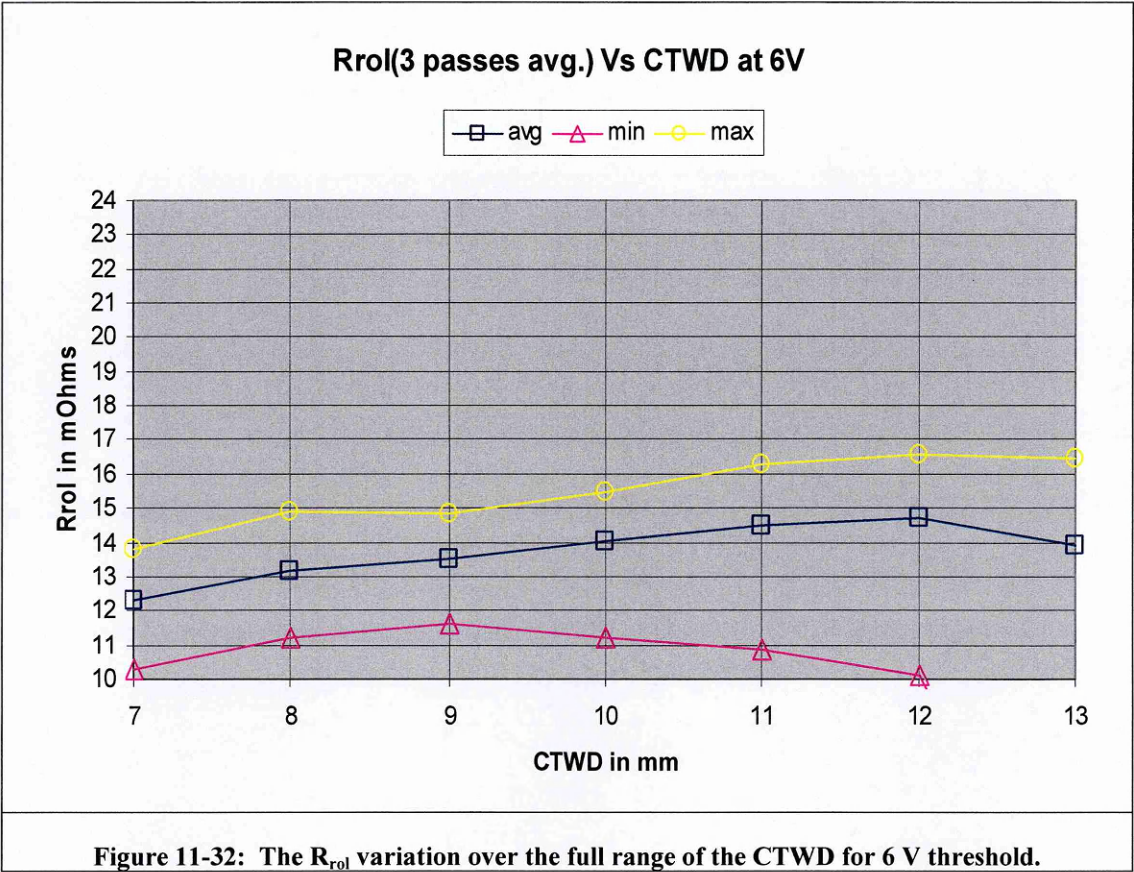
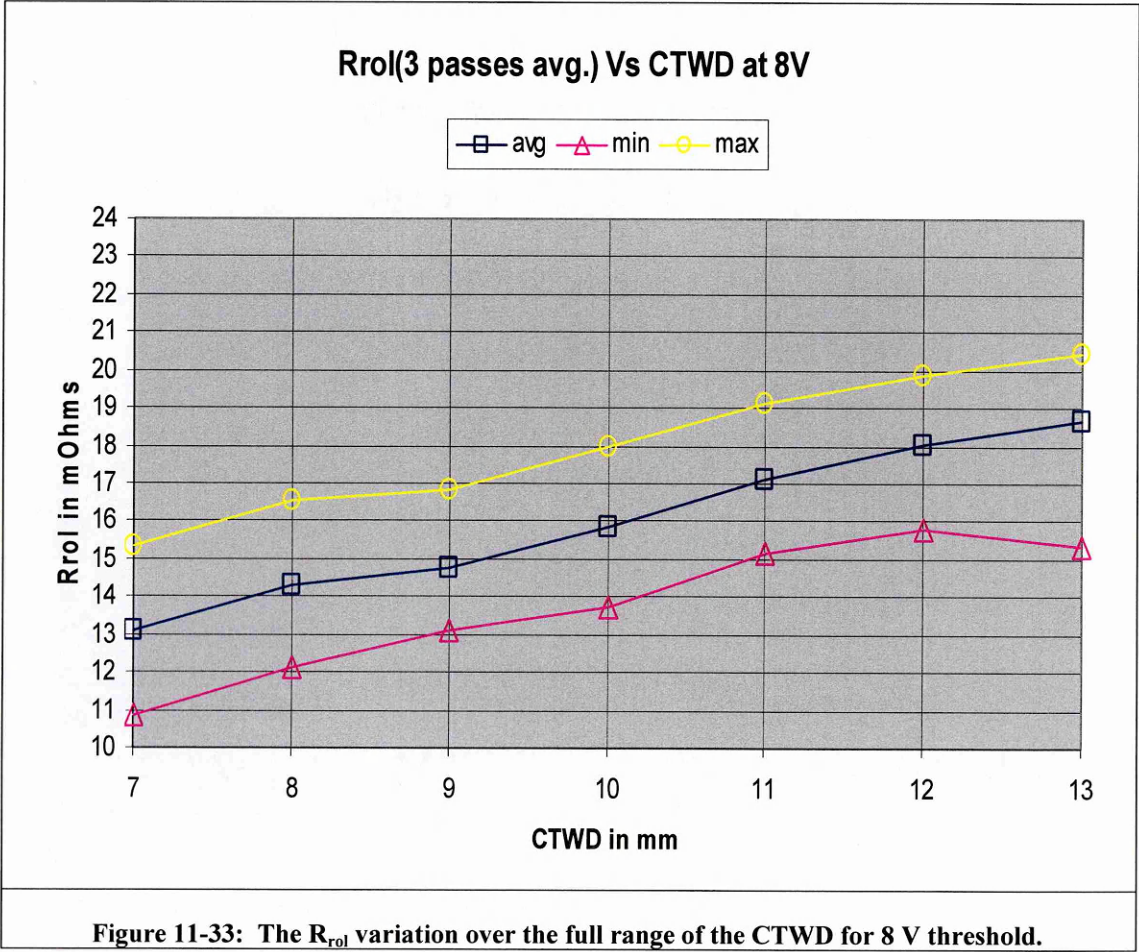


Figure 11-32: The R_{rol} variation over the full range of the CTWD for 6 V threshold.

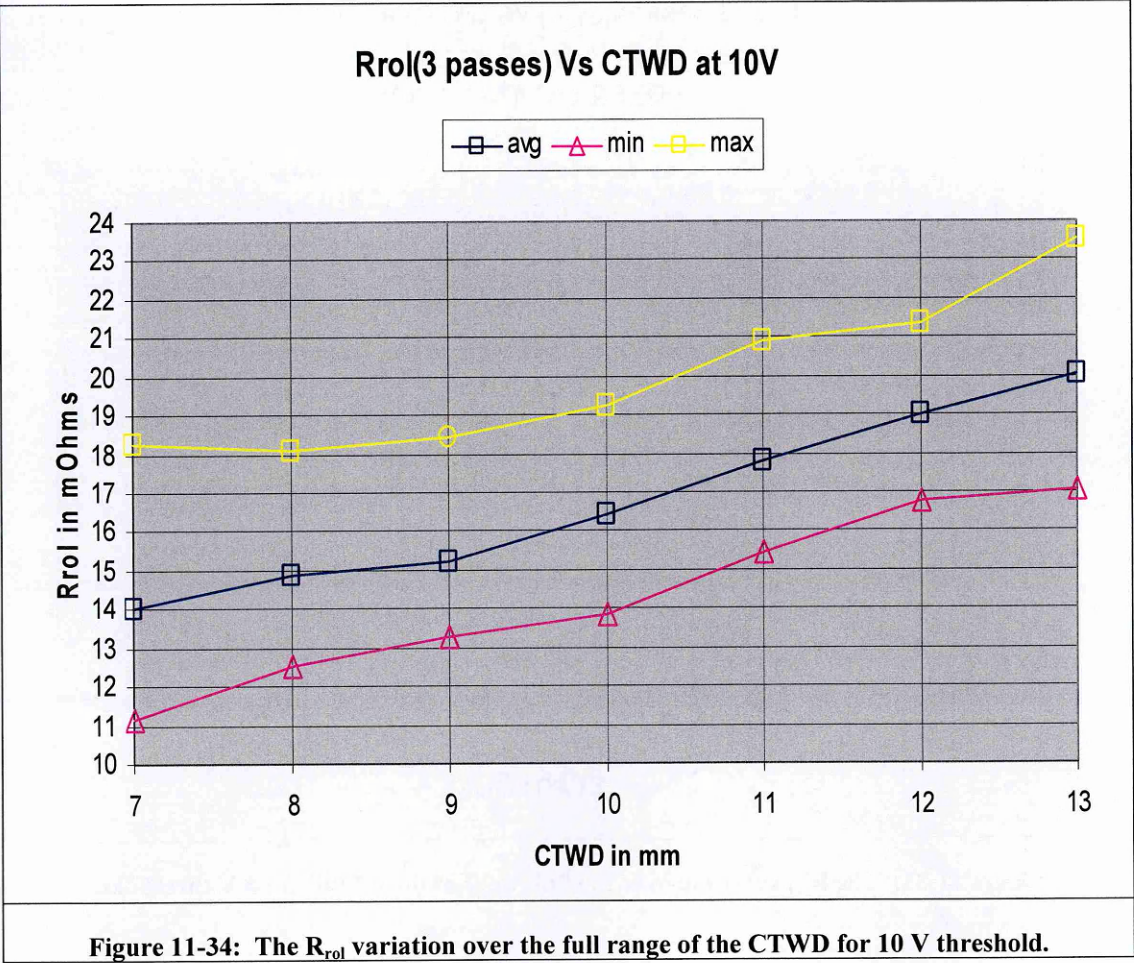
R _{rol} [500]avg. of 3 passes for 8 V threshold			
CTWD	min	max	avg
7	10.856	15.341	13.121
8	12.099	16.524	14.305
9	13.077	16.801	14.741
10	13.732	17.981	15.843
11	15.137	19.095	17.118
12	15.776	19.858	18.019
13	15.356	20.432	18.679

Table 11-5: The R_{rol} variation over the full range of the CTWD for 8 V threshold.



R _{rol} [500]avg. of 3 passes for 10 V threshold			
CTWD	min	max	avg
7	11.167	18.281	14.012
8	12.541	18.096	14.861
9	13.278	18.429	15.223
10	13.867	19.219	16.401
11	15.431	20.919	17.790
12	16.760	21.357	19.030
13	17.084	23.548	20.018

Table 11-6: The R_{rol} variation over the full range of the CTWD for 10 V threshold.



f _{sc} [500]avg. of 3 passes for 6 V threshold			
CTWD	min	max	avg
7	21.7	43.3	32.5
8	15.3	31.3	23.4
9	14.7	30.7	21.8
10	6.7	19.0	13.2
11	3.7	12.7	6.2
12	0.0	5.0	2.2
13	0.0	2.3	0.7

Table 11-7: The f_{sc} variation over the full range of the CTWD for 6 V threshold.

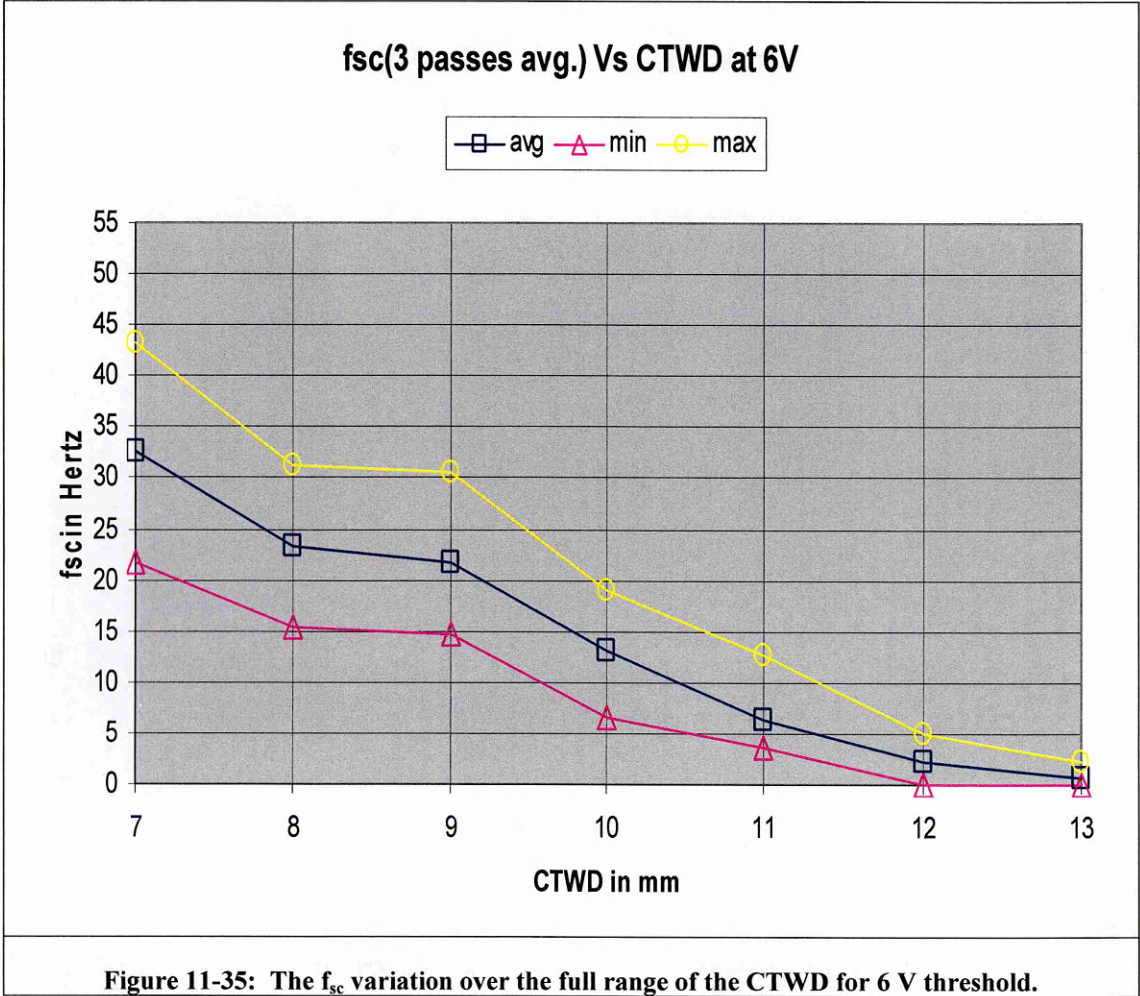
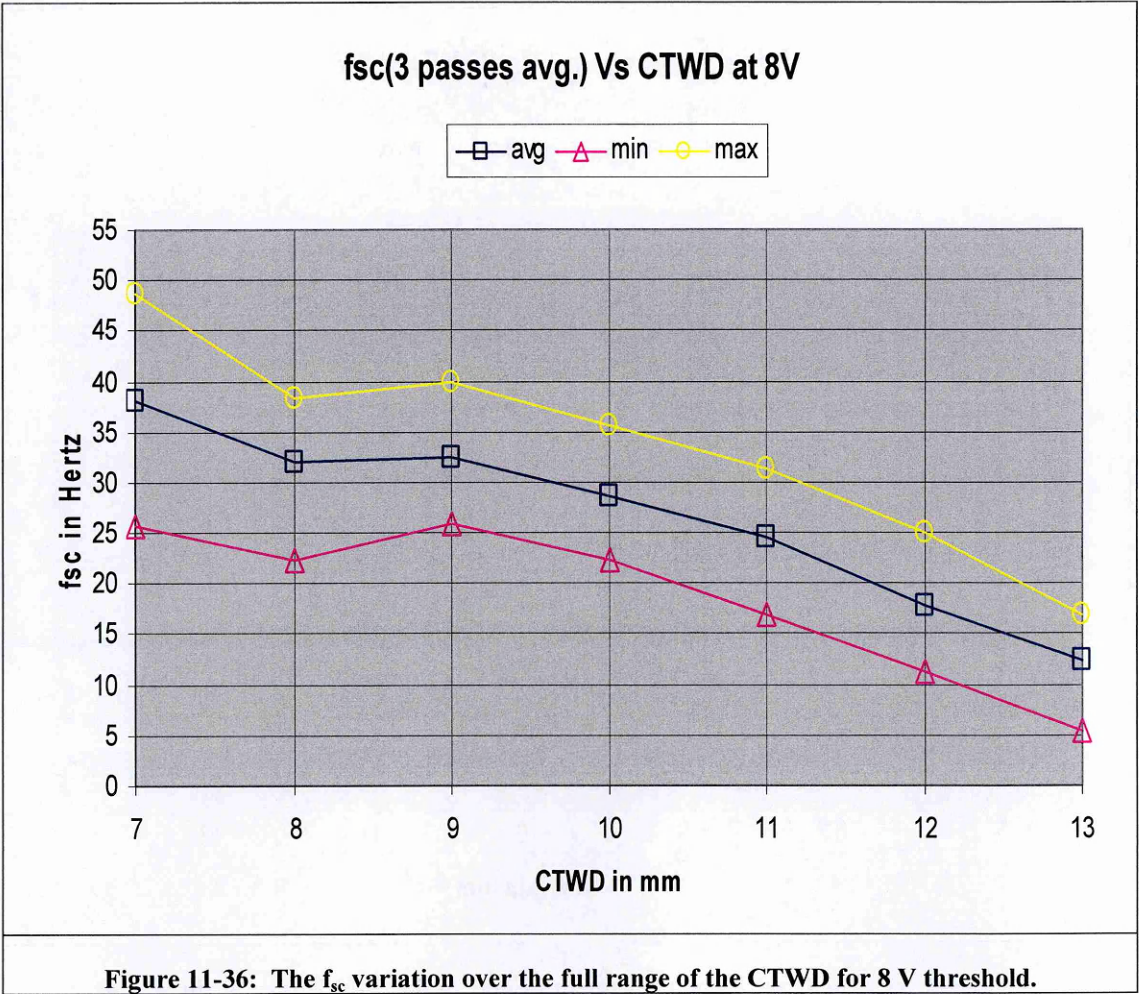


Figure 11-35: The f_{sc} variation over the full range of the CTWD for 6 V threshold.

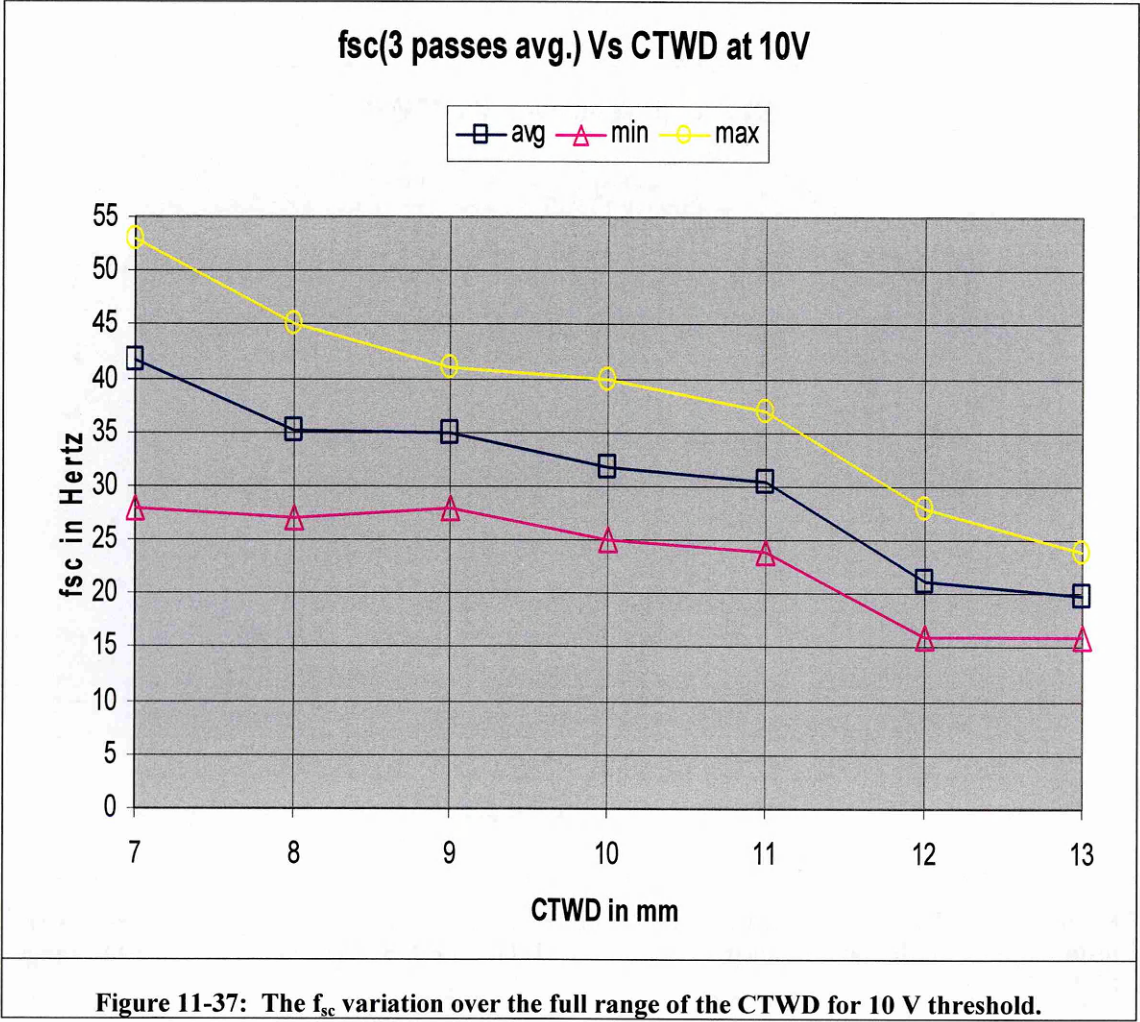
f _{sc} [500]avg. of 3 passes for 8V threshold			
CTWD	min	max	avg
7	25.7	48.7	38.2
8	22.3	38.3	31.9
9	26.0	40.0	32.4
10	22.3	35.7	28.7
11	17.0	31.3	24.5
12	11.3	25.0	17.7
13	5.3	17.0	12.4

Table 11-8: The f_{sc} variation over the full range of the CTWD for 8 V threshold.



f _{sc} [500]avg. of 3 passes for 10 V threshold			
CTWD	min	max	avg
7	30.7	52.7	41.6
8	24.0	42.0	34.2
9	27.7	41.7	34.5
10	25.0	39.3	31.0
11	22.3	34.3	27.7
12	15.7	28.7	22.2
13	13.0	23.7	18.5

Table 11-9: The f_{sc} variation over the full range of the CTWD for 10 V threshold.



V _{arc} avg. of 3 passes			
CTWD	min	max	avg
7	0.7	30.2	16.5
8	1.7	32.3	17.1
9	1.6	32.8	17.6
10	1.8	34.2	18.1
11	2.3	35.9	18.8
12	3.2	38.0	19.3
13	3.0	128.0*	19.9
*[out of scale – not drawn]			

Table 11-10: The variation of the welding voltage averages for the averages of the three passes instantaneous minimum and maximum values and the overall average value over the full range of the CTWD.

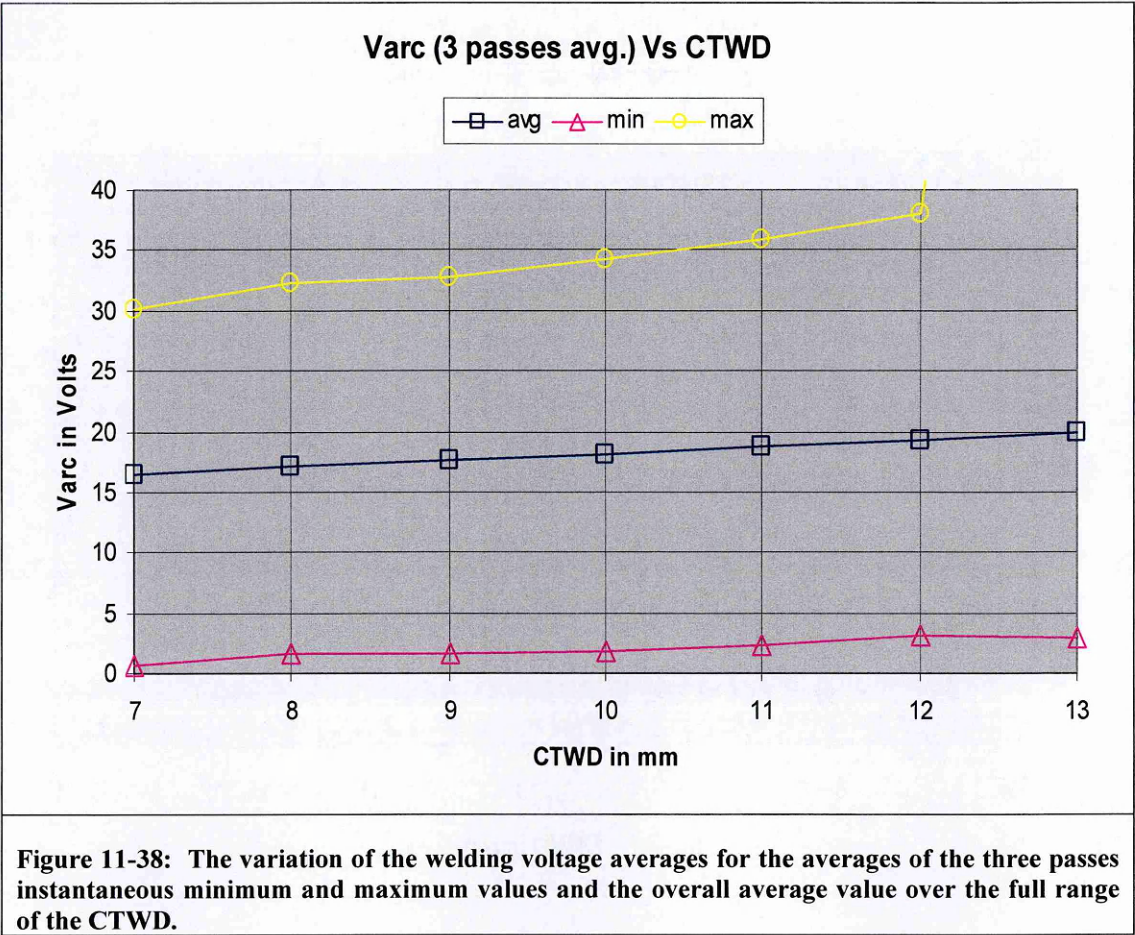
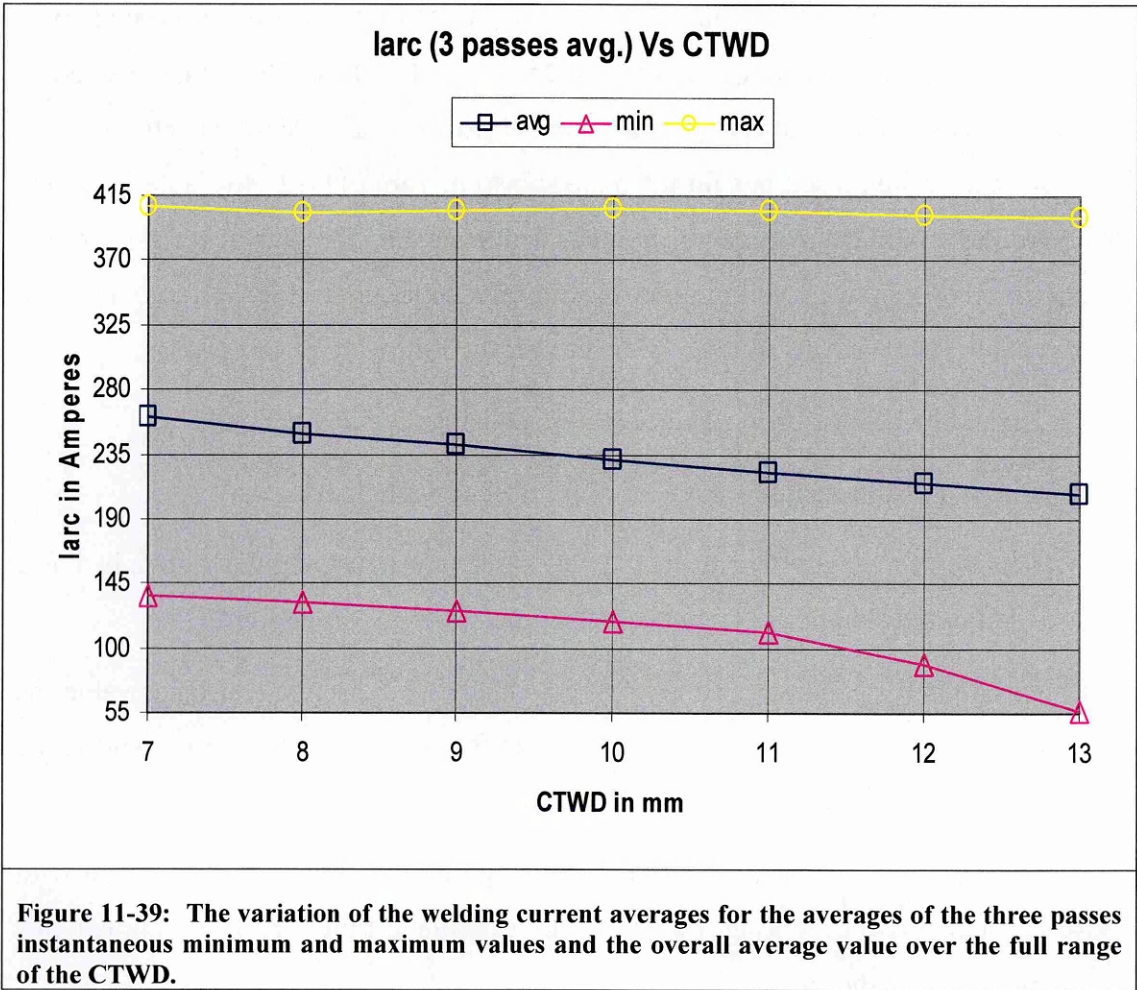


Figure 11-38: The variation of the welding voltage averages for the averages of the three passes instantaneous minimum and maximum values and the overall average value over the full range of the CTWD.

I _{arc} avg. of 3 passes			
CTWD	min	max	avg
7	137.0	407.7	261.1
8	132.4	403.2	248.8
9	126.5	404.8	242.1
10	118.8	405.7	231.8
11	112.0	404.0	221.7
12	89.4	401.6	214.6
13	56.6	399.9	206.9

Table 11-11: The variation of the welding current averages for the averages of the three passes instantaneous minimum and maximum values and the overall average value over the full range of the CTWD.



Rolling Average Filtering with Low Pass Filter

The previous results of using a resistance rolling average as a statistical analysis did not returned a resultant waveform that could clearly act as a strategy for CTWD estimation and control can easily be understood by looking for example Figure 11-14. Thus, the next step was to try to include an LPF [Low Pass Filter] in the analysis. The reason for this selection was that the resistance rolling average seemed to have generally slow variations with a high frequency 'noise' signal added on the underlying slow varying dip resistance signal. An example is shown in the unfiltered waveform of Figure 11-40, where the slow variation extremes seem to be $\approx 2 \text{ mOhms}_{p-p}$ with $\approx 0.25 \text{ mOhms}_{p-p}$ "noise" type variations. Nonetheless, it has to be noted that this is the norm, as indicated in the work in [52] and [54] and is shown in Figure 2-68. Low pass filtering could help remove the "noise" and reduce the variations occurred even in a constant CTWD. Sample results from this analysis shown in Figure 11-40 to Figure 11-46, were made using a rolling average of 500 samples, a high voltage threshold level of 10 V and data sets truncated by 4 seconds in the start and by 0.5 seconds at the end. The LPF filters that seemed to work best, were three Butterworth LPF connected in series. Various settings were tried and the optimum settings for them are shown in Table 11-12. In Table 11-13 the average filtered dip resistance output values deducted from the graphical results of the upper graph of Figure 11-40 to Figure 11-46, rounded to the nearest half-mOhm value is presented. The analysis of them helped to get the following observations:

- 1) The use of LPF helps to produce a more suitable for control signal,
- 2) The best results came from the use of multiple stage filtering,
- 3) The use of a single filter in such a way so as to produce similar results had as a result to over-dump the signal at the beginning of the welding run,
- 4) The filtered signals showed to produce outputs with discrete resistance values as CTWD changes and the step at 8 mm and 9 mm is not present; the trend is the dip resistance to go up as the CTWD level goes up,
- 5) The previous however refers to the average filtered dip resistance value with constant CTWD; during welding with variable CTWD [real conditions] this might not be the case,

- 6) These values however could overlap at large variations of the process and a solution/further treatment is deemed necessary.

STAGE	TOPOLOGY	Cut-off frequency [Hz]	Order
1st	LPF	2	2
2nd	LPF	0.5	2
3rd	LPF	0.1	2
Table 11-12: The settings for the Butterworth LPF used to smooth out the results of the resistance rolling average signals.			

CTWD:	7 mm	8 mm	9 mm	10 mm	11 mm	12 mm	13 mm
Average Dip Resistance in mOhms	14	15	15.5	16.5	18	19.5	20
Table 11-13: Average filtered Dip Resistance output values deducted from the graphical results of the upper graph of Figure 11-40 to Figure 11-46, rounded to the nearest half-mOhm value.							

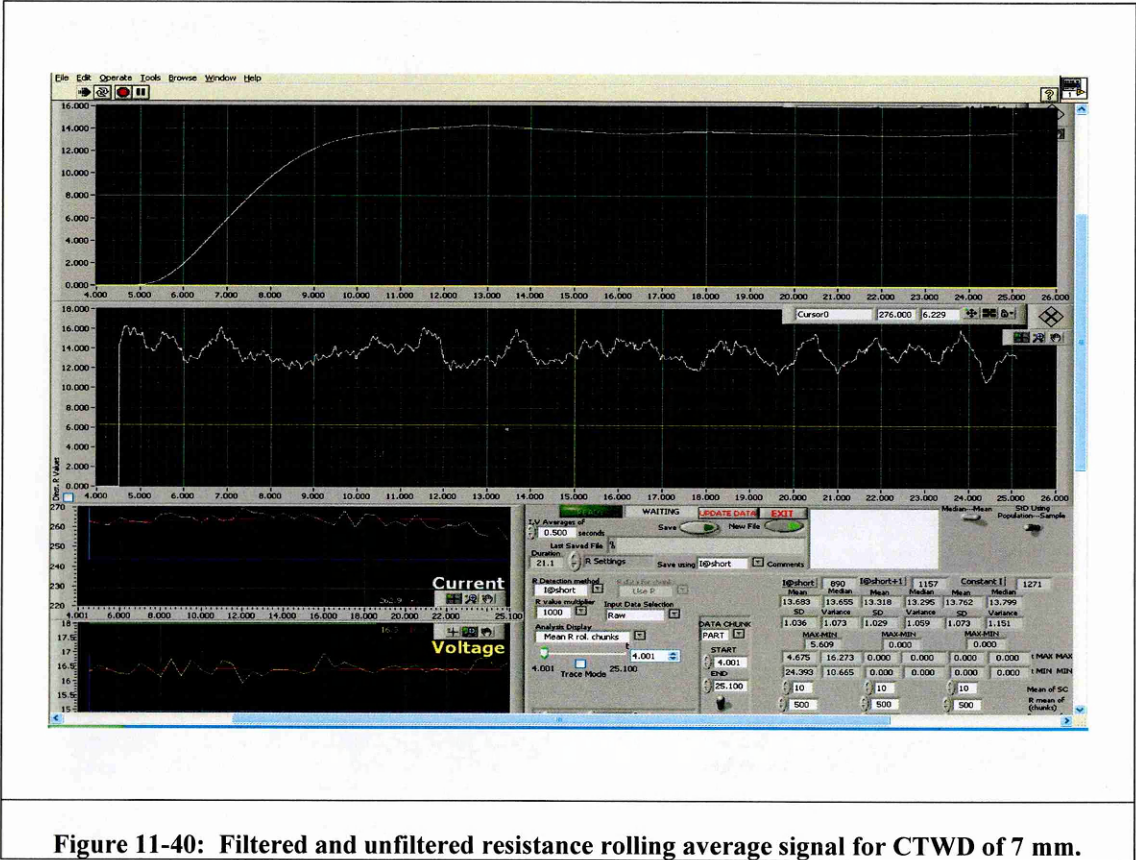


Figure 11-40: Filtered and unfiltered resistance rolling average signal for CTWD of 7 mm.

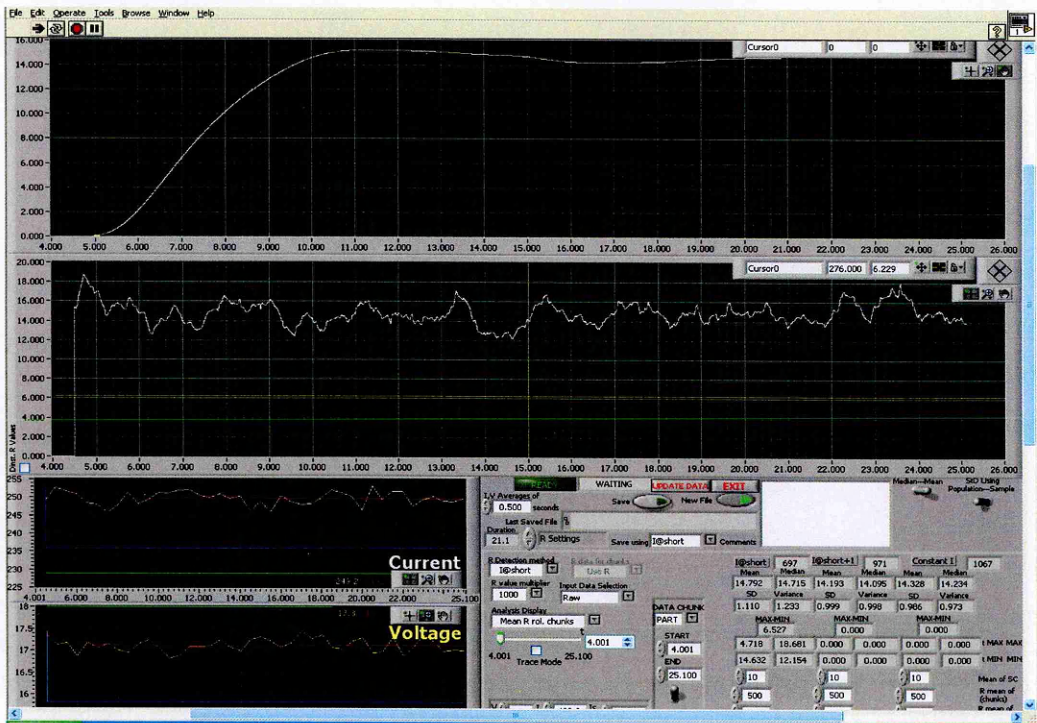


Figure 11-41: Filtered and unfiltered resistance rolling average signal for CTWD of 8 mm.

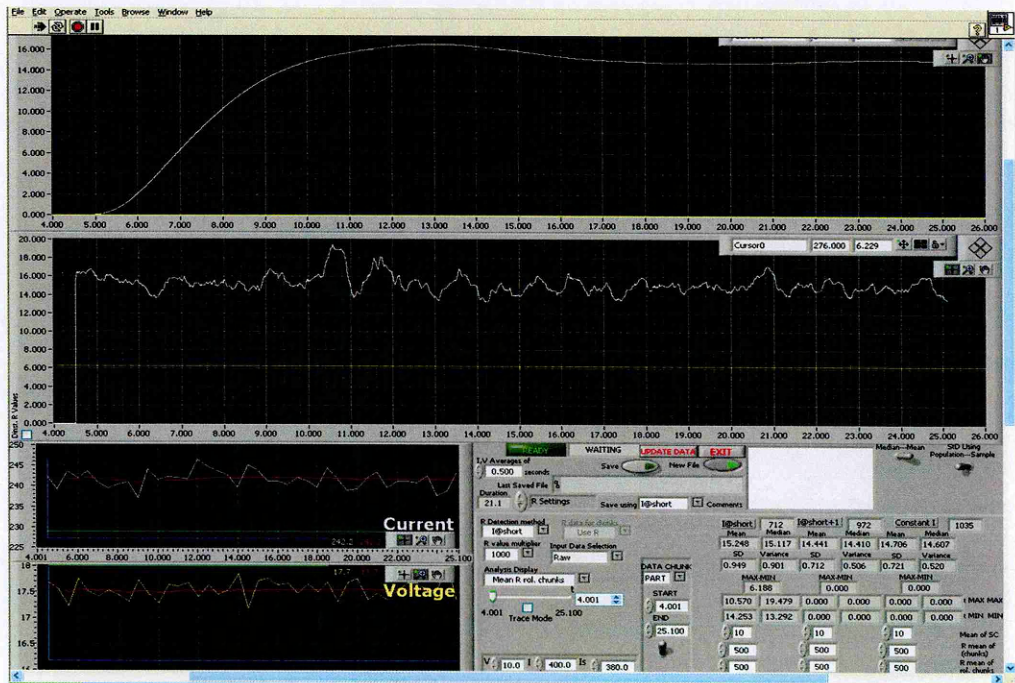


Figure 11-42: Filtered and unfiltered resistance rolling average signal for CTWD of 9 mm.

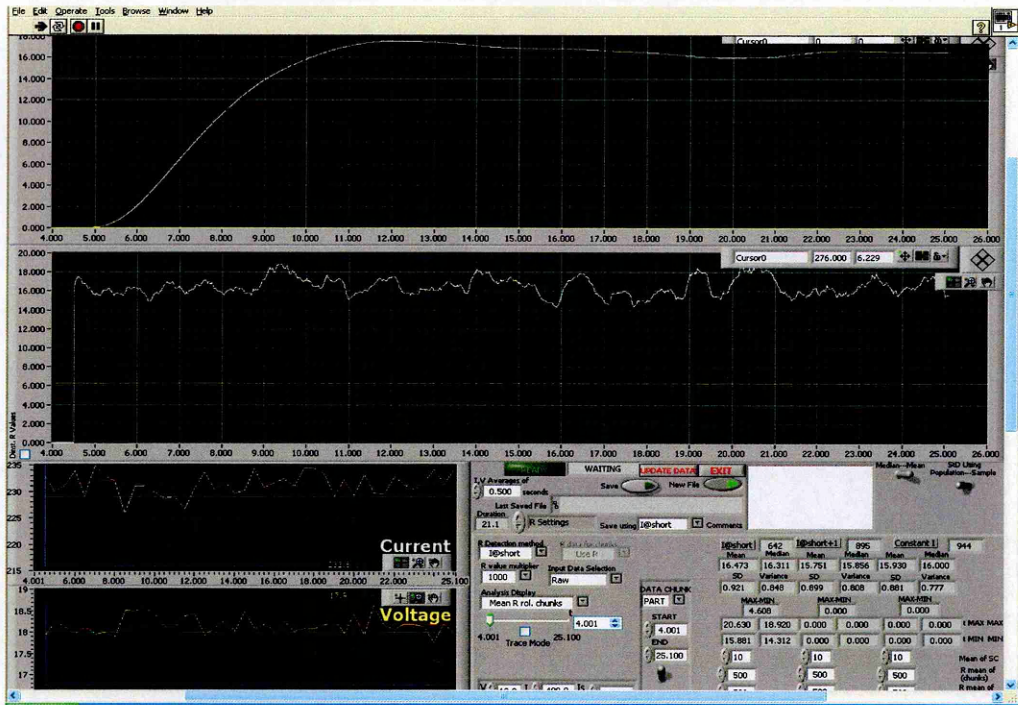


Figure 11-43: Filtered and unfiltered resistance rolling average signal for CTWD of 10 mm.

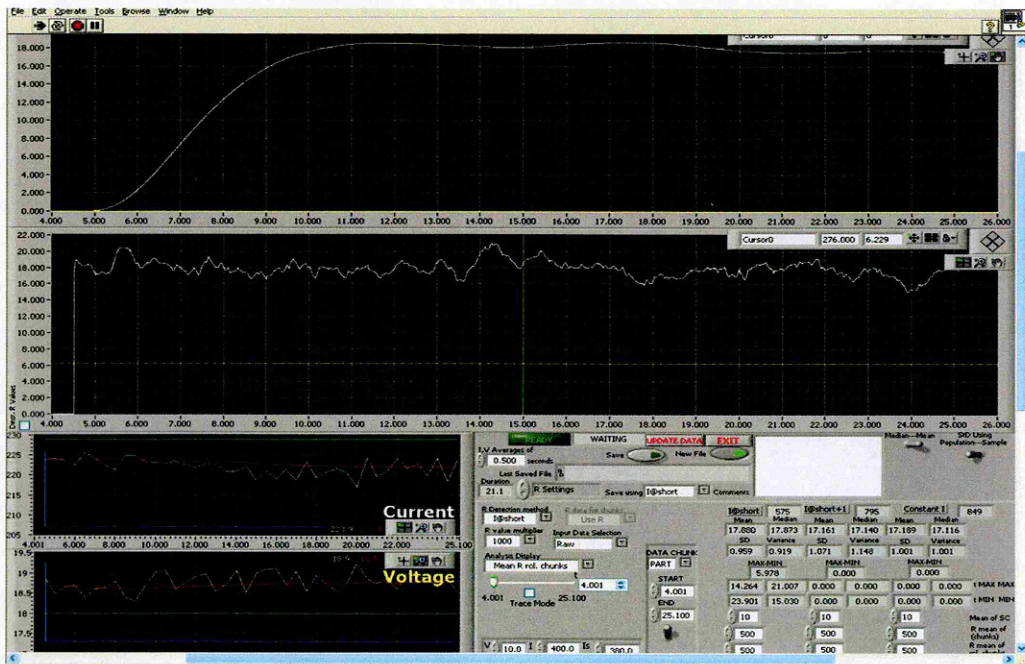


Figure 11-44: Filtered and unfiltered resistance rolling average signal for CTWD of 11 mm.

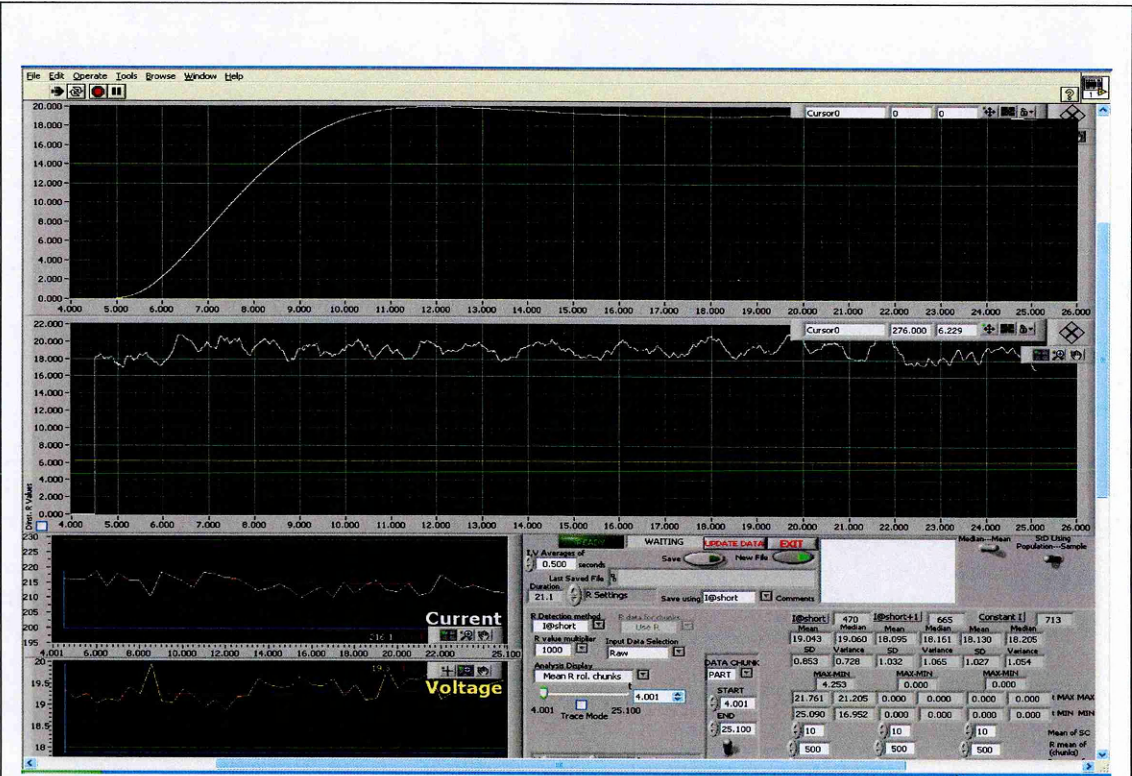


Figure 11-45: Filtered and unfiltered resistance rolling average signal for CTWD of 12 mm.

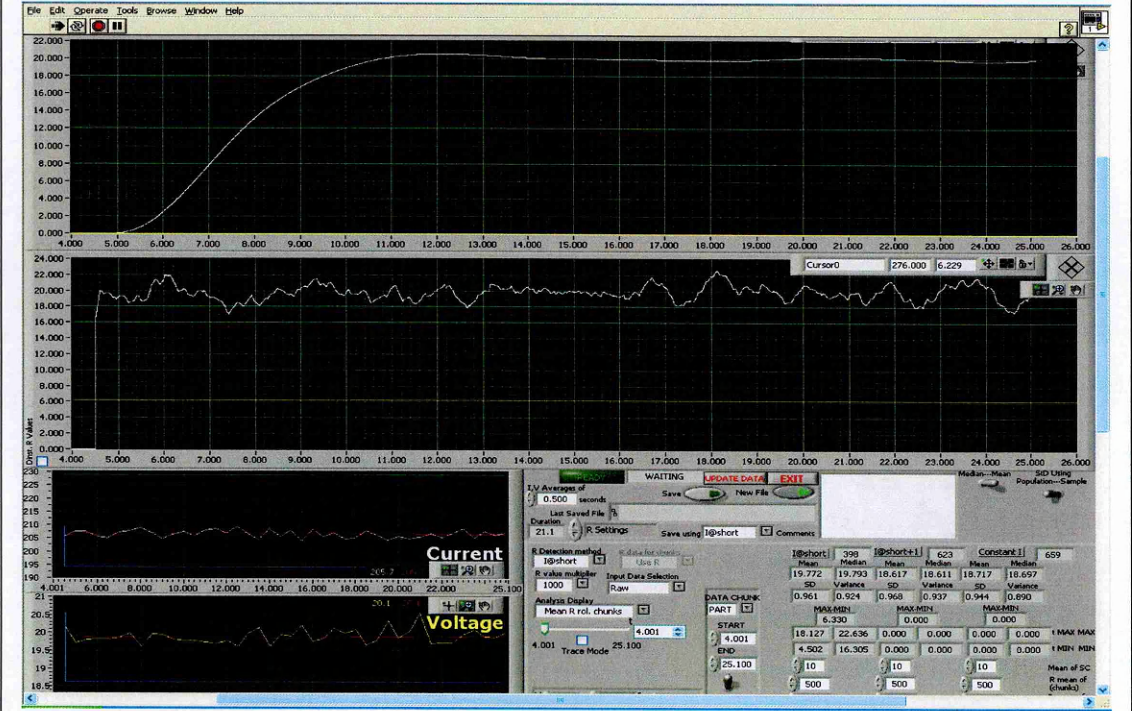


Figure 11-46: Filtered and unfiltered resistance rolling average signal for CTWD of 13 mm.

11.2 Review of the Experimental Strategy

After the evaluation of the initial results, the next step was to review the strategy for the data analyses. What was needed to be done was to check the response of the dip resistance with changes of the CTWD during the welding run. This could help determine if the step that appears at the previous experimental analysis between 8mm and 9 mm stand-off continuous to exists, or if it was a repeatable error on the measurements. The experiments were also designed so as to investigate the effect of the length of the welding earth path and also to investigate the influence of the parent metal temperature on the estimation of the CTWD via the dip resistance under Hyperbaric Conditions.

11.2.1 Design of Second Set of Experiments

In order for the above to be investigated, the new experiments included runs with variable stand-off. There were two ways to do that. The first one was to elevate the specimen and the second one was to move the torch over the Y axis [vertical direction in connection to the parent material] during the welding run. It was decided that it would be better to follow the second way, since that way there would not be any issues regarding the variance of the CTWD due to the specimen deformation during welding from the heat input. Also, there would not be any issues regarding the contact resistance between the specimen and the welding table. Thus, the investigation of any influence from the welding earth's path length could be performed. The specimen preparation was the same with the first set of experiments as well as the welding parameters and the target values. In order to investigate the influence of the welding earth's path length, two runs at constant CTWD of 10 mm were made. The runs were made next to each other but in different direction. The first run was starting away from the electrode connection point on the welding table and was finishing next to it, while the second one was starting next to the electrode connection point on the welding table and it was finishing away from it. In the case that the earth/ground path length has a significant effect on the dip resistance values this reversing in the welding direction would aid to detect this in direct graph comparison. It would also help to eliminate any unpredictable process factors.

In the sequel, two runs were made as constant slopes. The first one was starting with a CTWD of 7 mm and after 20 mm the torch was raised and it was reaching the 13 mm after 350 mm. The second one was made in the reverse direction. The initial CTWD was 13 mm this time and it stayed like that for 20 mm. Then, the welding torch started to move down gradually up to the point that it reached the 7 mm after a total run of 350 mm. The reason the torch height was maintained at its original level for the first 20 mm of the welding run was so as to stabilise the welding arc and to examine only the data produced with the appropriate welding parameters as for the first few seconds the welding parameters differ. The reversing in the directions would also help to investigate the influence of the welding path length. After that, three runs were made like a weave. This constant change of the CTWD would help to test the response of the system to constant changes.

Results Obtained and Analysis

All the results were analyzed using the tactic of ‘I@short’, the truncated data set [first 4 seconds were not logged and the last 0.5 seconds of data were truncated], a resistance rolling average of 500 samples and a series of three Butterworth filters. The settings for the configuration of the filters are shown in Table 11-12 [pp. 257] and are repeated for convenience in Table 11-14 below.

STAGE	TOPOLOGY	Cut-off frequency [Hz]	Order
1st	LPF	2	2
2nd	LPF	0.5	2
3rd	LPF	0.1	2
Table 11-14: The settings for the three Butterworth filters used to analyse the data from the resistance rolling average.			

The first results had to do with the investigation of the influence of the welding earth’s path length, or else, the location of the welding electrodes compared to the welding spot. As presented earlier in Measurement Accuracy [pp. 181] it has been reported by the authors of [9, 69, 74, 76, 77] that the flow of current through the parent material(s) can influence the process’ behaviour either due to interference [9] or due to Ohmic losses [69]. Figure 11-47 shows the result from the welding run where the welding torch was moving towards the electrode connection point on the

welding table and Figure 11-48 shows the results obtained when the welding torch was moving away from the electrode connection point on the welding table. Two runs were made in total and the CTWD was kept constant throughout. The waveforms show the rolling average of 500 samples [0.5 seconds worth of data in this case with 1 kHz sampling rate] and the same signal filtered through a three stage Butterworth filtering network. They also show the welding voltage and welding current traces averaged every 0.5 seconds [500 samples in this case of 1 kHz sampling rate] and their overall average.

The influence of the parent metal temperature was investigated as well since as reported in Temperature [pp. 183] it could influence the CTWD estimation using the through-the-wire sensor. For the first run shown in Figure 11-47 the parent metal's temperature at the start of the run was 36 °C. At the end of the run the parent metal's temperature had reached 51 °C. For the second run shown in Figure 11-48 the start and end parent metal's temperature was 49 °C. Visual examination of the graphs reveals that the shape of the dip resistance does not have any trend that can be attributed to the change of the temperature, hence the parent metal's electrical resistance, during the first run or between the two runs. It has to be noted that the range of temperatures investigated is not wide enough and further work with a broader temperature range spectrum might result in a different behaviour.

The following observations were made:

- 1) The location of the welding electrode connection point on the welding table does not seem to affect the results,
- 2) The previous might be true in laboratory conditions with small specimen's dimensions but in practice the results might be different due to larger structure's dimensions, welding setup geometry and ambient conditions like temperature and magnetic fields as analysed in 2.5.3; further analysis is deemed necessary,
- 3) The rise of the parent metal temperature, therefore alteration of its electrical characteristics, does not seem to affect the dip resistance estimation.

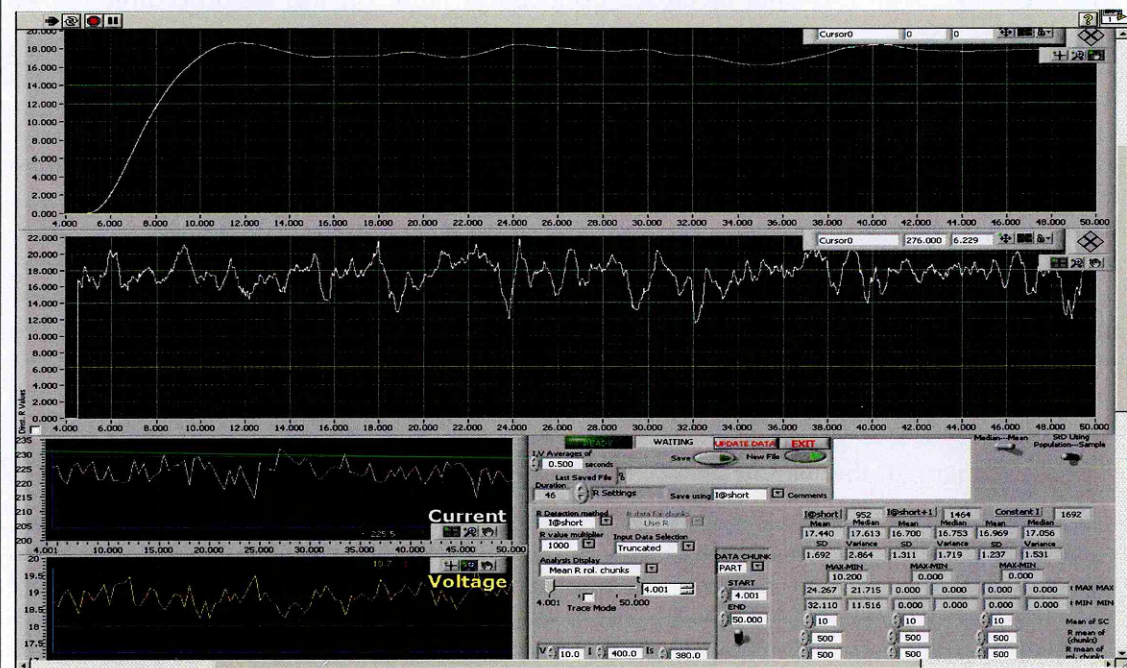


Figure 11-47: The trace of the rolling average of the dip resistance when the welding torch was moving towards the electrode connection point on the welding table.

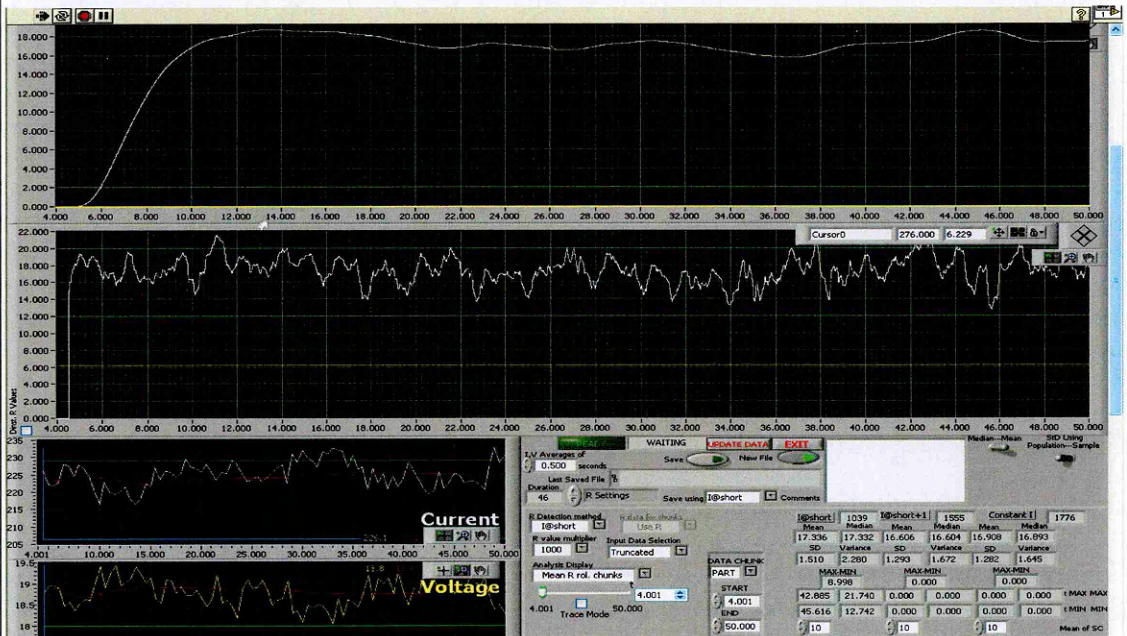


Figure 11-48: Traces of the dip resistance when the welding torch was moving away from the electrode connection point on the welding table.

The following graphs show the results from the welding runs where the welding torch was moving in a slope trajectory. Two runs were made with the welding torch moving towards the electrode connection point on the welding table. Figure 11-49 shows graphically the pre-programmed trajectory and Figure 11-50 shows the resultant signals after the analysis. Figure 11-51 and Figure 11-52 show the pre-programmed welding torch trajectory and the results obtained for the second slope run with reverse direction [away from the electrode connection point on the welding table] compared to the first one. The following observations were made:

- 1) The slope of the simulated ramp is evident in the traces of the resistance filtered and unfiltered rolling average,
- 2) The slope it is also evident in the current and voltage traces,
- 3) When the welding torch moves towards the table [decreasing CTWD] the signal seems to have more fluctuations.

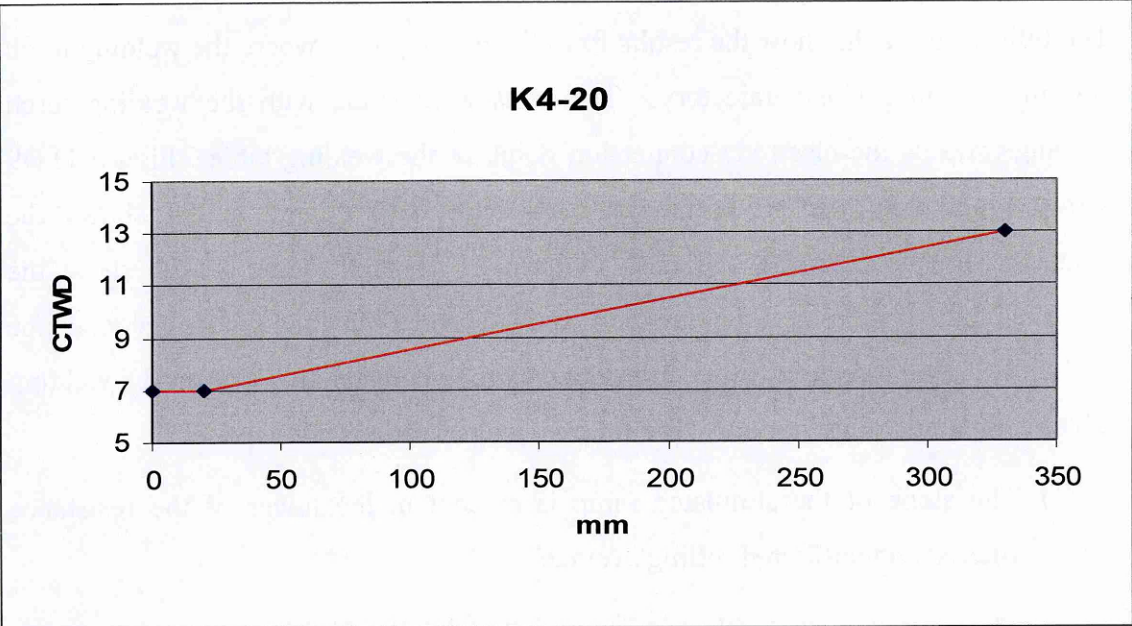


Figure 11-49: Graphical representation of the pre-programmed torch trajectory [CTWD 7 mm to 13 mm].

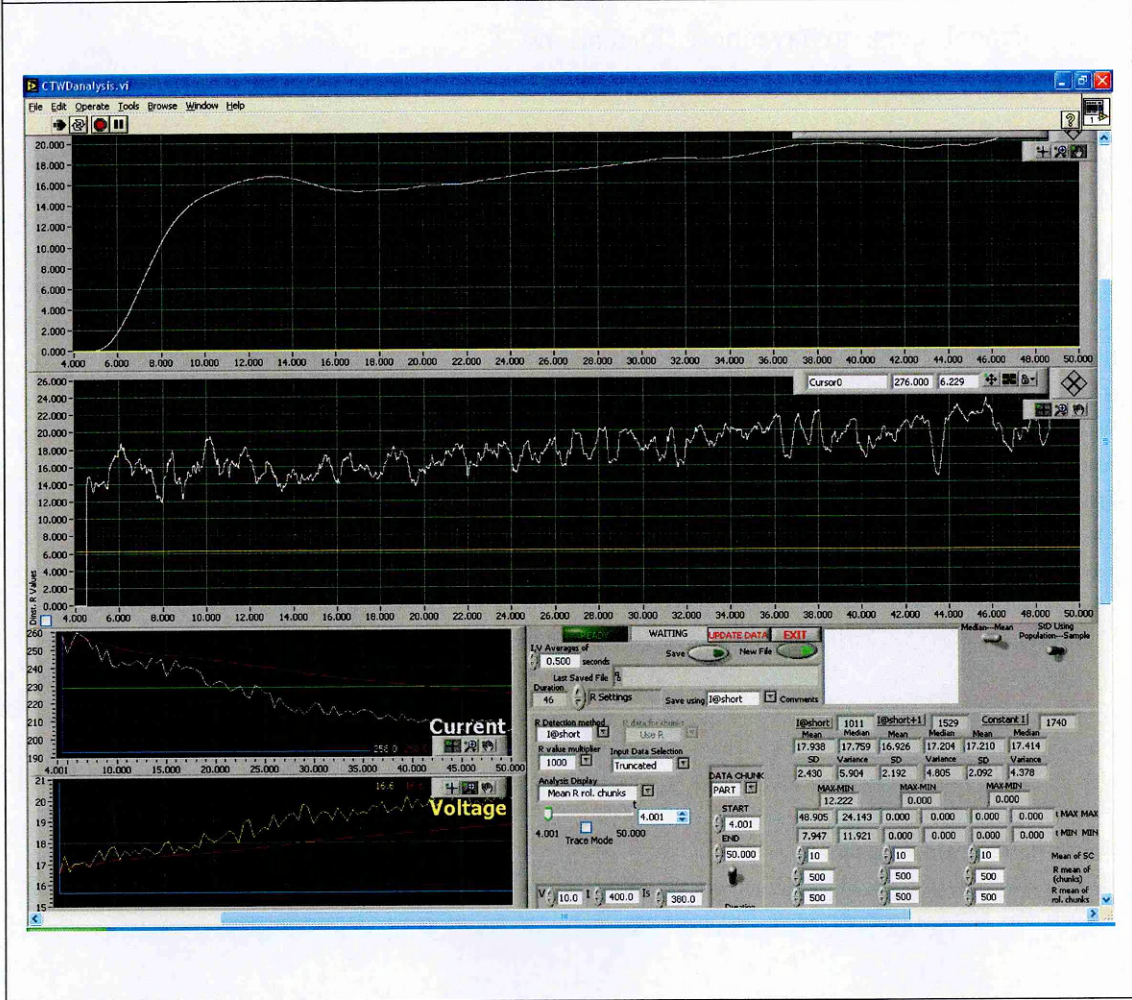


Figure 11-50: The results obtain based on the analysis algorithms for torch trajectory from 7 mm to 13 mm.

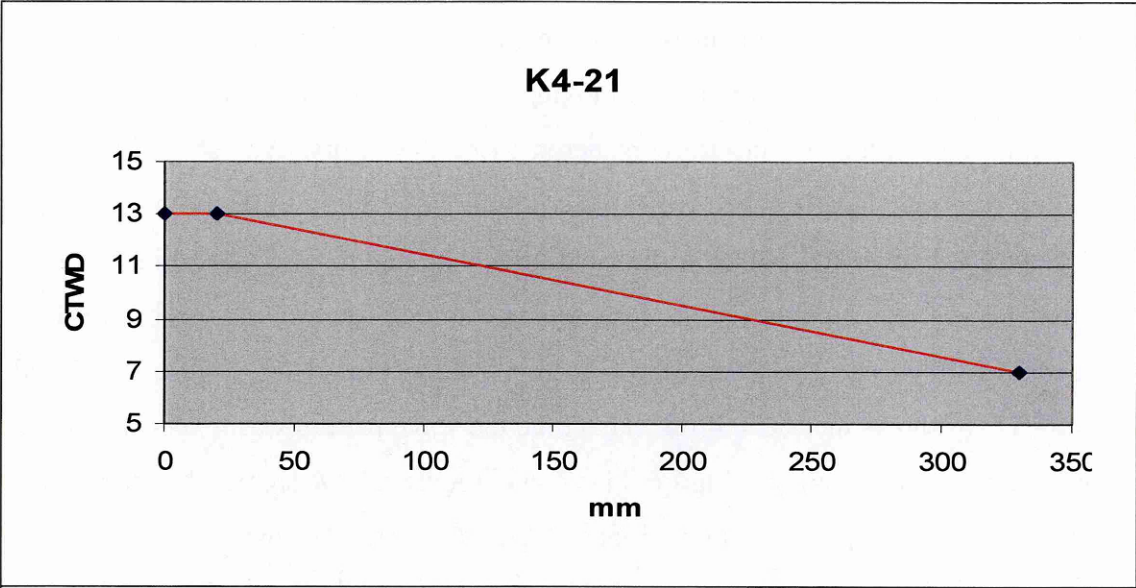


Figure 11-51: Graphical representation of the pre-programmed torch trajectory [CTWD 7 mm to 13 mm].

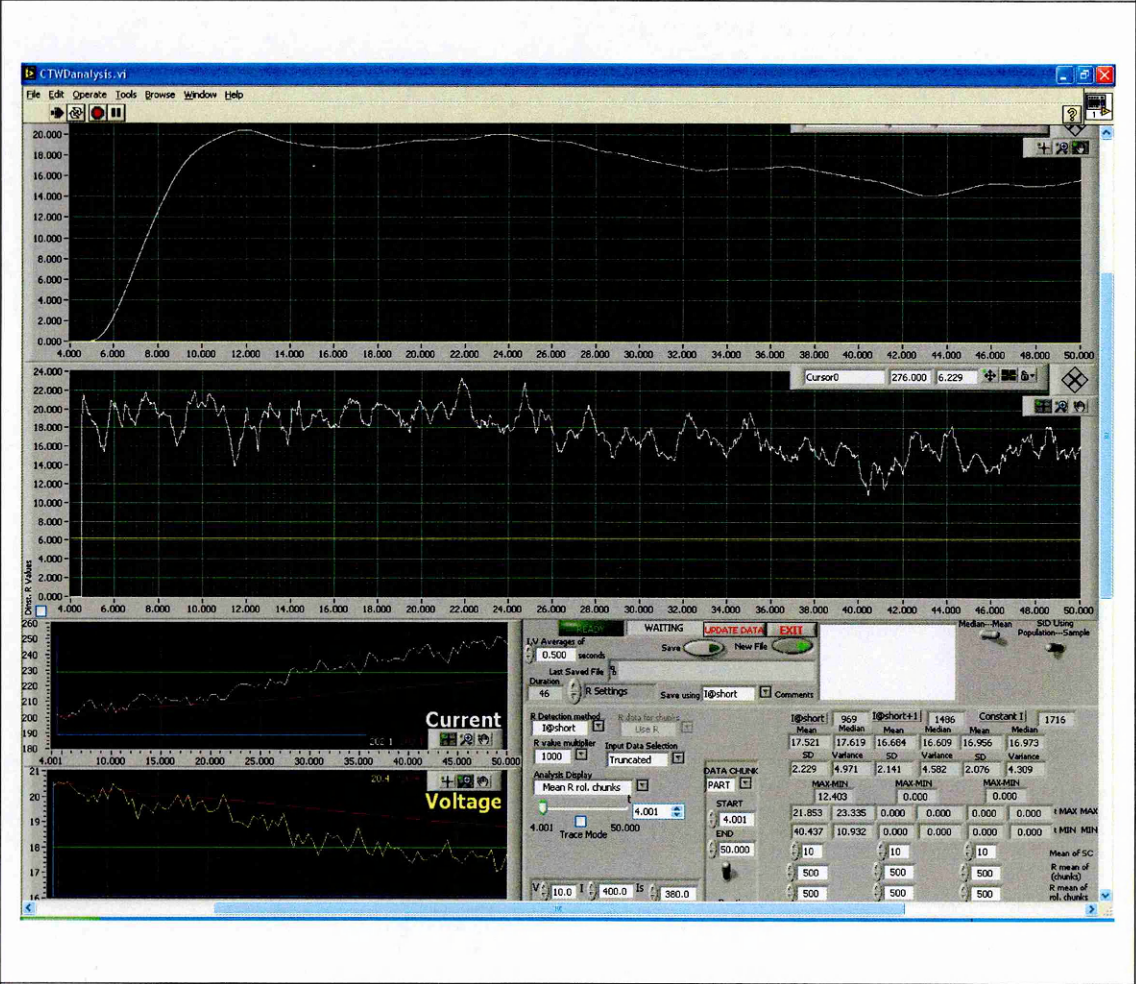


Figure 11-52: The results obtain based on the analysis algorithms for torch trajectory from 7 mm to 13 mm.

The third part of the experiment was to examine the behaviour of the dip resistance method whilst the welding torch was moving in a wave pattern with extreme points the 7 mm and 13 mm which are considered to be the “worst case scenario”. One welding run was made for each wave pattern with the welding torch moving towards the electrode connection point on the welding table. Figure 11-53 and Figure 11-54 shows the first wave pattern as it was pre-programmed for welding torch trajectory with two valleys and a peak and the result of the analysed data. Figure 11-55 and Figure 11-56 shows the second run. This time the wave pattern was reversed and had two peaks and one valley. Figure 11-57 and Figure 11-58 shows the final wave pattern as it was pre-programmed and then executed and the analysed results obtained. In this wave, there were two valleys and one peak again but the difference was that the welding torch was maintained in the extremes of the CTWD for 20 mm. The following observations were made:

- 1) The filtered and unfiltered resistance rolling averages showed to be able to sense the welding torch movement,
- 2) The voltage and current signals were also sensitive to the CTWD change,
- 3) The step between the 8 mm and 9 mm CTWD seems to be there in many cases but not always,
- 4) When the run has two valleys, it seems that the resistance in the second one is increased compared to the first one.

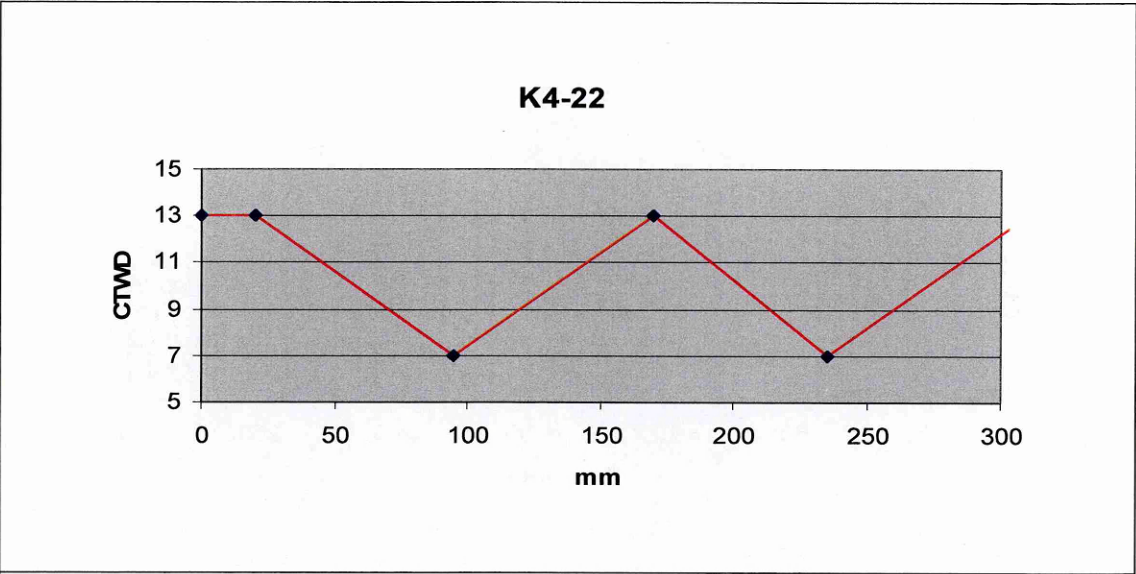


Figure 11-53: Graphical representation of the pre-programmed weave welding torch trajectory with two valleys and a peak.

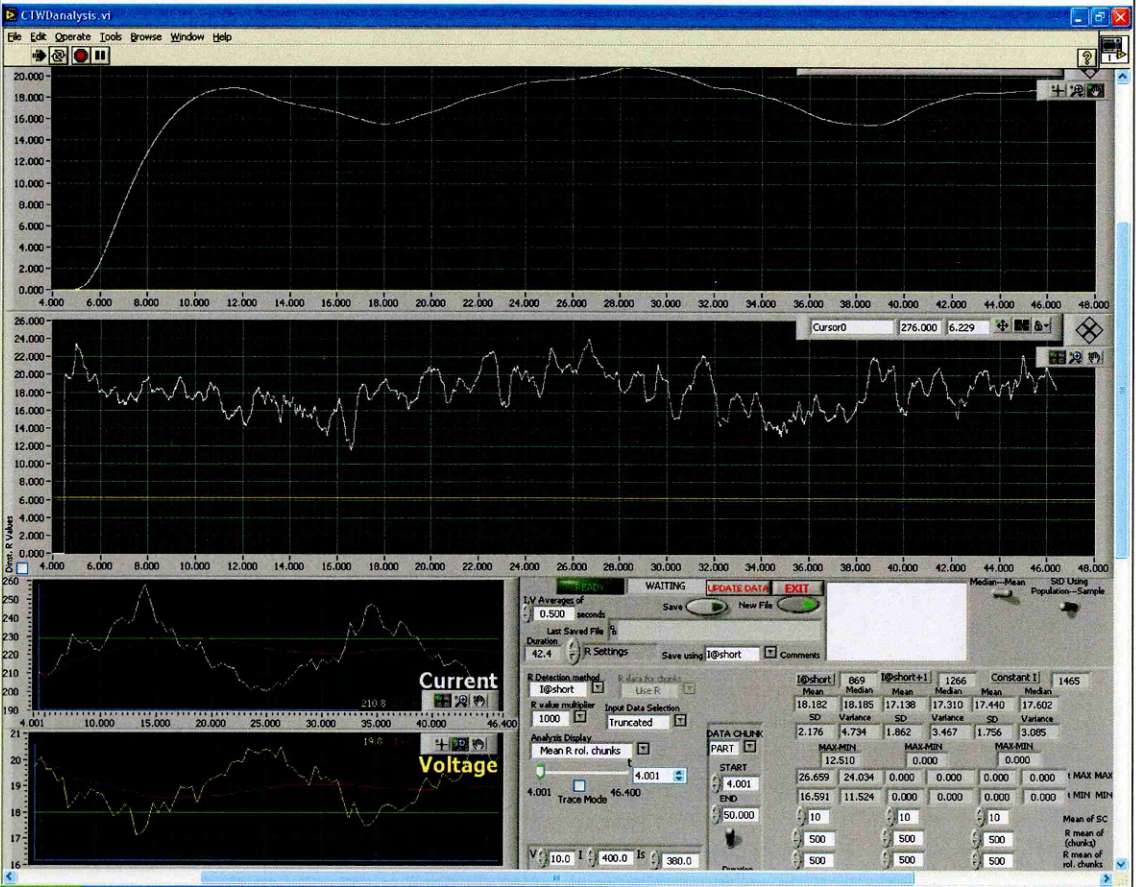


Figure 11-54: The results obtained after the analysis of the pre-programmed weave torch trajectory with two valleys and a peak.

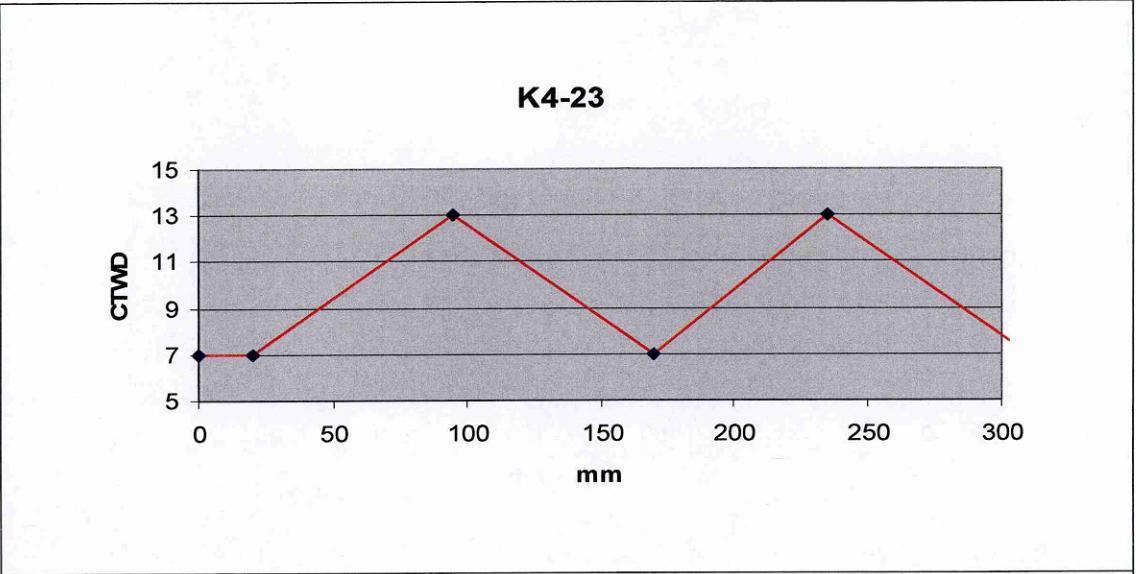


Figure 11-55: Graphical representation of the pre-programmed weave torch trajectory with two peaks and a valley.

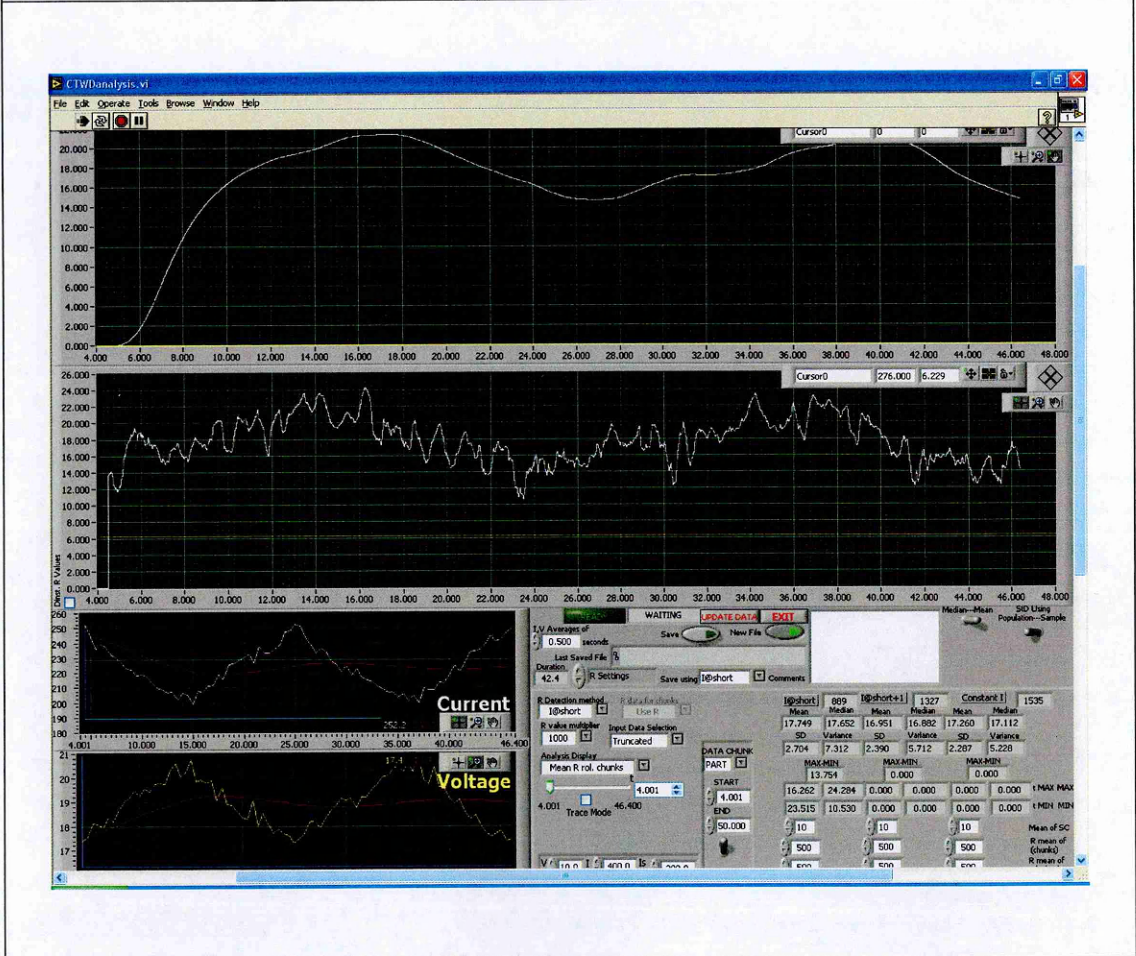


Figure 11-56: Analysis results of the pre-programmed weave torch trajectory with two peaks and a valley.

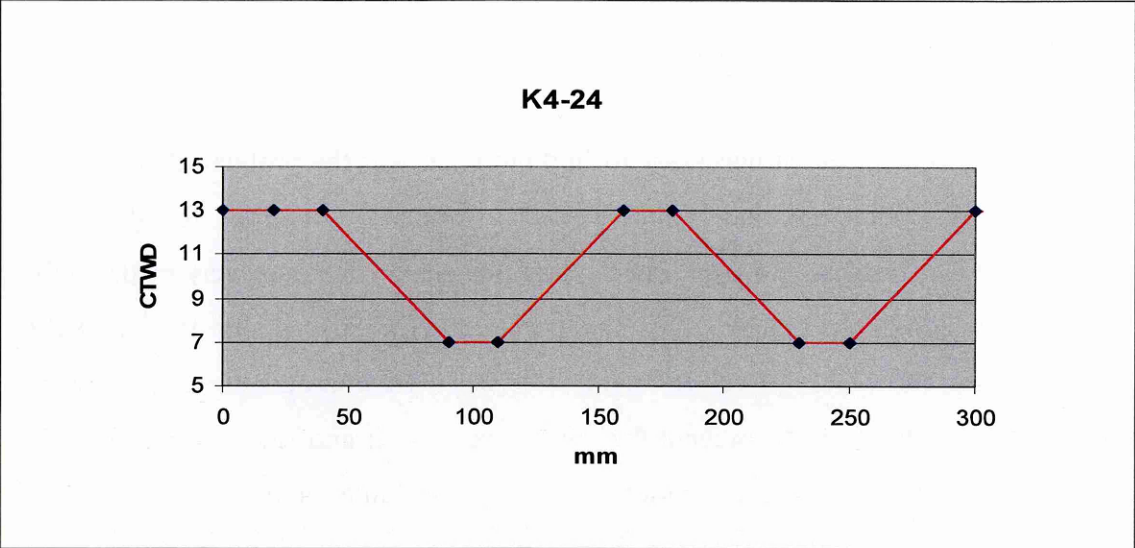


Figure 11-57: Graphical representation of the pre-programmed weave torch trajectory with two extended valleys and an extended peak.

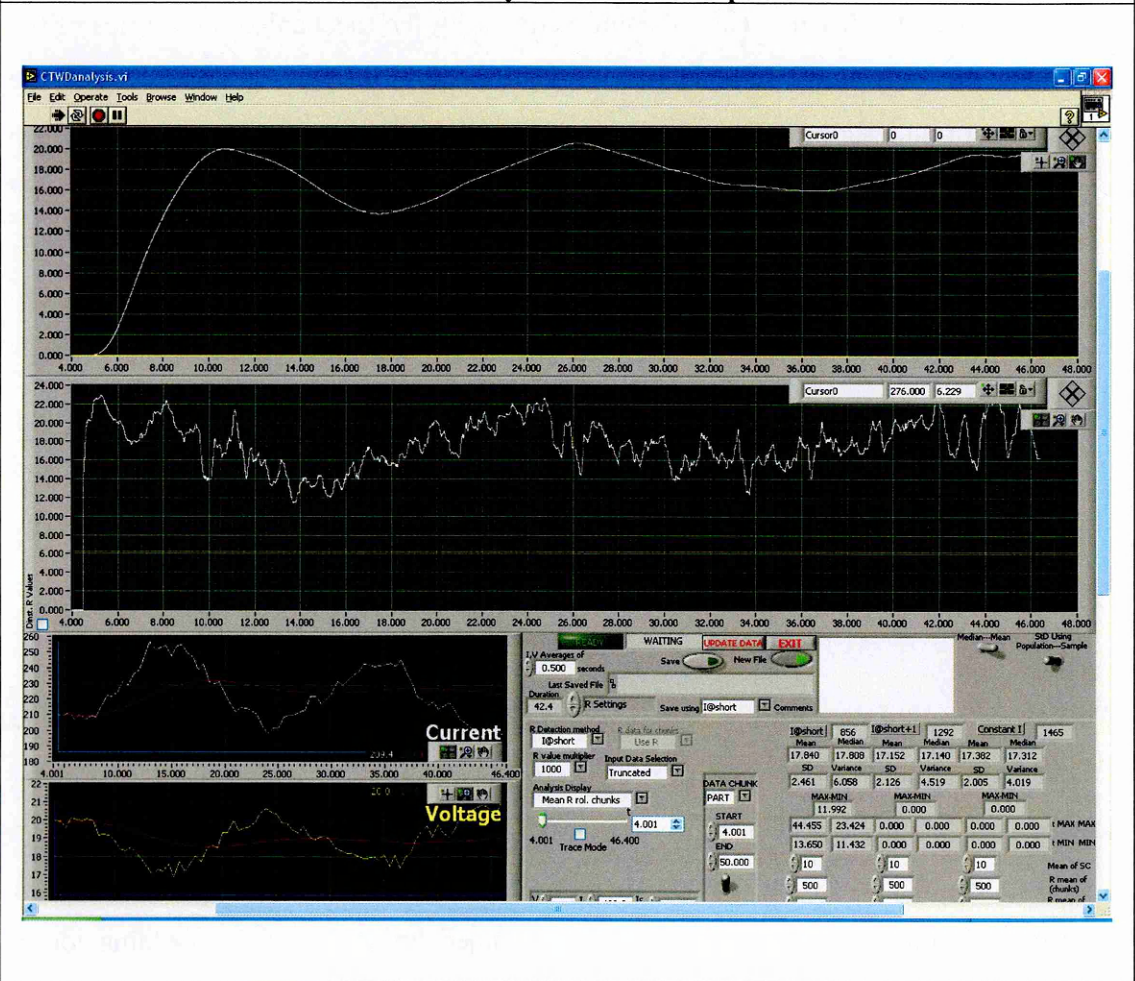


Figure 11-58: The results obtained for the pre-programmed weave torch trajectory with extended two valleys and an extended peak.

11.3 Third Set of Experiments

The results so far deemed necessary to find out what was the problem that made the step between the 8 mm and 9 mm CTWD to appear. In order for that to be investigated, a third set of experiments was designed. This set was made with a different welding torch tipp. For the previous experiments and for the RPRS development, the welding torch tip that is used has a 1.2 mm opening and the wire is 1 mm in diameter so as to prevent the wire to burn back and stack in the tip and/or spatter to block it or to restrict its move through the welding torch tipp. As a result of the wire bending slightly as it dips inside the welding pool and because of the slack of the wire inside the tip and the wire conduit, the wire actually touches not at the end of the tip but a bit further in. This in combination with the mechanical properties of the welding wire may make it bend inside the tip and influence the trend around the 8 mm, 9 mm and 12 mm CTWD. The CTWDs that are influenced must have to do with the geometry and the bend of the wire. It is suspected that short CTWD the wire is pushed back during its contact with the weld pool turbulence and the welding arc's feedback forces [arc blow, arc turbulence, electromagnetic forces] as presented in 2.5.3. At the higher levels of CTWD it is suspected that there is a lot of slack in the welding wire which allows it to make contact with the welding tip at different points during operation, again, as a result of the feedback forces from the welding arc and the wire's contact with the weld pool. This time a welding torch tip with 1 mm bore diameter was used.

This experimental set was the same with the second set in order for direct comparison to be easily made. All welding runs were made with the welding torch moving towards the electrode connection point on the welding table. There were three wave welding runs made with two extended valleys [for 20 mm] and one extended peak [for 20 mm]. Figure 11-59 shows the pre-programmed trajectory of the welding torch. Figure 11-60 to Figure 11-62 show the analysis results from the acquired data. Then two wave welding runs were made with two valleys and one peak. The welding torch's pre-programmed trajectory is shown in Figure 11-63 and Figure 11-64 and Figure 11-65 shows the analysed results. Another two wave welding runs were made,

this time the pattern was reversed, in other words, with two peaks and one valley. Figure 11-66 shows the pre-programmed trajectory and Figure 11-67 and Figure 11-68 show the analyzed results. From the experimental results the following observations were made:

- 1) The step between the 8 mm and 9 mm still makes its appearance but it is less intense,
- 2) The difference in the resistance values at the runs with the two valleys between the minimum valleys resistances seem to be less; however in one occasion, the first valley seemed to have higher resistance,
- 3) The voltage and current waveforms still show a trend that follows the welding torch's trajectory.

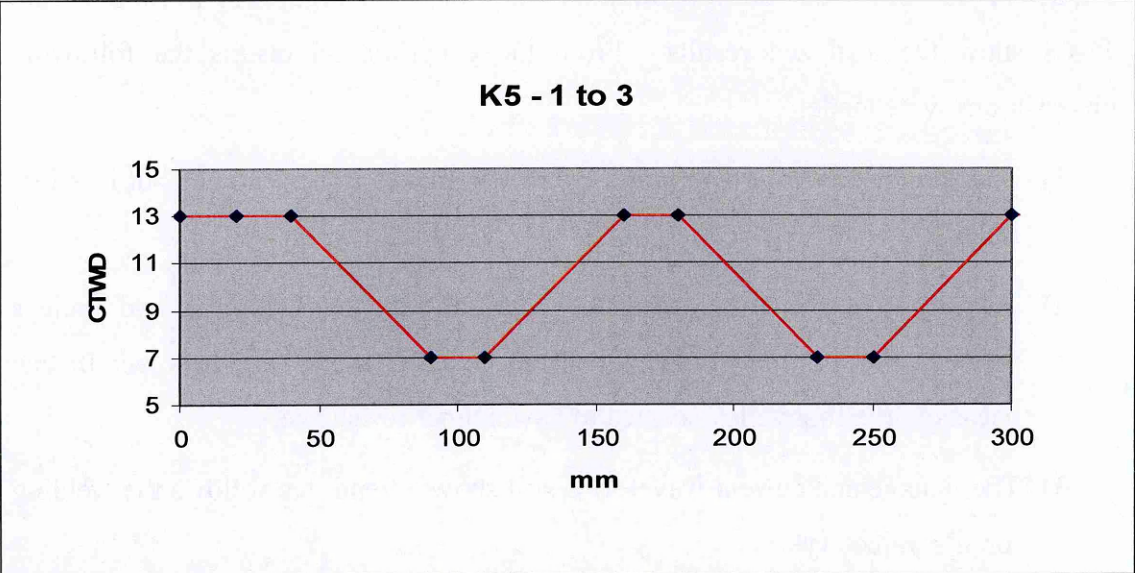


Figure 11-59: Graphical representation of the pre-programmed weave torch trajectory with two extended valleys and an extended peak.

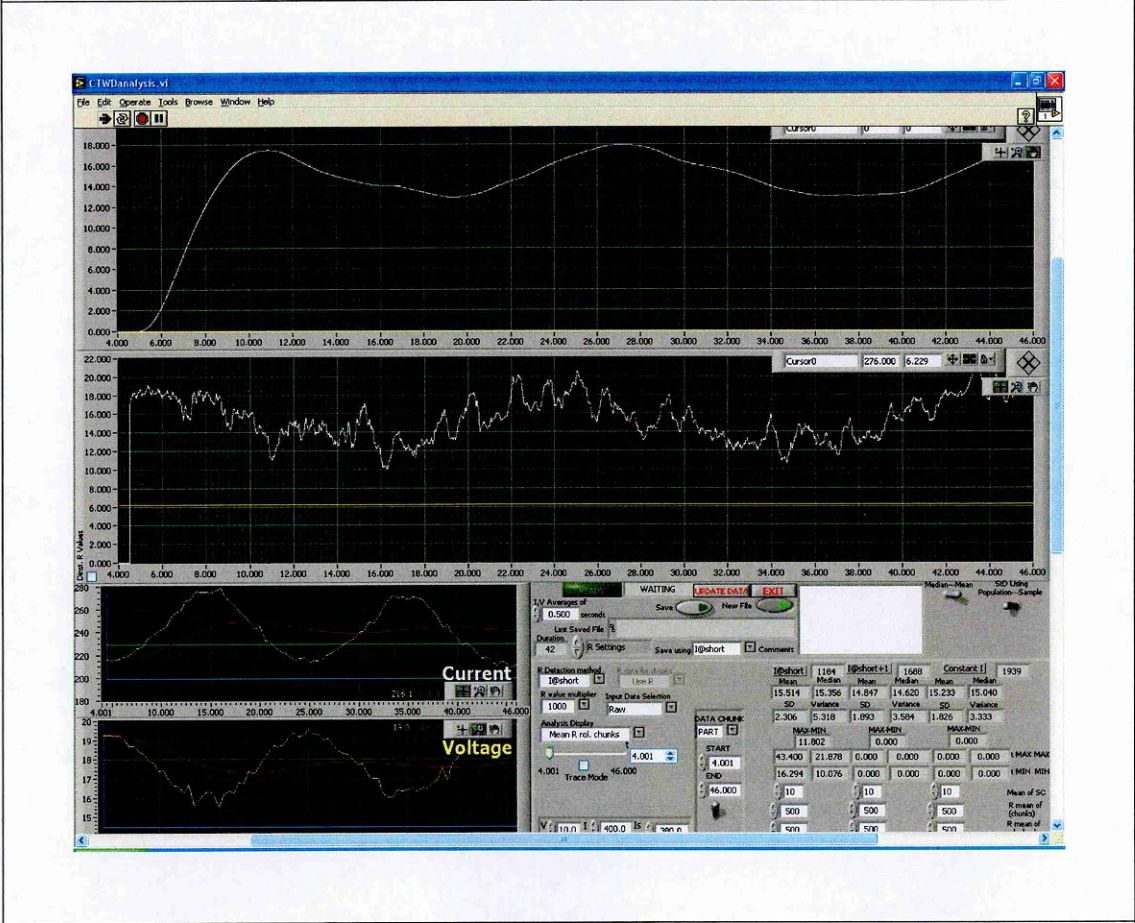


Figure 11-60: The resultant waveforms of the first run with two extended valleys and an extended peak.

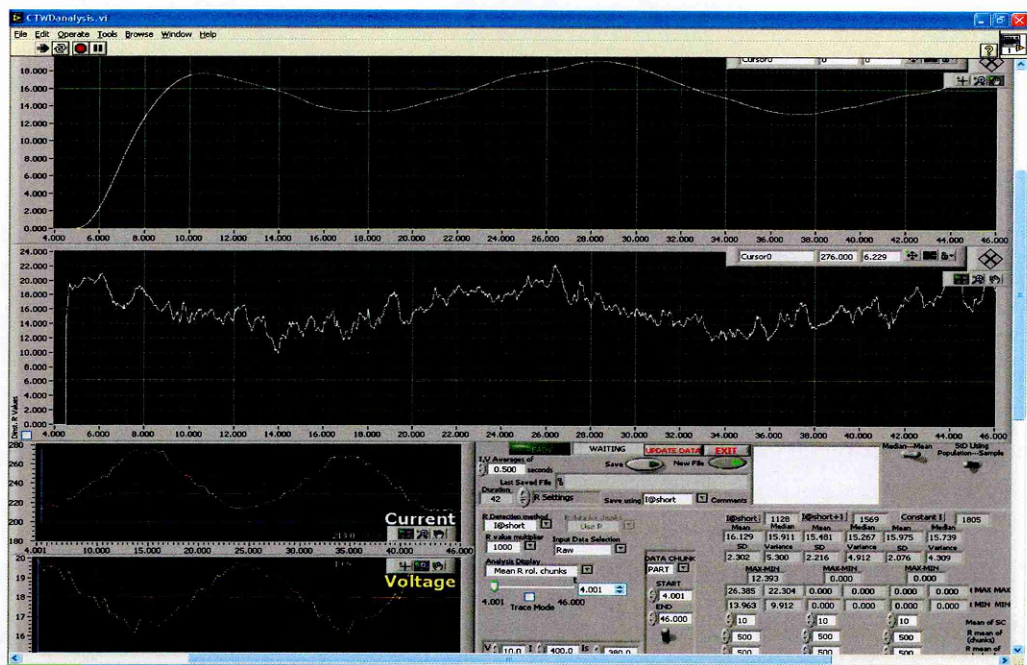


Figure 11-61: The resultant waveforms of the second run with two extended valleys and an extended peak.

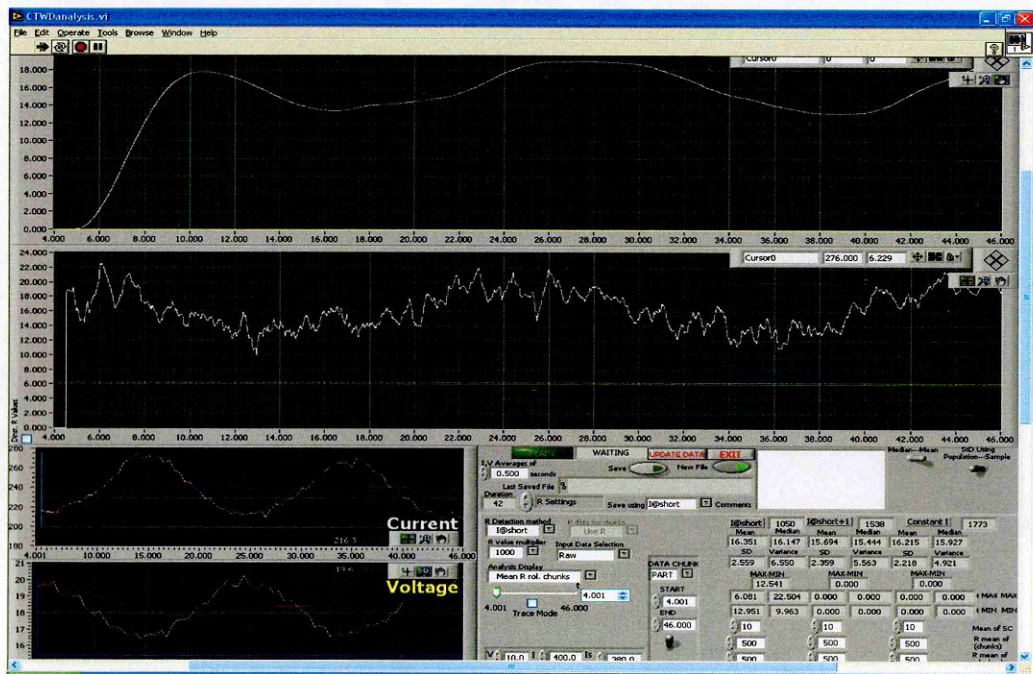


Figure 11-62: The resultant waveforms of the third run with two extended valleys and an extended peak.

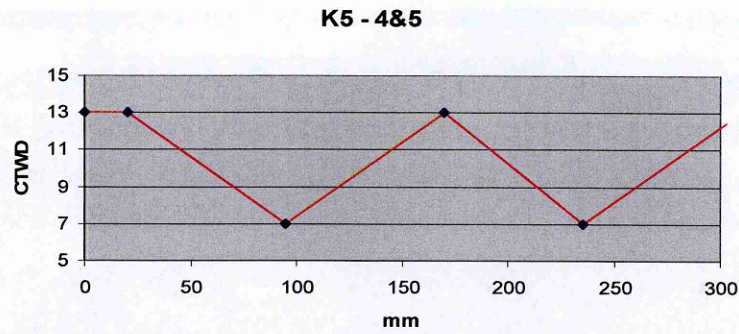


Figure 11-63: Graphical representation of the pre-programmed weave torch trajectory with two valleys and a peak.

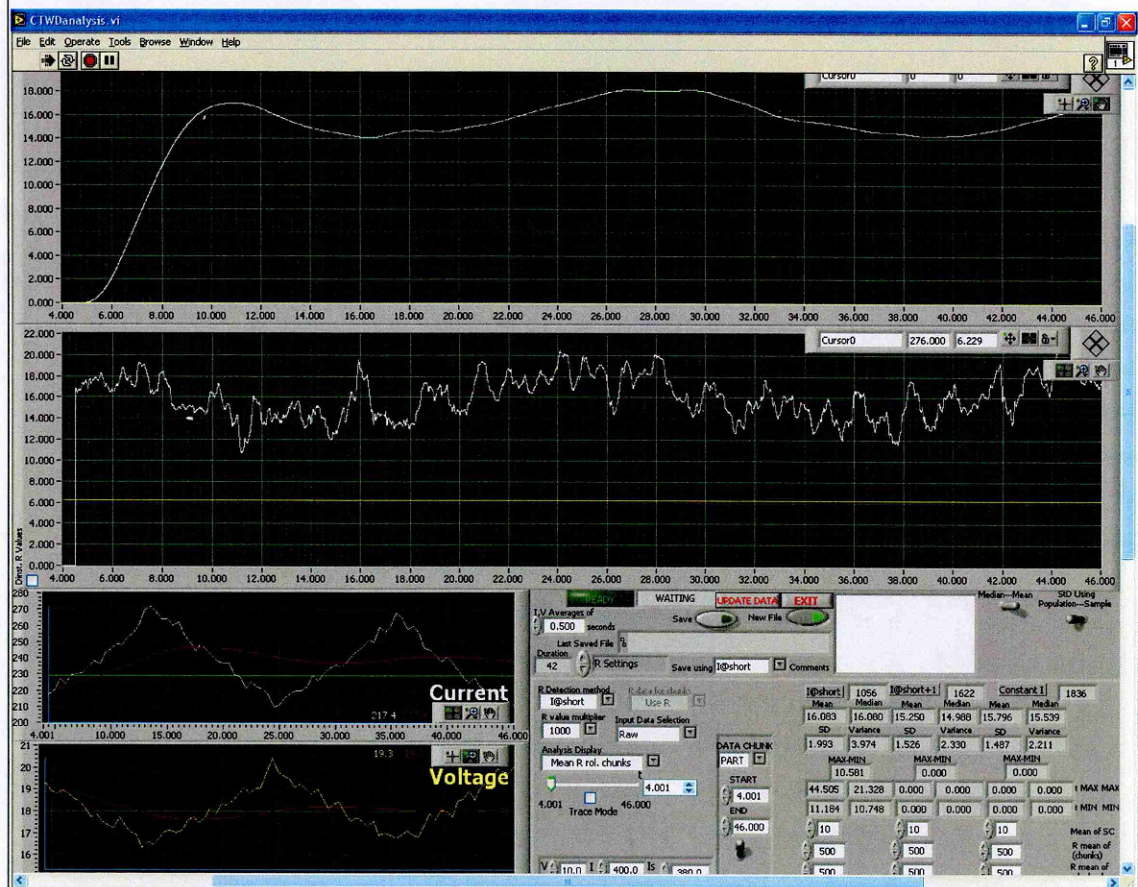


Figure 11-64: The result from the first run with two valleys and a peak.

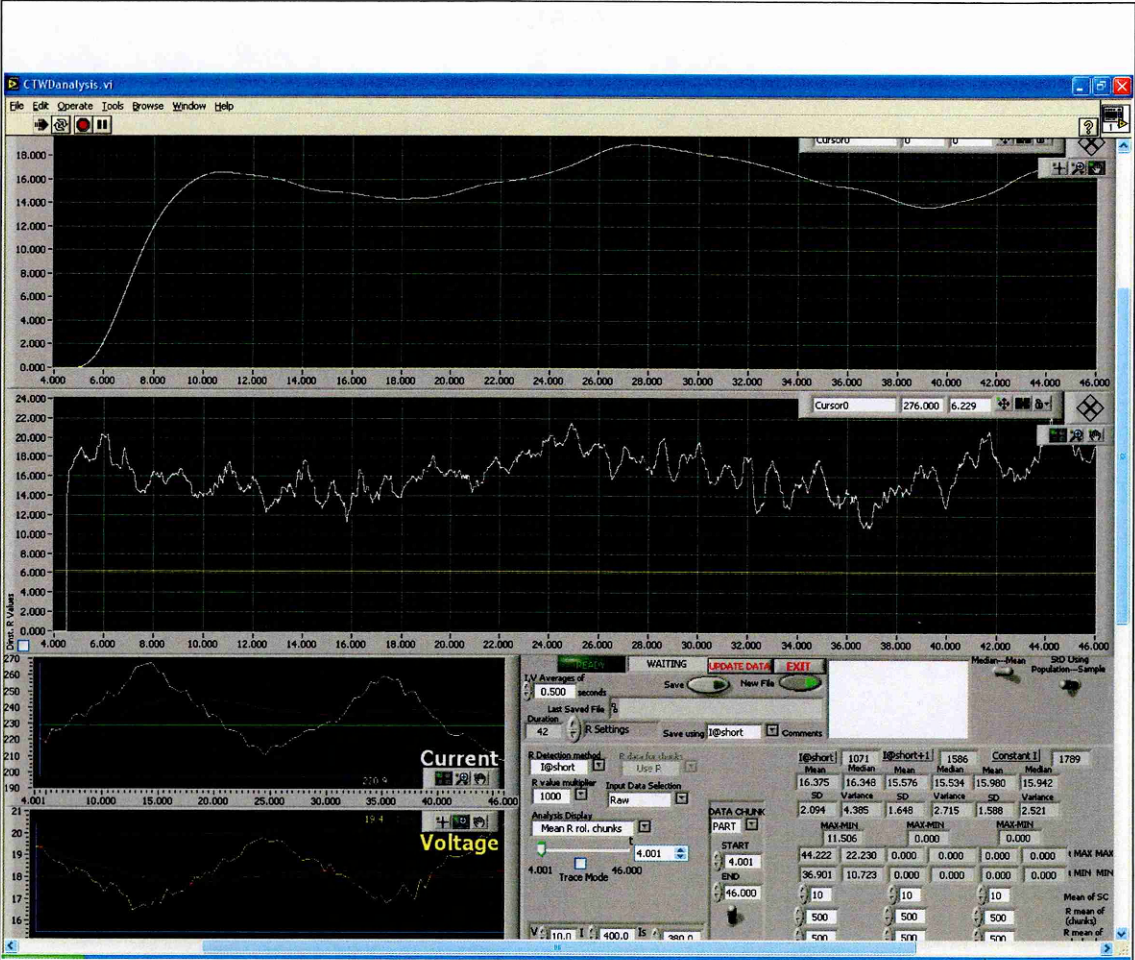


Figure 11-65: The result from the second run with two valleys and a peak.

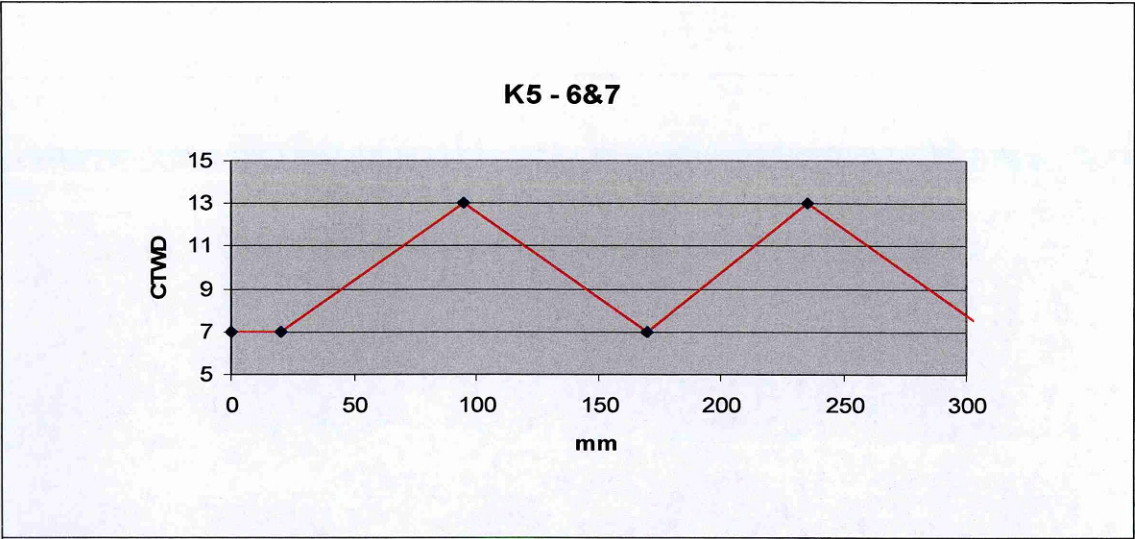


Figure 11-66: Graphical representation of the pre-programmed weave torch trajectory with two peaks and a valley.

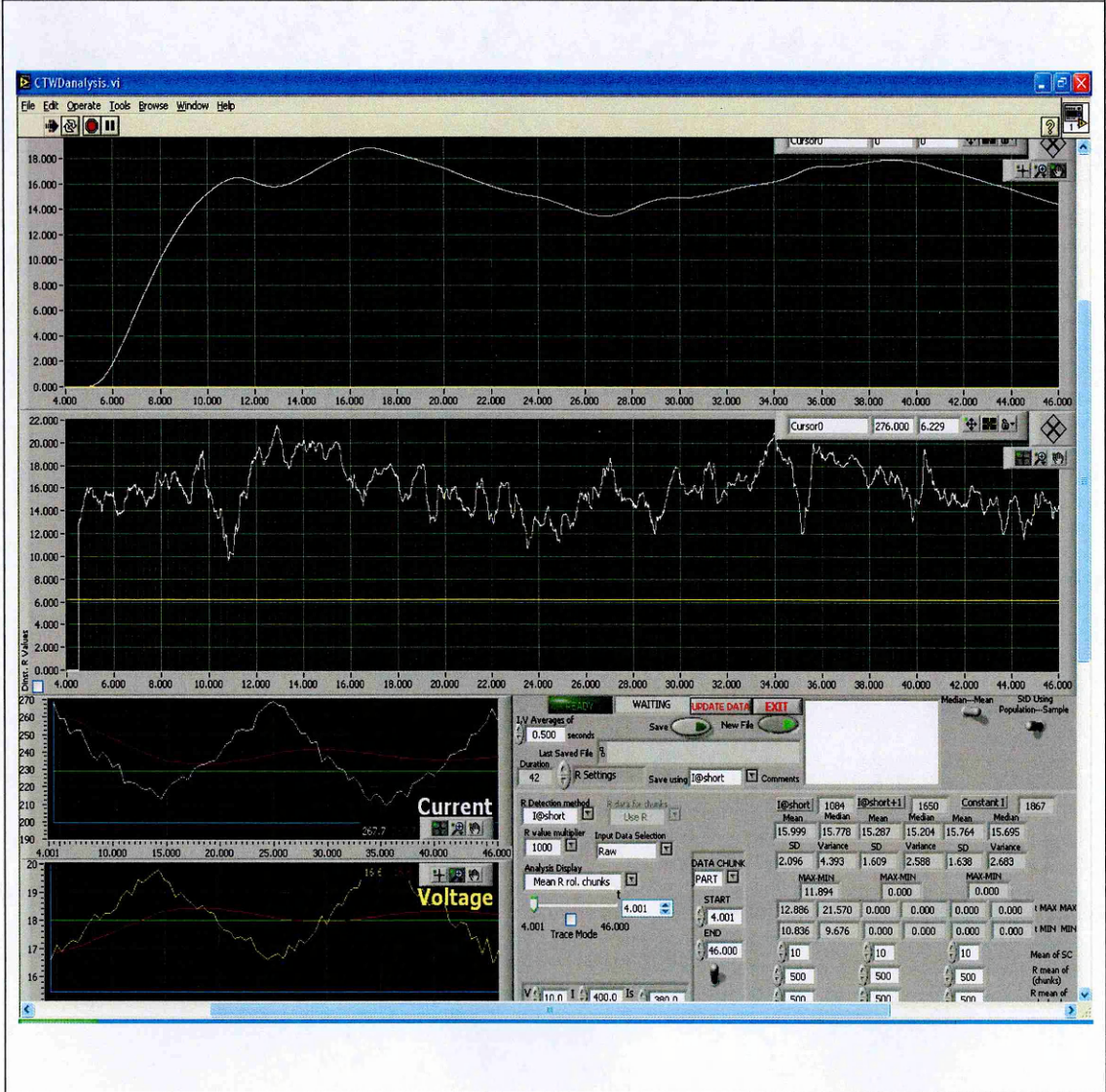


Figure 11-67: The results from the first run with two peaks and a valley.

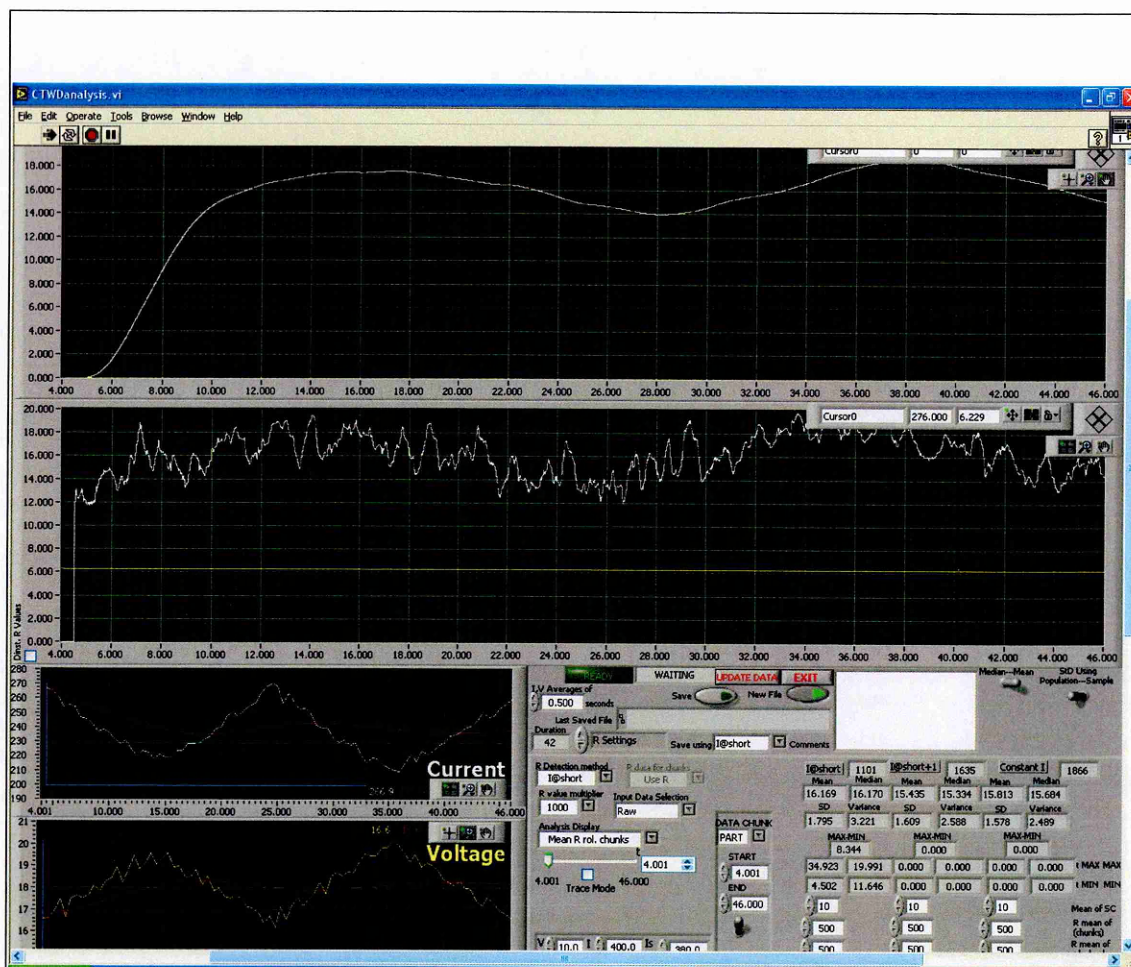


Figure 11-68: The results from the second run with two peaks and a valley.

Finally, two more slope welding runs were made in opposite directions. The trajectory of the first one, for which the welding torch was moving towards the electrode connection point on the welding table, is shown in Figure 11-69 and the resultant waveforms are shown in Figure 11-70. Figure 11-71 shows the torch trajectory for the second one, for which the welding torch was moving away from the electrode connection point on the welding table, and in the Figure 11-72 are the analysed results. The following observations were made:

- 1) The filtered and unfiltered rolling resistance averages still follow the trend of the CTWD,
- 2) The same is valid for the voltage and the current signals.

K5-8

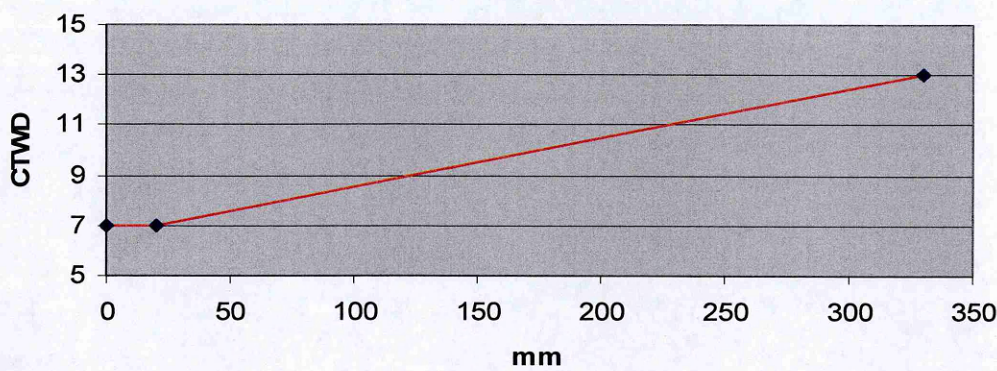


Figure 11-69: Graphical representation of the pre-programmed torch trajectory [CTWD 7 mm to 13 mm].

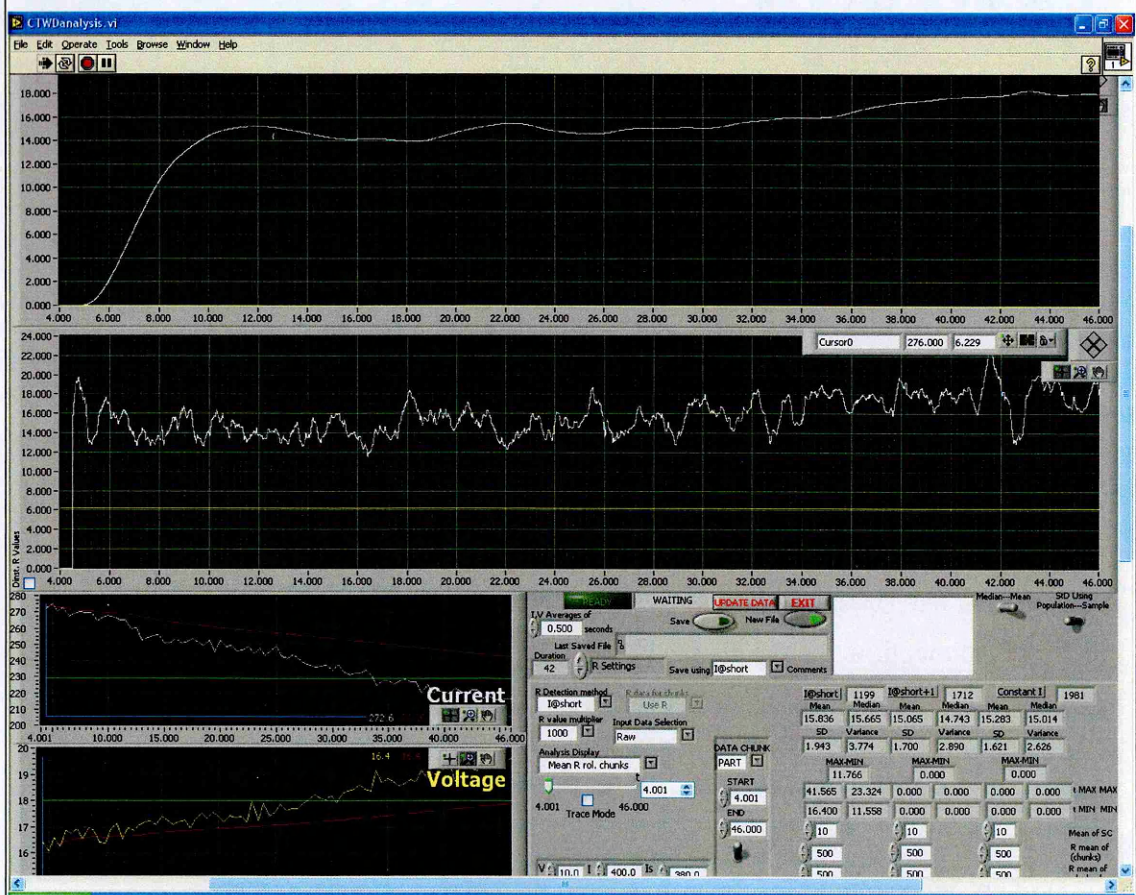


Figure 11-70: The results from the slope run with start at 7 mm and end at 13 mm.

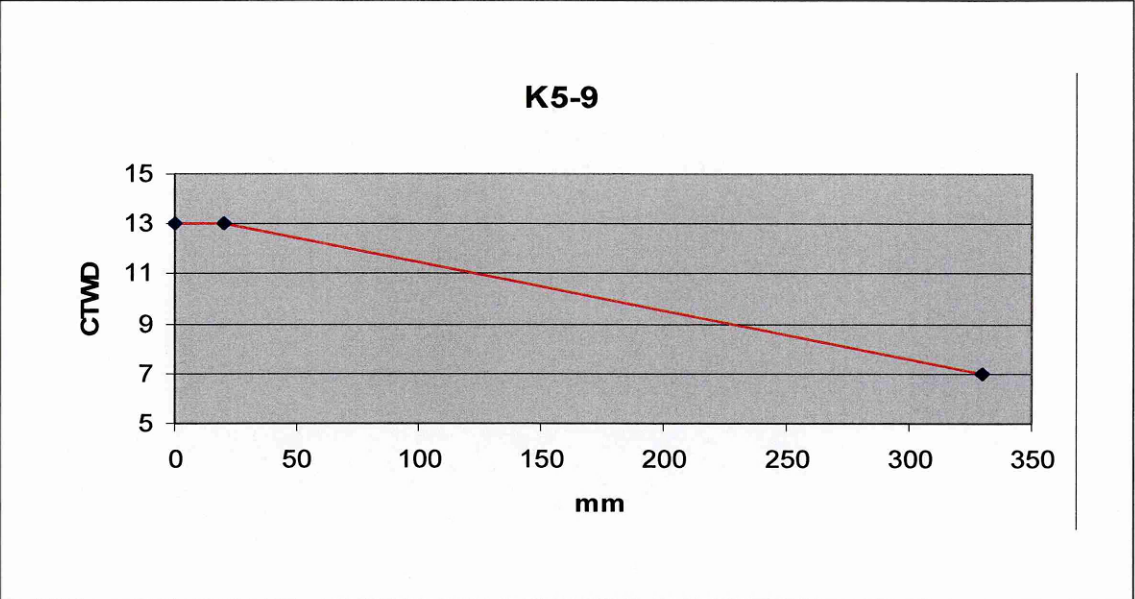


Figure 11-71: Graphical representation of the pre-programmed torch trajectory [CTWD 13 mm to 7 mm].

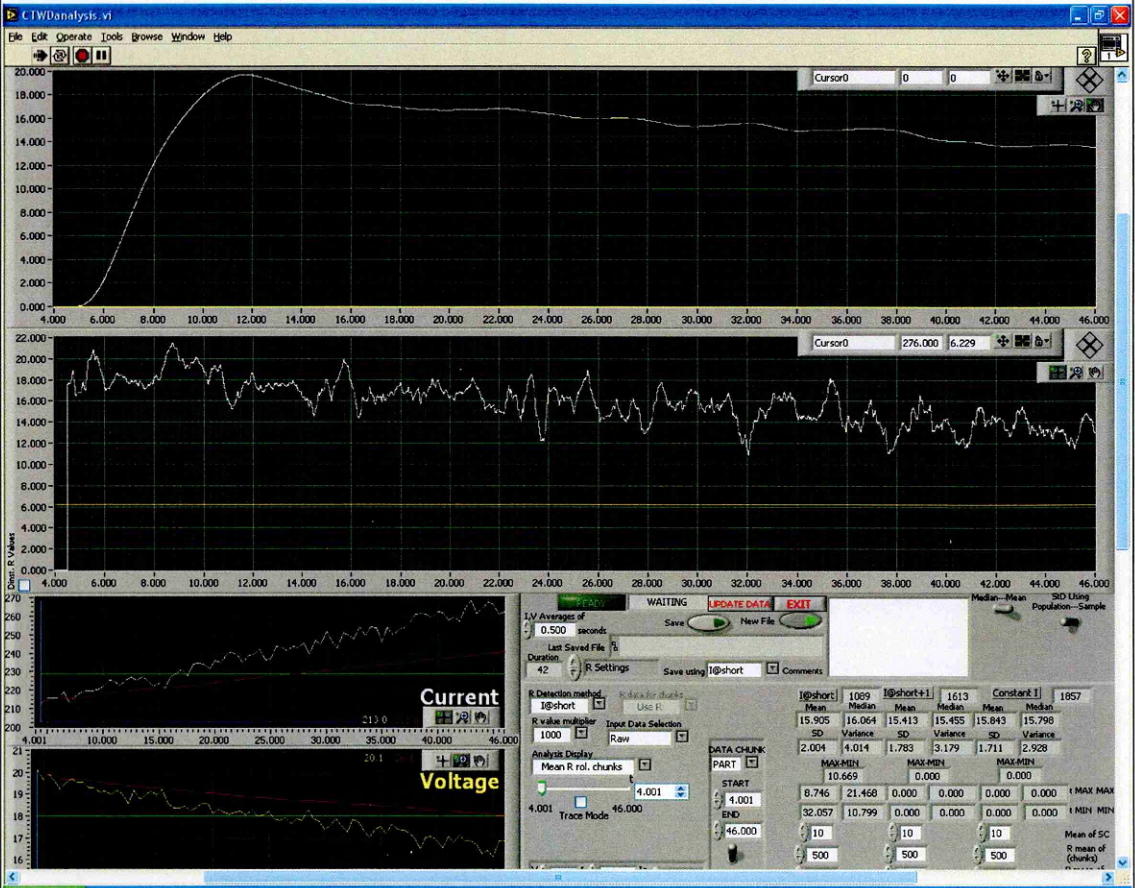


Figure 11-72: The results from the slope run with start at 7 mm and end at 13 mm.

12 Discussion of Results

The results obtained from the experimental work gave answers to most of the questions associated with measuring the dip resistance during short circuit occurrences in order to estimate and control the CTWD in real time. The three sets of experiments performed provided important observations regarding the factors involved in the method of dip resistance measurement. These observations are discussed next.

12.1 First Experimental Set Results

12.1.1 Initial Analysis

The initial analysis of the results showed that the raw values from the determination of the dip resistance on their own are not enough to give valuable information with respect to the CTWD value. The reason for this was the large fluctuations of the dip resistance values, even when the torch trajectory was such that the CTWD remained constant, an example of which is shown in Figure 11-1 and is in agreement with 1 Atm works - an example is shown in Figure 2-68. There were a number of different reasons for this. The most influential seemed to be factors that had to do with the process itself and the strategy which was used to detect the actual short circuit events. It appeared that there were a lot of local instabilities associated with the parent metal these could be local height or material composition alterations, electrical instability of the process as reported in Process Stability Vs. Electrical Stability [pp. 107] and influence from the weld bead and weld pool geometrical characteristics as reported in Influence of Weld's Bead Characteristics [pp. 118] and 2.5.3 respectively], influence from the welding equipment [inductance and possible operating tolerances], which as a result, had the short circuit frequency and the dip resistance value to fluctuate between very high and very low values. It was evident that some kind of analysis should be performed so as to reject these values and to keep only those that hold valuable information for the CTWD. These enormous fluctuations in the resistance values were significantly influenced from the strategy that was used in order to detect the short circuits during welding.

Detection Strategy

Depending on which strategy was used, the number of short circuits detected and their validity changed significantly, shown in Figure 11-2 to Figure 11-5, Table 11-1 and Table 11-2. The 'I@short' tactic seemed not only to detect fewer occurrences but also less false detections. The reason was that with this tactic both the voltage and the current should be inside the short circuit levels, otherwise the event was rejected as spurious input. This, in combination with the relatively slow sampling rate meant that the short circuits should have had a relatively long duration in order to be detected which in turn means that the process is indeed in a short circuiting phase.

The 'I@short+1' tactic gave more short circuit occurrences but with more erroneous detections. The reason could be that the delay in the welding current rise actually meant that in many of the events the process is not really in dip transfer mode, but the welding arc is present and its impedance actually confuses the results. Also, the influence of the inductance of the welding circuit with its natural tendency to object to voltage or current variations caused the latter to rise above its normal value in an attempt to keep unchanged the total power through the welding circuit.

The last tactic, the 'Constant I', gave even more short circuit occurrences from the other two tactics with even more errors. The reason was that this method examined only for the welding voltage values. Ideally, these values should only be low during a short circuit, and not in any other point of the process. It appears though, that it is normal for low values below the high voltage threshold levels to also exist during the processes. This fact meant that a lot of detected short circuit occurrences were actually wrong. The serious effect of the three tactics can be appreciated even better by looking at Figure 11-2 to Figure 11-5, Table 11-1 and Table 11-2.

Welding Parameters Trends

By averaging all the discrete values of a process parameter from each run and then by averaging the averaged values for each stand-off together, the possibility for a trend between the welding parameters and the CTWD was possible to be investigated, as presented in Figure 11-6 to Figure 11-13, Table 11-1 and Table 11-2. Also, the

verification of which one of the three tactics mentioned before would be the best one to be used could be studied as well as if there are any significant changes in the results by the use of the full data set or a truncated one.

Dip Resistance Trend

For the dip resistance, which was the main area of this research project, it was expected that there would be a clear tendency in the average value of the dip resistance to increase as the CTWD was increasing and to decrease as the CTWD was decreasing. This result was expected since according to Equation 2-3 [pp. 100], the electrical resistance of a current conductor increases as its length increases and larger stand-off means larger stick-out length for same welding arc length. The results showed that indeed this was the case for the 'I@short' tactic, as shown in Figure 11-2, Figure 11-3, Table 11-1 and Table 11-2. From the results it was also evident that the 'I@short+1' and the 'Constant I' tactic to detect the short circuits did not manage to follow a trend proportional with the CTWD variation like 'I@short' tactic did. This is justified by the appearance of the increased wrongly detected short circuits as mentioned earlier in Detection Strategy [pp. 284]. Additionally, the 'I@short+1' and the 'Constant I' tactic did not have a proportional trend with the CTWD value, and in addition it did not manage to keep the short-circuit frequency trend it had constant between the full and the truncated data set. Overall, the 'I@short' tactic seemed to have the same trend with either the full or the truncated data set.

It was thus concluded that the 'I@short' was the tactic that should be used in order to extract the most representative results of the CTWD from the dip resistance information as justified earlier in 11.1.1. Also, the truncated data set could be safely used cutting out the periods with the different parameters during the start and the end of the run which could give unstable results later due to the different process parameters as justified earlier in 11.1.1. An important point was that the resistance information seemed to make a step in the trend in the area of 8 mm to 9 mm for all three tactics, but most importantly for the 'I@short', as shown in Figure 11-2 to Figure 11-5 for the dip resistance and short circuit frequency and in Figure 11-6 to Figure 11-13 for the welding current and welding voltage parameters. This was very

important to be investigated even further, since this CTWD used in the RPRS is around this value. With the CTWD of 5 mm [vertical] that is wanted for the RPRS, the 8-9 mm CTWD in 45° is exactly the CTWD that is important for the RPRS as the welding torch weaves, which means that the problem with the step in the dip resistance waveform must be resolved before successful application of through-the-wire CTWD detection and control can be achieved. Another bend in the trend existed at around 12 mm CTWD as shown in Figure 11-2 and Figure 11-3 for the dip resistance for the tactic of interest, the 'I@short'. This is one more area to be investigated, but it was not considered to be extremely important since the value of the stand-off at which it appears it was not very important for the process. One possible reason for these two results might be that the process itself has this behaviour. Perhaps, the investigation of the process even at 1 Atm could help to solve this issue. Another possible reason, as explained earlier in 11.3, might be the fact that for the RPRS and these experiments welding torch tips with 1.2 mm opening in diameter and welding wire with 1 mm in diameter were used in order to allow the welding wire to slide easier through the tip and to prevent spatter to stack the wire inside the torch's tipp.

Short Circuit Frequency Trend

Another process parameter that was investigated was the short circuit frequency and the trend it followed as the CTWD was changing. It was expected that by increasing the CTWD the short circuit frequency should be reduced compared to its value with smaller CTWD. This should happen since the increased stick-out would allow for an increased welding arc length which would be more difficult to be covered from the filler wire and the transferred metal, thus the number of short circuiting occurrences should fall. This was verified in practice by studying the results shown in Figure 11-3, Figure 11-4, Table 11-1 and Table 11-2. Again, the 'I@short' tactic gave the most stable trend with the full and the truncated data sets. The 'I@short +1' tactic did not manage to keep a clear and constant trend for any of the data sets. Surprisingly though, the 'Constant I' tactic gave the best trend for the frequency parameter study, but only for the whole data set. The trend was not consistent with the truncated data set which suggested that the increased number of low welding voltage occurrences during the start and the end of the welding runs have a significant effect on the

parameter behaviour. Thus, this tactic was not considered to be a stable indicator. Finally, the step in the trend at the area of 8 mm to 9 mm CTWD appears in the short circuit frequency as well, indicating that indeed there is something that needs to be investigated for this CTWD range.

Welding Current Trend

The welding current behaviour is another important factor that was linked with the CTWD due to the fact that increased CTWD would allow for a larger stick-out, which means that the resistance of the welding circuit would increase and the welding current should reduce. With the same logic, a smaller CTWD would have as a result reduced stick-out and reduced welding circuit's electrical resistance, in other words the welding current level should go up. These CTWD variations were verified experimentally and the welding current seemed to follow a very stable trend in the change of its value with CTWD as shown in Figure 11-6, Figure 11-7, Table 11-1 and Table 11-2. The trend was the same for either the whole or the truncated data set. For the whole data set, the average welding current slope was shifted down for all the scale of the CTWD; this was due to the fact that the low current values during the beginning of the run were not included in the analysed data set. Again, the step in the trend between the 8 mm and the 9 mm was present.

Welding Current Deviation from Target Values Trend

One more parameter that was investigated was the deviation of the welding current from the target values of the process as shown in Figure 11-8, Figure 11-9, Table 11-1 and Table 11-2. This parameter appeared to follow the same trend with the welding current parameter. This was normal to happen, since the target values are set for the best welding quality results to occur, and correspond to a specific CTWD. By altering the CTWD, these parameters change from their optimum values and the deviation increases or decreases with CTWD. Again, the slope seemed to be shifted down for the whole data set compared to the truncated one, and once more the reason was the absence of the low welding current values during the initial phase of the runs. The step of the trend between the 8 mm and 9 mm CTWD is still there for either data sets.

Welding Voltage Trend

The next parameter that was studied was the welding voltage and its trend regarding the CTWD variations. The results of Figure 11-10, Figure 11-11, Table 11-1 and Table 11-2 showed that the welding voltage has a trend similar to the welding current but with reverse slope. This was normal since these two factors are interlinked and as the welding current goes up, the welding voltage goes down because the welding circuit resistance decreases as Ohm's law describes [Equation 2-5, pp. 100]. Consequently, as the welding current goes down the welding voltage goes up since the welding circuit's electrical resistance increases. This time, the slope for the whole data set was shifted up compared to the truncated data set, since it includes the higher welding voltage levels during the first seconds of the welding run. The step in the trend around the 8 mm and 9 mm CTWD is also noticeable in this parameter as well. Also, a second bend exists at 12 mm stand-off as per the dip resistance trend. This means that the welding voltage information is more sensitive to the process compared to the welding current and its sensitivity is similar to the dip resistance. This can be attributed to the smaller range of values of the welding voltage compared to the welding current; because of this difference, the same percentage of deviation will be more noticeable in the welding voltage parameter compared to its effect on the welding current parameter. It also verifies that there was a change in the process during welding and that the appearance of the bend at the dip resistance results was not due to any errors in the calculations.

Welding Voltage Deviation from Target Values Trend

The final parameter that was investigated was the deviation of the welding voltage from the target values. Again, the results in Figure 11-12, Figure 11-13, Table 11-1 and Table 11-2, showed a trend between the deviation and the CTWD, which was expected since just like the welding current target values, the welding voltage target value had been set for a specific CTWD. This time the slope from the whole data sets had been shifted up because the welding voltage averages were including the higher welding voltage values during the beginning of the welding run. The step and the bend in the trend appear in this case as well, like in the case of the welding current deviation analysis, something that was expected since calculation of the deviation is

based on the average welding voltage values which have been influenced by a process change as stated above in Welding Voltage Trend [pp. 288].

12.1.2 Further Analysis

The off-line analysis of the various parameters as discussed previously gave significant results for the behaviour and the trend of these parameters compared to the CTWD. Nevertheless, these results were obtained off-line after all the data had been acquired. The use of the same analysis for real-time CTWD estimation and control was obviously not adequate. The only way for a real time system to work would be to process the real-time signals in parallel with acquisition.

Dip Resistance Real Time Statistical Analysis

As mentioned earlier in 11.1.1 and 11.1.2, the raw resistance values shown in Figure 11-1 are not suitable for the estimation of the CTWD due to the large fluctuations these values have because of erroneous detections of short circuits. Thus, some sort of analysis should be used in order to extract the required information and reject the errors. These errors occurred when the tactic used to detect a short circuit was detecting a minimum peak value in the welding voltage and a maximum peak value in the welding current, both inside their threshold limits. Thus, given the fact that a way to minimize the erroneous detections of short circuit occurrences was to lower the welding's voltage threshold upper limit the effect of the upper threshold level on the final result and threshold values of 6 V, 8 V and 10 V were investigated.

One of the most common ways of statistically treating such signals is to average the values over a period of time. This way [assuming that the number of errors is much less than the correct detections] the influence of the erroneous value can be minimised. Analysis of the offline data in the analysis program showed that the best results were obtained when the use of a rolling average of 500 samples was used [equivalent to 0.5 second of data in this case of 1 kHz sampling rate]. The resulting graphical data with this kind of analysis had a much more smooth appearance compared to the other attempts of statistical treatment as reported in 11.1.2.

From the analysis of the dip resistance raw data with the method described above, the results looked completely different. The results are graphically shown from page 237 to page 245. The graphical representation of the dip resistance data from the runs at various stand-offs showed that the resistance information looks smooth and although variations exist, these are limited to a much smaller scale values of the order of μOhms , an example being shown in Figure 11-14. The comparison of the runs between them showed that although the information from the three runs is consistent around the same values of the scale, looking at distinct periods of the runs, there are times that the values between them are very different, an example is shown in Figure 11-14 between 11.5 seconds and 12 seconds. Whilst the runs were made one next to the other with a minimal gap between them as possible so as not to overlap, the results suggested that differences in values were due to the inherent instabilities of the process. This is not shown in the weld bead itself but metallurgical analysis is required in order to be able to say that with certainty.

The Influence of the Threshold Levels

In addition, from the results it was evident that as the upper voltage threshold value was increasing, the overall dip resistance data and short circuit frequency data were shifted up. This could be explained from the fact that as the frequency of the short circuit occurrences rose with rising threshold level, it resulted in more wrongly detected short circuits being taken into account. Based on the fact that the wrongly detected short circuits include the influence on the arc impedance, and considering that in such a case the welding voltage will appear to be higher means that in turn the dip resistance will appear higher according to Ohm's law, shown in Equation 2-5 [pp. 100]. As a result, the introduction of the false short circuits inside the data was rising causing the overall dip resistance value to rise.

The easy solution would be to keep the threshold values low. Unfortunately, this could not solve the problem. It appears that, as the CTWD level was rising the voltage threshold should rise as well. This can be seen easily by looking at 7 mm CTWD Figure 11-14 [6 Volts upper welding voltage threshold] and Figure 11-16 [10 Volts upper welding voltage threshold]. In this case, the low threshold gave a smoother output best suited for CTWD control. On the other extreme, for 13 mm

CTWD shown in Figure 11-26 [6 Volts upper welding voltage threshold] and Figure 11-30 [13 Volts upper welding voltage threshold], the low threshold resulted in sudden changes of dip resistance measurement, hence CTWD estimation, not suitable for CTWD control. Based on these two examples, it is concluded that if the upper welding voltage threshold value is not shifted up as the CTWD increases, then there will not be enough short circuits to produce a smooth transition from one value to another and the output seems to have step changes. This was evident by the fact that at large values of the CTWD with low voltage upper threshold, the short circuit frequency even dropped to zero at some intervals as shown in Figure 11-27. The situation Figure 11-27 describes where a 6 V upper welding voltage threshold was used could only be rectified by using a higher level of voltage threshold, as Figure 11-31 demonstrates where a 10 V upper welding voltage threshold was used.

The above suggests that there is no strict golden rule for the voltage upper threshold value. It was also evident that just a few short circuits could not produce a smooth dip resistance output as is evident from Figure 11-26, something that was necessary since the method was investigated in order to be implemented in a control system. Thus, the acceptance of a few errors is necessary in order to make the transition of the dip resistance values smoother, but if the number of errors becomes more than necessary, then the total outcome will be negative.

All of the above suggest that it is necessary to use the value of another parameter of the process, for example overall average voltage of all the acquired values, so as to alter in real time the voltage high threshold values according to the value of that parameter.

12.1.3 Min, Max and Average Analysis

Combining the previous analysis of 11.1.1 and 11.1.2 but this time using the average from the three passes of each stand-off of the minimum and maximum values of the resistance rolling average analysis suggests that in some cases the results are not as linear as the average of the averages presented in 11.1.1. This could be explained by the fact that this analysis was looking at the extremes as well [minimum and maximum values] of each welding run. As Woods and Milner [74] reported in [74] and is presented in General Discussion [pp. 132] arc welding exhibits a notorious behaviour for lacking reproducibility even under rigorously controlled conditions [74]. Since each welding run can exhibit significant differences with the others at the same stand-off, it is normal for the outcome to appear less consistent.

Dip Resistance Min, Max and Average Analysis

The analysis and use of the overall resistance rolling averages to investigate the existence of a trend between these values and the CTWD at different voltage upper threshold levels showed that the trend still exists as shown in Figure 11-32 to Figure 11-34 and Table 11-4 to Table 11-6. The step on the trend between 8 mm and 9 mm was still shown, which as expected and is justified from the fact that these results are effectively a smoother representation of the raw resistance values. A very important observation was that in the case of the 6 V welding voltage threshold, the resistance value above the 12 mm CTWD appeared to be lower than that at the 12 mm CTWD as shown in Figure 11-32 and Table 11-4. However, the trend tended to be more linear when the higher upper voltage threshold was used as shown in Figure 11-34 and Table 11-6.

Short Circuit Frequency Min, Max and Average Analysis

By analysing the average from the three passes at each stand-off of the average short circuit frequency the parameter had similar results to the rolling resistance averages; the results are shown in Figure 11-35 to Figure 11-37 and Table 11-7 to Table 11-9. However, in this case, the step between the 8 mm and 9 mm and the bend at 12 mm was more evident. In addition, none of the three voltage thresholds managed to produce an output with almost linear trend like in the case of the rolling resistance

average with the 10 V welding voltage threshold. This indicates that the short circuit frequency trend might not be as reliable and suitable to base the CTWD estimation.

Welding Voltage Min, Max and Average Analysis

When the analysis of the average of the minimum and maximum voltage values of the three passes in combination with the average values at each stand-off was made, the results were that the extremities of the voltage values are from almost 0 V to more than 35 V as shown in Figure 11-38 and. In some cases, the analysis showed that these values could become extreme, for example at 13 mm CTWD. For the case of the welding voltage, the average values suggest a linear relationship with CTWD although the minimum and maximum average values experience the steps at 8 mm, 9 mm and 12 mm. as shown from the tabulated data in Table 11-10 and the graphical representation of Figure 11-38. This suggested that the welding voltage on its own was not a reliable parameter for the estimation and later control of the CTWD as in real conditions welding conditions might shift the average up or down closer to minimum or maximum levels respectively.

Welding Current Min, Max and Average Analysis

Finally, the averages of the minimum and maximum values from the three runs for each stand-off for the welding current shown in Figure 11-39 and Table 11-11 produced a result very similar the results for the welding voltage. As in the case of welding voltage, the average welding current values suggest a linear relationship with CTWD; again, the minimum and maximum average values experience the steps at 8 mm, 9 mm and 12 mm. as shown from the tabulated data in Table 11-11 and the graphical representation of Figure 11-39. Again, the minimum and maximum trends with respect to the CTWD showed that during welding, using just the welding current might not be as reliable as it should be so as to assist in the CTWD estimation and control as in real conditions welding conditions might shift the average up or down closer to minimum or maximum levels respectively.

Low Pass Filters Implementation

From the analysis of the resistance rolling averages which is shown graphically from pp. 237 to pp. 245, it seemed that the fluctuations in the values were relatively slow

over time, but the signals had a higher frequency “noise” on them. For that reason, a digital implementation of the Butterworth filter was implemented in the analysis program. After trials, it was found that the best tactic was to use three filters in series each of second order but with different cut-off frequencies. The use of three filters allowed for the signal to be smoothed gradually and to keep the overshooting of the output to a minimum. If one filter was used the cut-off frequency should be set very low since the beginning and the overshooting was slightly larger, as well as the rise time which was also larger. The order of the filters was the best trade-off between smoothness of the output signal and overshooting. With lower filter order, the overshooting was even less, but the output signal was not as smooth as with the higher order. However, if the filter order was increased even more, then the overshooting and the rise time of the output was becoming even bigger something that it was not wanted, since the output should reach the value that is representative of the CTWD as soon as possible. When the combination of the filters above was used to filter the resistance rolling average traces, the results were indicative of what was needed. The filters produce an output, which level changes as the CTWD changes as shown in Table 11-13 the results of which represent the graphical data on the top waveform of Figure 11-40 to Figure 11-46.

The fact that the output values appears to follow the trend of the resistance rolling average shown in Figure 11-34, suggest that the filtering of the signals actually is the missing link between the real-time analysed statistically treated raw data and the trends produced from the off-line analysis. This can easily be justified by looking at the tabulated data on Table 11-6 [‘avg’ column] and Table 11-13 and the graphical data on Figure 11-34 and the top waveform of Figure 11-40 and the top waveform of Figure 11-43. From Table 11-6 the average dip resistance value for 7 mm and 10 mm CTWD are 14.012 mOhms and 16.401 mOhms respectively. In Table 11-13, the dip resistance values for 7 mm and 10 mm CTWD are 14 mOhms and 16.5 mOhms respectively, values very close to the ones of Table 11-6. These two values of Table 11-13 can be visually obtained by looking at the top waveform of Figure 11-40 and the top waveform of Figure 11-43 where the filtered output is presented. From these it is concluded justifiable to suggest that this could be the basis for a digital control system.

Nevertheless, further investigation is required in order to match the values even closer and to make the rise time and the overshooting of the filtered output even smaller. This is deemed necessary as at the moment in the case presented in Figure 11-40, the rise time [from 10 % to 90 %] is approximately 3 seconds and the overshooting is approximately 7.15%. As, for example, Figure 11-40 shows, some slow fluctuation on the output signal still exists, but it seems promising that with the implementation of the method that Di Pietro *et al.* [12] presented in 2.5.4 used for the output, in other words the use of thresholds before the torch position was altered, the system can effectively estimate the CTWD and provide adequate information for control.

12.2 Second Experimental Set

Following the previous results, the next set of experiments was designed in such a way so as to examine the response of the filtered signal as the CTWD was changing during the run. Also, experiments were made so as to investigate the influence of the welding electrode connection point on the welding table and the temperature with the dip resistance measurement estimation in Hyperbaric Welding.

12.2.1 Welding Electrode Connection Point on the Welding Table and Parent

Metal Temperature

In order to determine the influence of the location of the welding electrode connection point on the welding table with the dip resistance, two runs were made in opposite directions with constant CTWD and the results are shown graphically in Figure 11-47 and Figure 11-48. If the welding electrode connection point on the welding table affects the results, then the dip resistance information should produce a slope output which would show an increase of the dip resistance value as the torch was moving away from the welding electrode connection point on the welding table. In order to maximize the effect even further, 350 mm long runs were made. The results however did not show any influence from the welding electrode connection point on the welding table and the dip resistance information. However, it should be recognised that this result was based on a specimen with relatively small dimensions. In the real system where the dimensions of the parent metal will be extremely large compared to the specimen, the results might be different. In that case, one possible solution would be the connection of the welding electrode connection point on the welding table in multiple locations around the pipe.

A minimal investigation of the parent metal temperature influence was made during the same runs. In the first run the parent metal was less warm than in the second run. Since the resistance of the steel rises with increase in temperature, and if the temperature plays a significant role, it should show a shift upwards for the resistance values of the second run. The results however did not indicate that this was happening. This might be due to the fact that the temperature change in the parent

metal was not enough so as to produce a significant change in the resistance, detectable by the instrumentation and/or the analysis performed.

12.2.2 Ramp Response

The next part of the experiment had to do with the investigation of the sensitivity and speed of the system response in a ramp input. Again, two runs were made, one uphill and one downhill so as to investigate the influence of the welding electrode connection point on the welding table and temperature on the data obtained. The results are shown in Figure 11-49 to Figure 11-52.

The results showed that the system senses the change of the CTWD during the welding. This is evident not only in the rolling average resistance values but also in their filtered version. The change in the CTWD is also clearly evident in the welding current and welding voltage traces, which suggests that these signals could be used for the adjustment of the upper voltage threshold. One important observation was that in the downhill run, the filtered signal showed to have a step around the 9 mm stand-off as can be seen by comparing Figure 11-51 and Figure 11-52. Although the signal was not a straight line and this could not be said with absolute certainty, its appearance might mean that the system is sensitive to that as well something that has been analysed and explained earlier in Influence of Weld's Bead Characteristics [pp. 118] based on the results of Orszagh *et al.* [52] and Orszagh *et al.* [54] and is shown graphically in Figure 2-73 and is also correlated with the weld pool in 2.5.3 Further investigation in the following runs would help to clarify and quantify the effect in the case of hyperbaric welding for the RPRS. However, the results were positive and promising that with further development, the system could become even more adequate for implementation.

Once more, the welding voltage and welding current values presented in the small waveforms on the bottom left corners of Figure 11-50 to Figure 11-52 seemed to have a trend that follows the slope of the ramp. This adds up to the previous suggestion made in Welding Voltage and Welding Current [pp. 223] that these signals could be used as complementary to the dip resistance information for CTWD estimation.

12.2.3 Wave Response

In order to investigate the behaviour of the system even further, experiments were made where the torch trajectory was a wave. Three wave patterns were tried out. One had with two valleys and a peak with the results shown in Figure 11-53 and Figure 11-54, one with one valley and two peaks the results of which are shown in Figure 11-55 and Figure 11-56 and finally one with two valleys and a peak, but with extended time in the valleys and the peak periods with the results shown in Figure 11-57 and Figure 11-58.

Once more the results seemed to be positive. The dip resistance output seemed to have a trend that followed the slopes of the wave pattern as shown by the filtered output in the upper waveforms of Figure 11-54, Figure 11-56 and Figure 11-58. This was shown in the welding voltage and welding current as well as can be seen from the waveforms at the lower left corner of Figure 11-54, Figure 11-56 and Figure 11-58. Also, two very important observations were that the step that appears between the 8 mm and 9 mm does not appear to happen in every occasion. This seems to suggest that the earlier hypothesis that this step occurs because of the slack of the wire inside the welding torch and the conduit is the reason for this behaviour. If it was a process characteristic, it should be something that would always appear. In addition, the resistance during the lowest part of the second valley seemed to be increased compared to the resistance during the first valley of the run as shown in the upper waveforms of Figure 11-54 and Figure 11-58, although the downhill gradient of the slope was detected correctly. This could also suggest that the contact of the filler wire and the torch tip is moving up and down, depending on the force that is applied back to it from the welding pool and the parent metal and it cannot be a lag in the response of the system, since the gradient of the slope was the same for both valleys in the same welding run.

12.3 Third Experimental Set

The second set of experiments and its results strengthen the hypothesis that the diameter of the welding torch's tip is the reason for the step between the 8 mm to 9 mm CTWD and possibly for the bend that appears at 12 mm CTWD as explained in Dip Resistance Trend [pp. 285]. Thus, this set was effectively a repetition of the second experimental set, only this time more runs from each pattern were carried out so as the results to be more representative. Also, the welding torch's tip that was used had an opening of 1.0 mm in diameter instead of 1.2 mm.

12.3.1 Wave Response

The results from the wave runs showed that the step between the 8 mm and 9 mm is still evident but it is much smoother. Also, the resistance during the valleys seemed to be almost equal except from one occasion where the first valley seemed to have higher resistance. However, the overall dip resistance value seemed to be shifted down compared to the value in the second experimental set. This can be attributed to the fact that the welding wire was touching the welding torch's tip closer to the exit point as a result of the smaller welding torch's tip diameter compared to the case of the welding torch's tip used for the first and second experimental sets. Again, the welding voltage and welding current traces had a trend that followed the wave pattern. However, by comparing the welding voltage's and welding current's waveforms shown on the bottom left part of Figure 11-58 and Figure 11-60 the following can be said. For the welding current, its trace seemed to be smoother compared with the correspondent runs from the second set of experiments and its value was shifted up. The trace of the welding voltage trace was shifted down in value [consistent with Ohm's law shown in Equation 2-5 [pp. 100]] as the welding current went up and in general it can be said that it also had a smoother appearance. These results are really important since the direction in the shifting of the welding current and welding voltage suggests that the overall dip resistant was lower, something that it was evident anyway from the resistance trace itself suggesting that indeed the contact of the welding wire with the welding torch's tip was now done in a point closer to the parent metal and the smoother appearance indicate that the location of point(s) of contact which feed the welding current to the welding wire is now fixed.

12.3.2 Ramp Response

The results from the ramp patterns, shown graphically in Figure 11-69 to Figure 11-72, had, in general, the same outcome as the results from the wave patterns. Again, the welding voltage seemed to be shifted down and the welding current up, which suggested that the overall resistance was less. Also, in general terms the traces were smoother compared to the results from the second experimental set; an example of this can be seen by comparing the graphical results of Figure 11-50 and Figure 11-70. Once more, the trend in the dip resistance, welding voltage and welding current was to follow the slope of the welding pattern. Like in the case of the second experimental set, the step between the 8 mm and 9 mm CTWD was not clear.

However, the overall results suggest that the change in the welding torch's tip diameter from 1.2 mm to 1 mm was giving positive results. It would appear that the point of contact of the filler wire with the welding torch's contact tip is more stable [as mentioned earlier in 12.3.1] and that the results are more consistent.

12.4 General Discussion

From the experimental work that was carried out during this research project, the results produced gave rise to some issues. These issues are discussed next.

12.4.1 Dip Resistance Values

The first issue was the dip resistance values measured. Although the filler wire appears to have a resistance of no more than 192 μOhms per mm at room temperature (measured with the aid of a resistance measurement bridge), the values seem to reach tenths of milliohms for just a few millimetres. This can be explained from the fact that the overall resistance that is measured includes the resistance of other parts that are in series with the measuring leads that sense the welding voltage, for example like the specimen's resistance or the contact's resistance, makes the location of the pick-up points and the length of the welding circuit's electrical path and geometry can be important as analysed in Weld Pool's Characteristics [pp. 120].

12.4.2 Welding Parameters Combination

Earlier in The Influence of the Threshold [pp. 290] it was suggested that the CTWD estimation could be improved by dynamically altering the upper threshold value of the welding voltage. This could be done by using another welding parameter in parallel with the dip resistance information, like the welding current or the voltage itself, to control this threshold. From the results, it appeared that the best parameter to use was the overall welding current or the overall welding voltage averages since their variation seems to be very smooth something that would improve the stability of the method.

12.4.3 Welding Current and Welding Voltage as Control Signals

From the results it is apparent that the welding voltage and welding current waveforms give a pretty good estimation of the CTWD. However, there is a problem if one of these is going to be used. The problem is that under hyperbaric welding conditions, there are instantaneous [41] or prolonged periods where the welding arc is extinct [69]. For the RPRS it has been reported [78] these periods to be around 20 ms

to 30 ms as shown in Figure 2-18 [78]. During welding arc extinction without the welding wire dipping into the weld pool, the welding voltage goes to its highest possible value for the power source's settings and the welding current goes to zero. Thus, even if these signals were statistically treated, for example by averaging, it is possible that the averaged values would be far from what they should normally be according to the CTWD. As a result, such a method of estimation and control would be inadequate to be used by its own.

12.4.4 Time Lag

From the analysis it appeared that the parameters like the overall welding voltage and overall welding current of the filtered output of the analysis program have a time lag of about three seconds with smooth changes in the process. This value might seem large, but for the hyperbaric welding for the RPRS this is not a big time delay since the changes of the pipe ovality are not expected to be steep.

12.4.5 Significance of the Welding Torch's Tip Diameter and Its Influence on the RPRS

The third experimental set showed that the welding torch's tip diameter used for the RPRS program to date, which has been used for the first experimental sets of this work as well, create a slight difficulty in the exact CTWD estimation from the dip resistance information due to the slack of the wire and presumed contact point within the tipp. One solution could be the use of a smaller diameter tipp.

13 Conclusions

The work undertaken during this research project fulfilled the aim of establishing the feasibility of the method of dip resistance monitoring for the estimation and control of the CTWD under Hyperbaric Welding conditions.

The research and development of a combined hardware-software Through-The-Wire system to estimate the CTWD via the dip resistance information and provide the basis for CTWD control has been achieved. The use of a relatively inexpensive hardware and software setup was satisfactory for the RPRS's hyperbaric MIG welding process to be monitored and controlled accurately in real-time.

The investigation of an algorithm for the detection of a short circuit event in 1 Atm GMA welding and the welding wire's resistance value has been fulfilled based on experimental data analysed with MS Excel[®]. It was shown that slow sampling rate of 1 kHz can be adequate for short circuit event detection and dip resistance value determination. Nonetheless, for detailed process analysis especially with a scope beyond the through-the-wire dip resistance based CTWD control, higher sampling rates must be implemented. The results for the fluctuation of the dip resistance value were in agreement with the work from other researchers for 1 Atm GMA or even other types of processes. The capacity of MS Excel[®] for off-line data analysis was proven inadequate for the wealth of data that can be collected and analysed so as to evaluate the GMA process.

The time invested in determining the hardware requirements for a data acquisition system for welding applications and in developing the combined hardware and software data acquisition system gave results. The system has been developed, successfully tested and commissioned in the permanent instrumentation of the Hyperbaric Lab in Cranfield University during this research project. This system is now routinely in use and will continue to operate and be further developed in parallel.

The realization and implementation of a PC based DAQ system customized with the use of the graphical programming language LabVIEW 7.1 is a very good solution for new welding implementations. It provides great flexibility for the customization of the system for the exact needs of every application. The merging of the DAQ program and the data analysis program in a single program, would produce a powerful tool for real time welding data acquisition and analysis, as well as for off line data processing of welding operations.

The hyperbaric GMA experiments at 27 Atm ambient pressure which is the mid-point of the intended RPRS's operating depth have been conducted and valuable conclusions have been drawn. It has been found that the best sampling strategy for detecting short circuits is the 'I@short' technique, where the welding voltage and welding current must comply with predetermined magnitude and time limits for a short circuit occurrence to be considered valid. Also, it has been established that the best way of making the signals robust is to filter the signals using a series of Butterworth filters, each one with a different cut-off frequency. This resulted in dip resistance signal trends which closely followed the CTWD range.

A highly important conclusion is that the operation of the dip resistance method can be optimised by the welding voltage threshold level used in the calculations. It has been shown that the method would produce the best results when used in combination with the information from another welding parameter, for example, the average welding voltage, to set the appropriate threshold level. The welding voltage seemed to be more sensitive to the CTWD and the hyperbaric GMA process; however the welding current must be checked as well to avoid control problems due to the extended periods of arc's extinction in the hyperbaric GMA.

The response of the derived dip resistance calculation method was tested in several ways and found to be satisfactory for a real-time system under ramp changes or wave patterns.

The rest of the process' parameters do follow the variations of CTWD but they are not as robust as dip resistance, for example, welding voltage and welding current averaging would include arc extinctions influencing the values; this has been the case as is noted in [78] for the RPRS's qualification trials. They may be used however for sensing and control the welding process under hyperbaric conditions by supporting the dip resistance measurement strategy as mentioned earlier.

The influence of the parent metal's temperature according to the work of other researchers does not mean that exact knowledge of the temperature and the variation of the electrical characteristics of the filler wire with temperature are needed in order to produce valuable results. This has been confirmed in the case of the hyperbaric RPRS process.

Also, laboratory based experimental work verified that the location of the welding electrode connection point on the welding table does not influence the values of the dip resistance as the welding current's path is reducing or increasing. Thus, the resistance of the parent metal does not seem to alter the results. This can be explained from the fact that the cross-sectional area of the parent metal is so large when compared to the cross-sectional area of the filler wire that any change in the physical properties resulting in resistance alterations will be much smaller compared to the changes of the filler wire resistance changes; thus, the most influencing factor will be the filler wire resistance.

14 Suggestions for Further Work

The time available for this project did not allow every single aspect to be fully investigated. However, a lot of new research and development areas in hyperbaric welding automation and control have been initiated and these can be used as the basis for a number of other projects. These projects could focus on the further development of the DAQ and control system that was produced for this project. This system could also be evolved further so as to include features that currently are implemented with the use of additional PC based controllers for the RPRS program. Also, further experimental and off-line analysis could be performed to produce optimum results for CTWD estimation. The system could then be implemented and used for the control in real time of the CTWD without the intervention of the operator. In this, great help would come from the further development of the DAQ system so as to include the information from the actuators that control the welding torch's movement. This would open the way for the development of further automation and process monitoring technology for other hyperbaric applications. As an example, one very important factor would be the real time analysis and estimation of the weld quality.

During this research project, the temperature dependency and welding current's path on the dip resistance was only briefly investigated as far as it concerns the change in the temperature of the parent metal and the length of the welding current's path. However, it is possible that the temperature of the filler wire, the welding torch and the parent metal could play a significant role in the dip resistance sensing. Thus it is considered reasonable to suggest that this topic should be further investigated in order to find a more complete answer as far as it concerns the influence of the temperature.

The same is proposed for the effect of the welding current's path geometry and length and welding electrode connection points with the welding area. In addition, some fairly basic work was done regarding the dip resistance estimation during fillet built up using weaving with the torch at 45°. In practise, this configuration is very similar to seam tracking for V-butt welding. The initial results suggested that the sense of the

CTWD during weaving can be monitored with good accuracy. Nevertheless, time limitations did not allow for this topic to be fully investigated. It is strongly recommended though that further work is performed in this area which could lead to new hyperbaric applications of the dip resistance. From the results it was evident that the underlying reasons for the dip resistance 'step' at around 8 mm to 9 mm CTWD must be fully explored as this is the CTWD of interest for the RPRS program. Initial investigation suggests that the free-play of the welding wire might be responsible for this. It is thus suggested that the welding wire's feed actuator to be relocated very close to the welding torch, to minimise the welding wire's conduit length [more than 1 m in length in the Hyperweld 250 facility at the moment] and the welding torch's tip to be customised so as to be as tight fit as possible for the welding wire. This should almost eliminate the welding wire's ability for free-play and will also allow to examine the wire feed speed as a complementary method for process control.

Finally, after successful development of a system for horizontal welds, it is suggested that experimental investigation with orbital welds, like the ones that are going to be used in the RPRS, to be performed as the weld pool's and weld bead's geometrical characteristics and dip resistance values will change therefore the system must be able to cope with the influence of the welding position. Perhaps feedback for the welding torch's position and appropriate compensation based on experimental evaluation to be enough.

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