# SYNTHESIS REPORT FOR PUBLICATION

## ADAPTABLE MODULAR ORBITAL SYSTEMS [AMOS] FOR PROCESS PIPE FABRICATION


**Contract No.:** BRE2-CT92-0152
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**Project Coordinator:** WELDING GROUP
CRANFIELD UNIVERSITY


**Partners:**

| | | |
|---|---|---|
| Partner 1 - | Cranfield University | [UK] |
| Partner 2- | BOC | [UK] |
| Partner 3- | Technical University of Denmark | [DK] |
| Partner 4- | European Marine Contractors | [NL] |
| Partner 5- | Instituto Soldadura e Qualidade | [P] |
| Partner 6- | Mague | [P] |
| Partner 7- | Migatronic | [DK] |
| Partner 8- | Isotek Electronics | [UK] |

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## NOMENCLATURE

| | |
|---|---|
| A/D | Analogue to Digital |
| CPU | Central Processing Unit |
| FFT | Fast Fourier Transform |
| HF | High Frequency (Ignition) |
| MIG | Metal Inert Gas (or GMAW, Gas Metal Arc Welding) |
| PPKAW | Pulsed Plasma Keyhole Arc Welding |
| SEM | Scanning Electron Microscope |
| TIG | Tungsten Inert Gas (or GTAW, Gas Tungsten Arc Welding) |
| UHP | Ultra High Purity |

# 1. SUMMARY

## 1.1 KEYWORDS

**The following five keywords are used to describe the project:**

*orbital, welding, microprocessors, pipe, process control.*

## 1.2 ABSTRACT

**A computer-based solution has been developed for a range of fully automated orbital welding applications, based upon a modular"VME-bus control rack. The rack provides the control for all motion axes for the orbital heads (stepper and *servo* motors for rotation, weave, stand-off and wire-feeding), calibrates gas flow control valves, and remotely programmed and controls an independent welding power source in real-time. Serial links are used to interface the control computer with the control rack, and the control rack with the power source CPU. All the welding and orbital motion parameters are configured and stored in a database on the control computer.**

**The derived core modular system (comprising the VME-rack and power source) was used to control a range of orbital heads for various multi-process applications:**

- **autogenous small-bore TIG for ultra-high purity tubing (SS316L),**
- **pulsed plasma keyhole and MIG welding of medium diameter steam generating plant pipelines (SA 106 Gr C and also SA 335 P22), and**
- **large diameter lay barge pipes (carbon steel API 5L X65 and duplex stainless steel SAF 2205).**

**Significant development work was also undertaken on optimised procedures for the UHP tubing, with respect to minimizing the surface roughness of the inner weld bead for improved UHP commissioning time for example. Real-time penetration monitoring of the process was demonstrated for small bore tubes. The system employs a dedicated signal conditioning unit, A/D card, 486-processor and software which utilises weld pool oscillations generated by current pulses and detected in the arc voltage. Plasma keyhole opening and closure parameter development for the completion of a full orbital root pass was also significantly improved by programmable simultaneous control of gas and current sloping parameters for both the power generating and lay barge pipe applications.**

## 2. CONSORTIUM ,

### 2.1 ADDRESSES & CONTACTS


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## 2.2 Consortium Description

Many proprietary orbital welding systems are limited to a specific size range of orbital heads and, also to the specific welding process applied (MIG, TIG or plasma), and several systems may need to be acquired to meet the common goal of orbital welding pipelines. A single system offering multi-process capabilities and flexible control for standard stepper/servo motion drives is not currently available. Consequently, the primary aims of the Brite project consortium were:

- to develop a prototype modular system capable of supporting a wide range of orbital welding processes,
- to provide optimised process development for three application areas.

Academic and industrial partners collaborated to achieve these aims.

Prototype hardware and software was developed by Isotek Electronics (UK) for the computer control system and user-interface computer, and Migatronic (DK) for the multi-process welding power supply.

Separate academic/industrial partnerships researched the different application areas:

- BOC Ltd (UK) and Cranfield University (UK) for the high purity electronic pipelines,
- the European Marine Contractors Ltd (NL) and the Technical University of Denmark (DK) for the lay barge pipe, and
- Instituto de Soldadura e Qualidade [ISQ] (P) and Mague Industrial Metalomecanicas (P) for the steam generating plant pipeline.

A brief description of the partners' main activities is contained in the following table:

| *Consortium Partner* | *Main Area of Business/interest* |
|---|---|
| Cranfield University (Welding Group) | fundamental and welding process research |
| BOC Ltd | supplier of ultra clean pipelines to the electronics industry |
| Technical University of Den-mark (Lab. of Thermal Proc. of Matls. ) | thermal processing research-of materials and joining techniques |
| European Marine Contractors | offshore pipe line fabricator (oil and gas) |
| Instituto de Soldadura e Qualidade | technical training centre for engineering (quality assurance specialist) |
| Mague Industrial Metal. S.A. | production of steam power generating plant |
| Migatronic A/S | welding power source manufacturer |
| Isotek Electronics Ltd | control systems for subsea and offshore applications |

## 3. TECHNICAL ACHIEVEMENTS

The three fundamental application/ material areas investigated were:

1. SS316L electro-polished tubing, 6.35 mm to 25.4 mm in diameter, (*small bore tubing),*

2. SA 106 Gr C (C/Mn), SA 335 p22 (Cr/Mo) pipe, 141 mm diameter *(medium diameter pipe),* and

3. duplex SAF 2205 and carbon steel API 5L X65 200 to 660 mm in diameter *(large diameter pipe).*

*Figure. 7* summarises the overall modular system concept, illustrating the different heads that are used with increasing material size, and *Figure 2 is* a photograph of the power source, user-interface and control system set-up in the laboratory.

### 3.1 PROTOTYPE CONTROL SYSTEM AND POWER SOURCE

An industrial rack was used to house all the component parts of the controller: gas flow display, industrial VME-bus with 486 processor, stepper and servo control boards, stepper and servo drive amplifiers and gas flow control valves for accurate plasma and shielding gas flow supply. The VME-bus was chosen for its flexibility, speed, and isolation from electrical noise. Software was written in AMX real-time code for the 486 VME-processor to facilitate the simultaneous control, of all the motion, gas and welding parameters. A serial communications protocol was further developed for the control of all the Migatronic BDH welding power source functions via its own internal CPU, and robust operation was proven with a 9.6k baud rate. Both serial communications links were made with optical cables for robust operation - initially several problems were experienced with the communication links as a result of the high frequency (HF) arc ignition used for TIG/plasma welding despite the use of optically isolated connectors with the original electrical leads.

Selection of the welding process (TIG/plasma or MIG ) and the arc initiation method (either high frequency or 'LIFTIG' for TIG/Plasma) were made automatically via the software at the user-interface. Tests showed that with the use of a pilot-arc, the plasma arc could be easily transferred to the workpiece with the LIFTIG/'touch start' option for many operating conditions - however for large stand-off distances ( > 5 mm) or small orifice diameters, the use of a high frequency start was necessitated ‘ either with or without a pilot-arc.

The real-time operation of the welding power source was applied ‘automatically in either one of two modes:

a) the TIG/plasma pulsing parameters were controlled by the VME-processor for a synchronised horizontal traverse/weave with current pulsing (for current pulses greater than 100 ins), and precise current sloping between segments if required, or

b) the pulse parameters were controlled by the power source CPU for either rapid current pulsing for TIG/plasma (pulses less than 100 ms) or MIG welding (constant voltage or pulsed-MIG operation) with global parameter changes for each segment.

The control software allowed for up to 16 orbital segments to be defined with control of all current/voltage welding conditions in each segment. Start/stop segments with independent control over the current level, current pulsing, rotation speed and gas flows were also implemented for up- and down-slope parameter definition (primarily important for determining plasma keyhole opening and closure behavior).

Inverter modules (100 kHz) were used for the welding power requirements (maximum peak current of 550 Amps deliverable for the plasma/MIG set-ups) with a modification to enable the high voltages (65 V. maximum) required for the plasma applications.

A separate control PC was used for the user-interface for both the preparation and storage' of procedural data (D B/2 on 0S/2) and also the start/stop and abort functions. Software was written in 0S/2 to enable multi-tasking for additional arc monitoring functions (for autogenous TIG and plasma keyhole in the first instance). Provision was also made for the adjustment of both motion and welding parameters ('Hot-Keys' pre-determined toggle amounts up to an offset limit) whilst welding.

The integration of the control PC, prototype control rack and welding power source enabled:

- a *modular* solution to all the orbital welding processes applied (plasma, TIG and MIG) without change of fundamental hardware or software, and
- different application needs to be met by a single core orbital system - highlighting its high degree of *flexibility.*

Only the orbital heads were changed between applications.

### 3.2 SMALL-BORE TUBING

Ultra high purity tubing is used predominantly in the electronics (1), food and medical industries. The usual material choice is currently 3'16 stainless; with the diameter ranging from 6.35 to 152.40 mm and wall thickness 0.9 to 2.5 mm with the inner bore electro-polished (average surface roughness - $R_a$ - 0.75 $\mu$m absolute maximum). Minimizing the surface roughness of the inner weld bead is a highly important process consideration since the weld can retain moisture and particulate contamination. Other primary process goals include: control of cast-to-cast variations, reduced manganese inner surface contamination, reduced particle generation during welding and reduced weld bead corrosion.

During the optimisation work on the UHP tubing, BOC identified a number of ways of producing more consistent. weld beads in accordance with the goals outlined above. Predominantly these involved alterations in either the shielding and purge gas type, travel speed and/or the pulsed current profile. It was proposed that the grain growth mechanisms and segregation during solidification were the principal causes for the level of surface roughness generated - this was reinforced by analysis of the inner weld surface using a scanning electron microscope (SEM). The effect of heat input (via the travel speed) on the resulting inner bead surface roughness is shown "in *Figure* 3 (the profile shown is for the high sulphur cast). An optimum minimum value is reached at 160 mm/min for both the standard and low sulphur casts, used. SEM photographs of high sulphur cast inner bead surface's are shown in *Figure* 4. Examination of the surface profile reveals a relatively consistent comb-like structure, which was indicative of many 'high sulphur' welds examined.

The following methods were found to decrease the average surface roughness generated:

- use of material that has a 'reduced minor element' composition, ie. double-melt or casts with low sulphur for example,
- use of argon shielding and purge gases with 5 to 10% hydrogen additions (1.5% hydrogen was also shown to provide notable benefits),
- use of multi-pass welding procedures,
- use 'of a slightly faster welding speed (160 mm 'rein is recommended) than usual, and the
- use of non-pulsed current parameters.

By combining all these factors, an optimal inner bead surface roughness of 0.84 $\mu m$ ($R_a$) was generated on 38.1 mm diameter, 1.6 mm wall thickness AISI 316L as a validation trial.

A database of all the UHP autogenous TIG welding procedures applied was generated and algorithms were derived to recommend suitable welding procedures for other cast/gas/ thickness combinations of SS31 6L tubing.

In order to further the integrity of the welding procedure adopted, Cranfield University, investigated the feasibility of applying an arc monitoring strategy to the small bore tubing. The geometry of the weld joint and welding head necessitated a non-intrusive technique ie. favouring a through-the-arc or top-face sensor. Work published by Xiao (2) indicated that weld Pool oscillations could be employed to monitor the state of the penetration of the pool by signal processing the arc voltage. Kotecki (3) showed that the frequency of oscillation of the molten pool is dependent upon the acting surface tension, the shape, size and density of the pool. Since the magnitude of the arc voltage reflects changes in arc length, the arc voltage can be used to monitor the frequency of pool oscillations once they are triggered during welding by a small duration, large magnitude (delta, $\delta$) peak current.

The sensitivity of the technique is dependent both upon the amplitude and duration of the oscillation of the pool itself, the mode of vibration of the pool, and the quality of the signal processing as well as some of the welding conditions (predominantly arc length, travel speed and the electric field strength).

Software written in 'C' (compiled for DOS) was used to monitor pool oscillations in real-time by using a Fast Fourier Transform to derive the dominant pool frequency from the transient voltage signal, yielding an on-line monitor of penetration (a 1024 point FFT was used with a sampling frequency of 2 kHz yielding a 2 Hz accuracy). *Figure 5* demonstrates the clear transition from a low to a high frequency signal response from the full penetration to 'the partial penetration state with the corresponding change in welding current during a single pass around a 38.1 mm SS316L tube.

*Figure* 6 shows the frequency response over time for different base currents in a stationary pool in SS31 6L 35 mm diameter, 2 mm wall thickness material. The clear transition from high frequencies (Mode 1 oscillation - 400 to 200 Hz) for low base currents that' progresses to lower frequency (Mode 3 oscillation -90 to 60 Hz) either with time or with increasing base current is shown, as the pool progresses from being unpenetrated, and having a narrow lower free surface to more fully penetrated with a more established lower free surface.

A region of transition occurs at 20 Amps, where it was observed that both Mode 1 and Mode 3 signals exist, although the low frequency Mode 3 signal was more dominant.

Cast differences in austenitic stainless steels radically affect the pool behaviour and consequent penetration profile under the same welding conditions. Pool oscillations have been used as a material test to identify the cast behaviour before welding using the time-to-penetrate as a characteristic parameter under stationary arc conditions.

The basic membrane relation for (Mode 3) oscillation n a plane circular pool is as follows:

$$f_{M3} = \frac{0.54}{a} \sqrt{\frac{\gamma}{\rho H}}$$

where:

| | |
|---|---|
| $f_{M3}$ | is the Mode 3 freq. of oscillation, |
| a | is the pool radius, |
| $\gamma$ | the acting surface tension, |
| $\rho$ | the density of the liquid and |
| H | the material thickness. |

Small differences in material composition have been shown (4) to affect pool surface tension and the surface tension/temperature gradient ($\delta\gamma/\delta T$) which can in turn alter fluid flow in TIG welding pools at currents below 3C O Amps. The acting surface tension can be a relatively unknown quantity - for this reason the work focused upon the monitoring and establishment of the full penetration condition ie. as distinct from a partial penetration condition, rather than predicting pool geometry from the frequency signal observed.

## 3.3 MEDIUM DIAMETER PIPE

The conventional welding procedure of a manual TIG root and MMA fill was replaced with a automated plasma root and MIG fill on a steam generating plant double-vee joint. It was calculated that this offered a potential productivity benefit of 40%. Trials On SA106 Gr C and SA 335 P22 material tubes were performed initially with a Tesch orbital head incorporating rotation and weave axes, arid ISQ concluded that the standard plasma torch nozzle would benefit from a more optimised' design to enable greater control over the plasma keyhole formation in the production joint. The re-designed plasma torch is illustrated in *Figure* 7. Additional information on the delivered welding parameters before optimisation was provided by a data acquisition set-up monitoring the delivered voltage, current, weave characteristics and rotational position.

A metallographic analysis, by Mague, of the resulting joints established that the use of pre- and post-weld heat treatment was not critical on the '1 06' material with the automated procedure. The MIG fill had refined the coarse structure resulting from the rapid cooling of the plasma root, and the overall hardness profiles were acceptable without further treatment. However, the weldability of the Cr Mo SA 335 P22 was more difficult and the use of a pre- and post-weld heat treatment of 200 to 250"C produced welds with the lowest hardness values, despite an observed degree of refinement from the MIG passes.

Satisfactory conditions for a full orbital plasma root were obtained and applied to both the materials studied.

### 3.4 LARGE DIAMETER PIPE

Work on the large offshore pipeline was focused in two areas:

- the orbital pulsed plasma keyhole root run on duplex 2205 and 2507 with 7 mm material thickness (this would enable a higher through-put at the root pass welding stage on the lay-barge) by DTU and
- MIG welding for fill passes on the above duplex, and carbon steel work to assess productivity and quality benefits offered by full automation by EMC.

Previous work has highlighted the typical problems encountered for a plasma keyhole root in the 5G position (5), and accurate control of the delivered parameters has been strongly recommended . The critical problems posed by the orbital plasma keyhole run are the opening and closure of the plasma keyhole, and the control over the all the welding parameters (specifically current pulsing and plasma gas flow) around the joint to offer an acceptable root profile, without sagging or Significant undercut. Keyhole opening and closing was implemented easily in the 12 and 6 o'clock positions using synchronised sloping current and gas flow controls. A full orbital pass was made, with acceptable bead profile, using the prototype system implementing all the current and gas controls available.

For a 7.3 mm thickness root pass, the plasma keyhole run offers a potential 80% reduction in arc time in comparison with TIG. An acceptable austenite composition of 38°A (balance ferrite) was achieved in the weld metal from the applied plasma welding conditions without the need for filler metal or nitrogen in the shield/purge gases.

For the precise control required to maintain a constant plasma torch height around a typical pipe outer profile, a mechanical tactile sensor was initially implemented. This was subsequently substituted for an electrical signal using filtered analogue signal conditioning (arc voltage control - AVC with a 4th order, 6-pole Butterworth, 10 kHz Low Pass filter) with A/D conversion and a stepper motor. Averaging the signal over time was necessary to account for the current pulsing and consequent changes in voltage amplitude.

Research was also carried out into the feasibility of either using the efflux light or voltage from the plasma keyhole to model the behaviour/size of the keyhole - the voltage was the most robust signal, although it necessitates the accurate set-up and use of an inner ring to generate a potential difference.

Using the finite-difference MAGMAsoft package, DTU modelled a plasma torch with optimised shielding and cooling characteristics from an earlier blade type design. The torch was specifically designed for a narrow-gap joint application. A nozzle was also re-designed for ease of use and electrode setback consistency. The thermal analysis of the original blade torch is shown in *Figure* 8.

For automated MIG welding EMC Ltd developed a prototype 4-axis welding head (wire-feed and rotation with servo motors, vertical and horizontal with 5-phase steppers), running on standard track with external gearing. Satisfactory pipe weld trials were made with pulsed and non-pulsed MIG on carbon steel and clad pipe (AISI 316 plus API 5L X65), though the promising future benefits appear to lie in the precise control necessary for the more critical higher quality application with TIG root runs or MIG welding stainless and duplex materials.

## 3.5 CONCLUSIONS

The main conclusions from the work undertaken are a; follows:

- The core control and power source requirements for orbital systems can be met by a single flexible modular system. A prototype has been built that fully supports three fusion welding processes (plasma, TIG and MIG) and the various heads required for the application areas investigated.

- Optimised minimal inner bead surface roughness profiles can be produced in ultra-high purity tubing with selected welding conditions, and results have indicated that materials with low sulphur content are particularly good.

- The state of penetration of the orbital weld in small bore tubing can be monitored by signal processing the arc voltage if a triggering pulse is used to generate pool oscillations.

- Productivity benefits are gained by using a fully automated plasma keyhole root pass and switching to a MIG fill for steam Generating pipe applications.

- Plasma keyhole welding the 'root pass of large ciameter duplex pipes offers significant productivity savings with a single pass to join material of 7 mm wall thickness.

- Precise programming of the current and gas sloping parameters during all stages of the plasma pass facilitates highly accurate control over the keyhole behaviour, especially the opening and closure performance.

## 3.6 ACKNOWLEDGEMENTS AND REFERENCES

This project could not have been completed without the funding of the Commission for the European Communities for the BRITE-EURAM programme BE-51 14-92 'Adaptable Modular Orbital Systems for Process Pipe Fabrication'.

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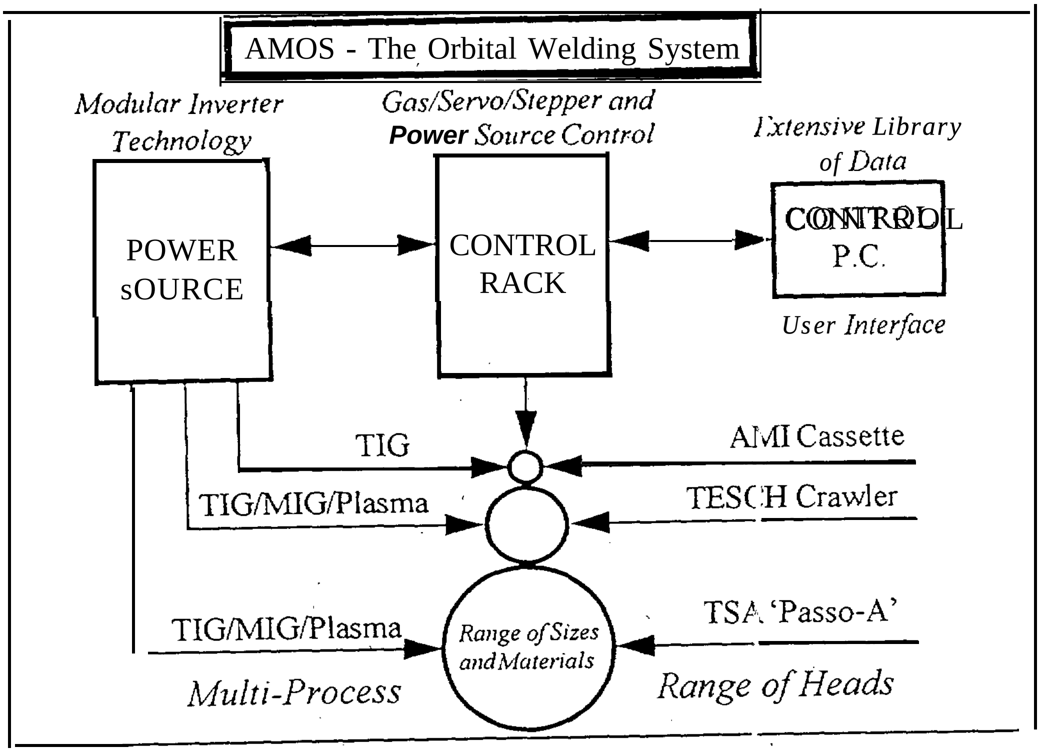



FIGURE 1 - Modular Concept shown Schematically

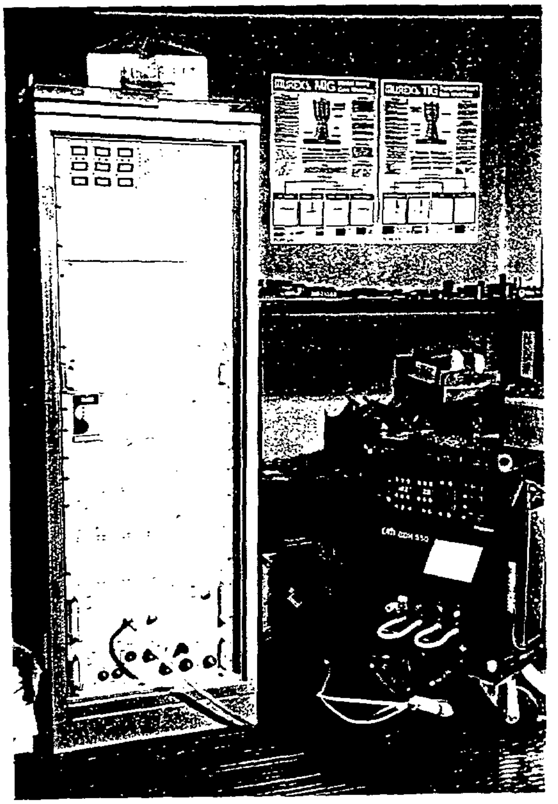


FIGURE 2- Photograph of Prototype Development System User-Interface Computer, Control Rack and Power Source)

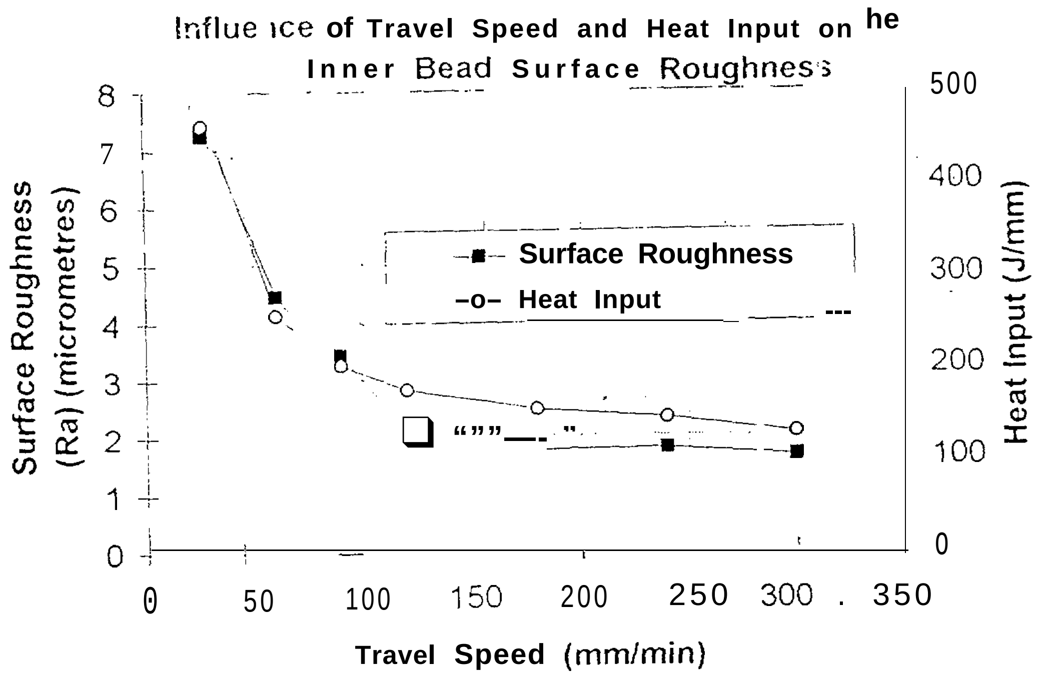
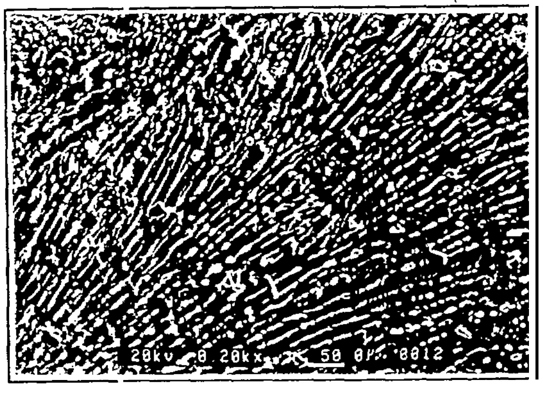



**FIGURE 3- Inner Bead Surface Roughness Results with T avel Speed/Heat Input (Results shown are for a 'High' Sulphur Cast Material [0.007%1)**

High Magnification



Low Magnification

**FIGURE 4- S.E.M. Plots of High Sulphur Cast Inner Bead Surface Profile (High and Low Magnitude -,5 $\mu$m to 4 mm [Left], 50 $\mu$m to 4 mm [Right])**

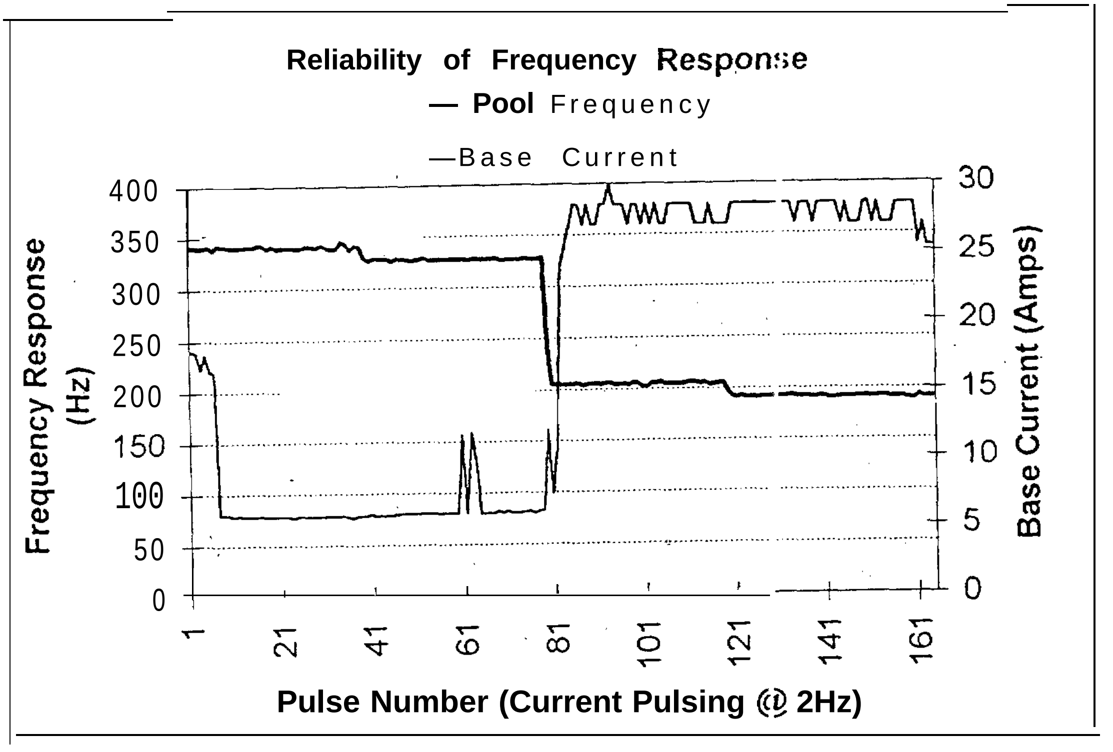



**FIGURE 5- Frequency Behaviour during Single Orbital Pass using Non-penetrating and Penetrating Welding Currents**

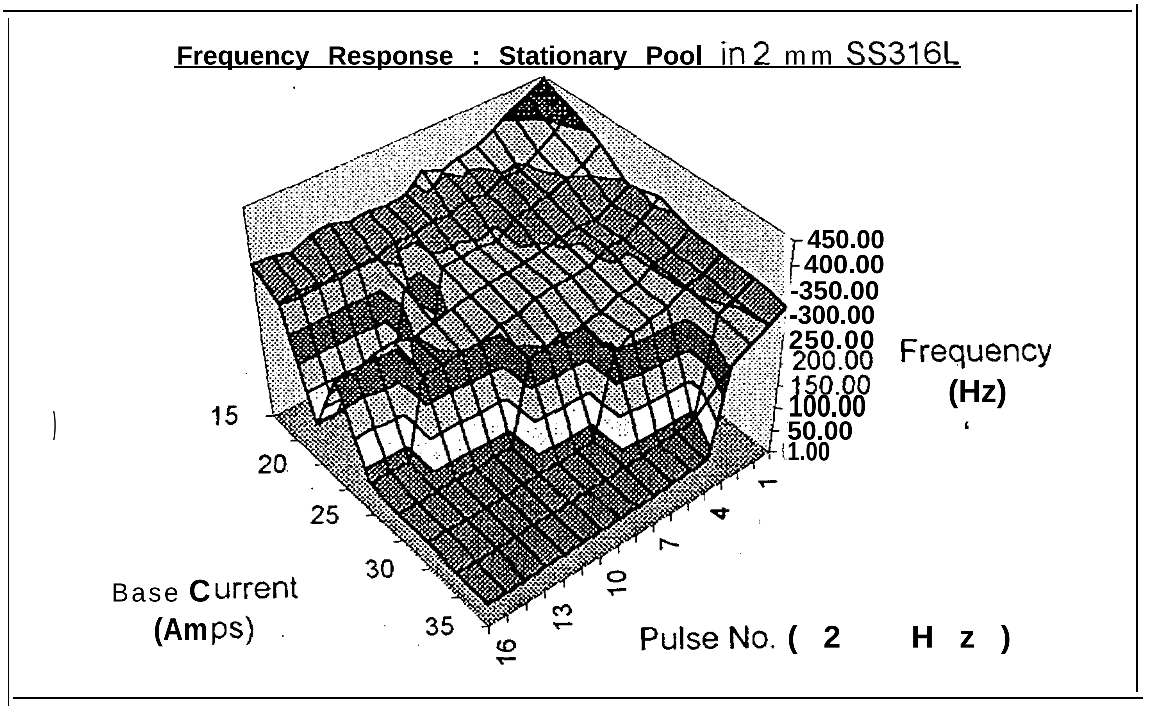



**FIGURE 6: 3-D Plot of Stationary Pool Frequency Behaviour (Real-Time) against Time and Base Current**

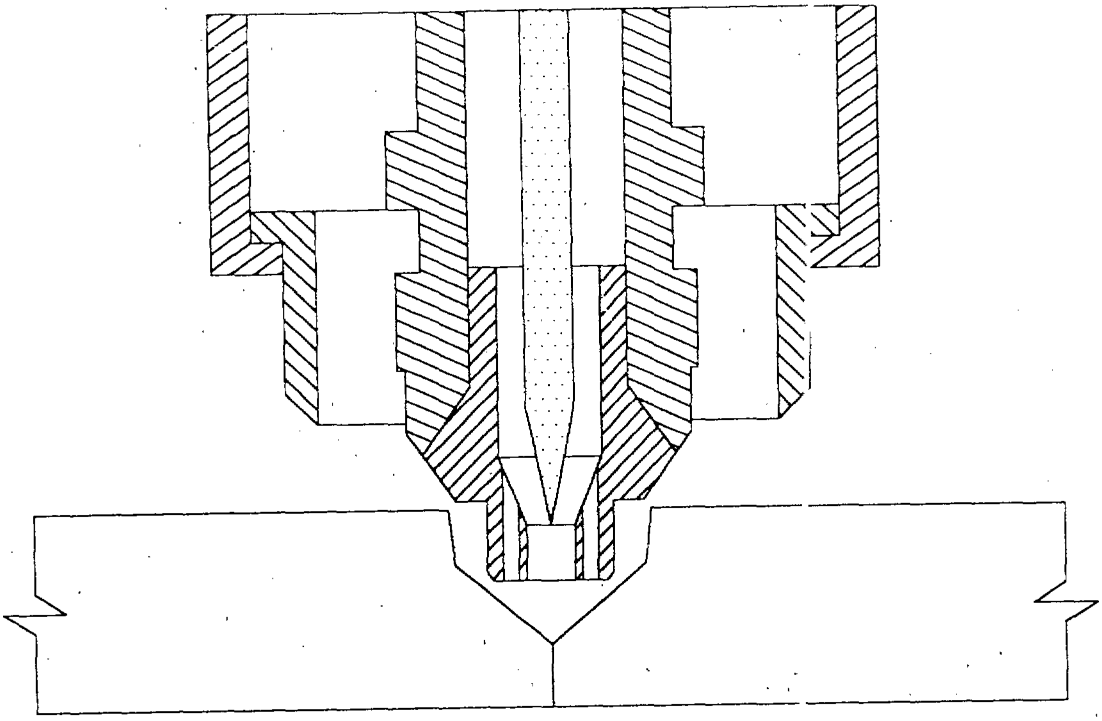


FIGURE 7 - Re-designed I.S.Q. Plasma Torch for Double-Vee Steam Generating Plant Joint

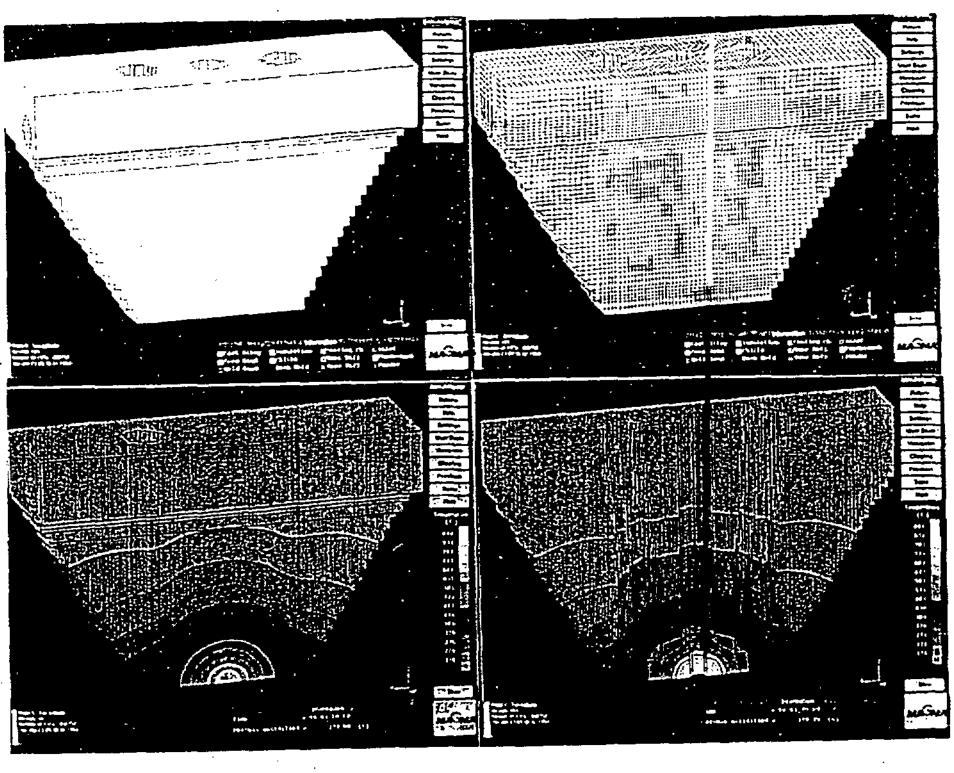


FIGURE 8 - MAGMAsoft Thermal Analysis of Narrow Gap 'Blade' Torch for Pulsed Plasma Arc Keyhole Welding of LayBarge Pipe

## 4. EXPLOITATION, FOLLOW-UP AND FUTURE COLLABORATION

### 4.1 EXPLOITATION OF RESULTS

The primary results of 'the project are the development of the hardware and software for the adaptable modular system for the various orbital application areas investigated, and the process optimisation of the application areas. It is anticipated that the development of the prototype welding control system is pre-competitive and that a further development phase is required to bring a potential product to the market-place. Academic and industrial partners' work in the application areas investigated will be exploited on an individual basis.

It is intended that the control rack and software associated with its control be developed further after the project-end. This would be primarily done by Isotek, with third party funding for the development phase. Migatronic would offer support in terms of supplying welding power sources that are fully compatible with the serial communications developed under the project and that can be integrated into a dedicated system, as well as used independently. Migatronic also intend to develop the serial communications protocol which would enhance the future performance of the system.

Subject to the feasibility and the robustness of the feedback control signals, Isotek would intend to support the development of the control computer and rack over the next 1 to 2 years, to derive a robust system that is capable of being used in a manufacturing environment.

All the industrial partners have had a good opportunity to develop the welding processes that they apply, and use fully automated equipment developed during the 'project. Optimised process applications have been researched in conjunction with the academic partners. This experience will be exploited by the industrial partners in their future work areas and a commercial advantage has keen gained by the partners in terms of process knowledge. Continuation of the process optimisation work is also envisaged by the industrial partners.

### 4.2 FOLLOW-UP OF PROJECT "WORK

All the partners involved in the project foresee a continuation of the process optimisation work started during the A. M.O-S. project, in particular progressing the feedback control aspects of the work to a further stage. Monitoring of the TIG process has been demonstrated using weld pool oscillations, and feedback control using the user-interface computer has been implemented. A control strategy using the arc voltage of the plasma keyhole welding has also been proposed and could also be implemented. The flexibility of the computer solution derived facilitates a relatively straightforward implementation of control strategies. This aspect of the work enhances the competitiveness of the 'overall system, and makes it more of a viable proposition if it offers real-time process control capabilities.

## 4.3 FUTURE COLLABORATION

The consortium are keen to continue the work developed, although future work is not necessarily limited to tube/pipe applications - the flexibility of the system allows for full axis control, whether they are orbital or linear axes. In particular, the possibility of a future collaboration focusing on the full implementation of feedback control strategies for the welding processes investigated on a single flexible system is a strong consideration for all the partners.

Discussions with respect to potential future collaborations would be welcomed from:

- academic partners with experience implementing welding' process control strategies (specifically plasma, TIG and MIG) - in particular using through-arc-sensing methods,

- industrial partners with a requirement for the development of a robust flexible process control solution to improve orbital tube/pipe (or linear/robotic) joining applications, (possible examples might include: an application with a variation in heat dissipation characteristics that does not easily facilitate off-line programming, unpredictable variations in material thickness that might be more effectively accounted for).

## 5. PUBLICATIONS RESULTING FROM THE PROJECT

Ultra-High Purity and/or Small-Bore TIG Wetding:

'Ultra High Purity Orbital TIG Welding: Inner Bead Surface Integrity and Penetration Monitoring Using Pool Oscillations', Neil Woodward and John Norrish, Welding Review International, Vol. , No. , October 1994.

'Process Control and Improved Penetration Parameters for Autogenous Gas Tungsten Arc Welding of 316 Stainless Steel', Julian Tapp and Neil Woodward, Seventh International Conference on the Joining of Materials, JOM-7, May 31 - June 2, Helsingor, Denmark.

Power Generating Pipe:

*Publication of results from the collaboration of 1. S. Q. and Mague is planned for the national 1. S. Q. magazine, to be distributed in Portugal.*

Overall Project:

'Research and Development of Adaptable Modular Computer-Based Equipment for Orbital Welding Applications', Neil Woodward and Ian Richardson, Sixth International Conference in Computer Technology in Welding, June 9 - 12, 1996, Belgium (planned).

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