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Process Control and Automation Developments in Welding

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Abstract

With an international shortage of skilled welders and concerns about exposure of personnel to welding hazards it is appropriate to consider how joining processes can be simplified and automated.

The paper reviews the process control techniques which have been applied to enhance the productivity and quality of welded joints. It seeks to explain the influence of power source design and computer control on these developments. In particular it will address the real time control of short arc GMAW and explain how by modulation of the transient electrical properties and high speed wire feed oscillation process performance has enhanced in several recent variants of controlled short circuit transfer.

An attempt is also made to put these developments in context when compared to conventional GMAW, and to explain the potential benefits and to classify them according to recent IIW metal transfer scheme. The process control potential of other developments; such as tandem and hybrid laser GMAW with also be described.

The trends in welding automation are reviewed and in particular the techniques for off line and rapid programming of welding robots and on line monitoring and control techniques will be reviewed.

Finally the continued importance of fundamental studies into process control and automation is stressed.

Introduction

Why do we need to develop improved welding process control and automation techniques? The answer lies in current international concerns about the restricted availability of skilled welders, the increasing need to improve occupational health and safety both in the workshop and general environment, pressure to improve productivity and reduce cost and the need to maintain joint integrity in critical structures.

The shortage of skilled welders has been highlighted in the media; for example The Wall Street journal reviewed the problem in 2006 [1] indicating a major shortage of welders and escalating weekly earnings. The same article claimed that on current estimates demand for skilled welders in the USA will outstrip supply by 200000 by 2010. This is by no means an isolated problem; it has be reported as an international problem in countries such as Japan, and Australia as well as in Western Europe. There is believed to be a link between the perceived OH&S hazards associated with welding and the ability to recruit new welding personnel.

OH&S is an issue which must be addressed due to our moral responsibility to welders and society in general as well as the recent and sometimes ill conceived spate of litigation which often exploits our lack of technical knowledge concerning the physical effects of welding hazards.

In terms of cost and productivity it is known that in most common welding operations (on plain carbon steel) labour accounts for 70 to 80% of the total welding cost. Since labour costs are escalating , and will inevitably do so even in developing economies, total fabrication costs will increase accordingly. Productivity improvements are difficult to envisage in such a labour intensive, highly skilled and OH&S affected environment.

So how can we use technology to radically change this seemingly endless cycle? I would suggest that all the tools we need are either available. By application of current and emerging developments we can:

- Reduce skill requirements
- Enhance training
- Improve OH&S
- Improve productivity
- Reduce cost
- Improve quality

In order to develop and exploit these technologies we need to understand some of the underlying technology and objectively assess the most appropriate systems based on the dominant

requirements and a clear recognition of their fundamental benefits and limitations. Some examples of the technologies are reviewed below with the aim of demonstrating how they developed from a fundamental undestanding of the processes and how can address the problems highlighted above. Many of these processes are dealt with in more detail in other papers in these proceedings.
The technologies selected as examples are:

- Understanding metal transfer in GMAW
- Optimised pulsed transfer
- Controlled short arc GMAW
- Extended operating modes
- Tandem GMAW
- Laser hybrid GMAW
- Conventional automation
- Novel programming techniques
- High accuracy robotics
- Near net manufacture

Understanding GMAW metal transfer

Early attempts to classify metal transfer modes in consumable electrodes started in the early 1900's but it was not until the advent of improved high speed cine` techniques in the 1970's that a full phenomenological classification of natural transfer modes was attempted. The work of many researchers was coordinated by the International Institute of Welding (IIW) in 1976 [2]. Table 1 shows the resultant classification scheme adopted at this time. Sub group 1.2.4 Drop Spray transfer was added by the current author following the discovery of this mode by Ma [3]. Most of these common modes occur naturally under the influence of a steady electrical supply of DC current and the mode which is found depends mainly on the welding consumables and the value of current and voltage. The transfer modes may be modelled in several ways but for simplicity the driving forces are often considered to be a balance of; elecromagnetic, viscous drag, gravity and surface tension.

Table 1. Original IIW metal transfer classification

Transfer Group	Sub Group	Example
1.0 Free flight		
1.1 Globular	1.1.1 Globular drop	Low current GMAW
	1.1.2 Repelled	CO_2 Shielded GMAW
1.2 Spray	1.2.1 Projected	GMAW above transition
	1.2.2 Streaming	Medium to high current GMAW
	1.2.3 Rotating	High current extended CTWD
Added Later	1.2.4 Drop Spray	At transition in GMAW
2.0 Bridging		
2.1 Short circuiting		Low current GMAW
2.2 Bridging without interruption		Welding with wire addition
3.0 Slag protected transfer		
3.1 Flux wall guided		SAW
3.2 Other modes		SMAW (MMAW), FCAW

Drop spray transfer however was only observed with stable ripple free current from an electronically regulated power supply. Under such conditions it is found within a very small current range around the globular to spray transition current. It is distinguished by the formation of very stable droplets slightly larger in diameter than the filler wire. These droplets transfer smoothly and axially across the arc.

Optimised pulsed transfer

The first attemts to control metal transfer in the 1960's [4] by modulating the voltage output of the power source enjoyed some success; allowing spray type transfer to be obtained below the mean globular to transition transition current. However these systems were commonly fixed frequency (a multiple of mains frequency) and adjustment was difficult and was not amenable to parameter model fitting. The discovery of drop spray enabled clear process models to be developed for pulsed transfer; process control rules could be established and even automated [5], and 'optimised' pulsed transfer obtained over a very wide current range. The following empirical relationships were established;

For one drop per pulse;

$$Ip^n tp = D \qquad (1)$$

Where Ip is the pulse current, tp is the pulse time, n is a constant (between 1 and 2) and D is the detachment constant.

$$WFS = kf \qquad (2)$$

Where WFS is the wire feed speed, k is a constant and f is the pulse frequency. The mean current is given by:

$$Imean = Iptp + Ibtb/tp + tb \qquad (3)$$

Where Ib is the background current and tb is the background time.
These simple empirical relationships are consistent with physical models of the process based on the transfer forces mentioned above and they allow 'ideal' welding parameters to be preprogrammed into the power sources. Control algorithms which automatically adjust the pulse waveform to match increases in wire feed speed as well as in situ compensation for contact tip to workpiece distance (CTWD) variations are also possible. From a practical point of view this development offers the ability to simplify equipment set up (reduced skill) whilst offering spatter free, low particulate fume transfer over a wide mean current range.

Controlled short arc GMAW

In conventional short arc or dip transfer (2.1 in table 1) the arc is interupted by short circuit events between the continuosly fed electrode and the weld pool as indicated by the transient current and voltage traces shown in figure 1.

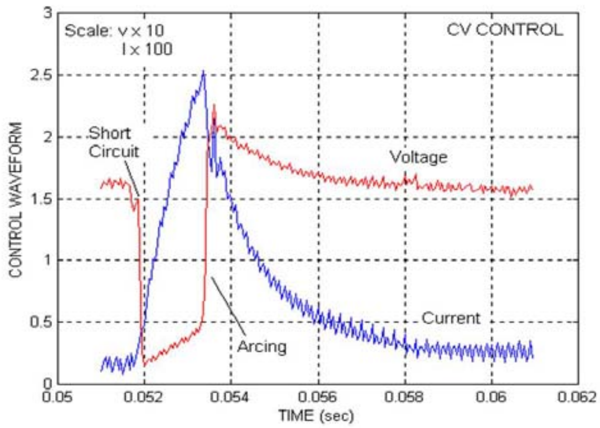

Figure 1. A single cycle of a conventional dip transfer waveform (short circuit and arcing period)

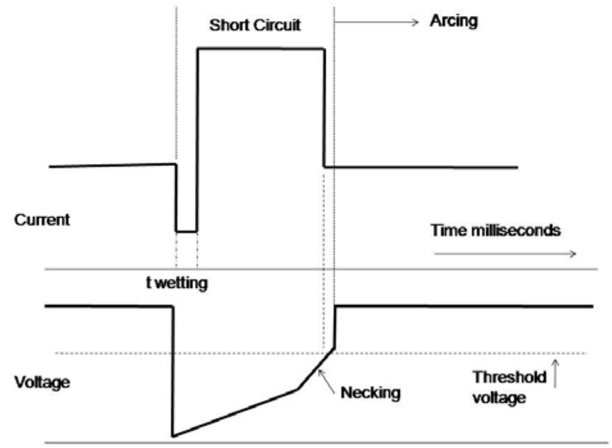

Figure 2. Diagramatic illustration of short circuit control system devised by Boughton

The frequency and regularity of these events is a function of the wire feed speed, the welding current and the voltage or static and dynamic current - voltage relationship of the supply circuit. Heating of the workpiece occurs predominantely during the arcing period [6] but it is a common tendency for operators to adjust the process variables to achieve the maximum short circuit frequency and hence the shortest arcing/heating period. This condition may be moderated slightly by limiting the peak short circuit current (by decreasing voltage and increasing secondary circuit inductance) to minimise explosive short circuit rupture and spatter. The constraints on the adjustment of the process and the common tendancy to adjust ‘by ear’ to achieve high dip frequency may account for the reputation of the process for high levels of spatter and lack of fusion defects on thicker sections of material. Both of these drawbacks may be regarded as quality and OH&S limitations of this process mode.

Due to the stochastic nature of the process it is not possible to impose a fixed frequency on the short circuit events, similar to that used in pulsed transfer. In the 1970’s. Boughton [7] adressed these problems by using a transistor series regulator power supply to control the dip transfer current waveform in real time. He theorised that spatter could occur at the start of a short circuit period by incomplete ‘wetting in’ of the filler wire into the weld pool prior to the abrupt increase in short circuit current (causing instantaneous and incomplete short circuit rupture) as well as at the end of the short circuit when excessive current caused explosive rupture. To address the first problem he imposed a current rise delay or current reduction at the onset of each short circuit; this allows a substantial short circuit to be established and maintained during the subsequent current increase. In order to prevent explosive rupture at the end of the short circuit Boughton ‘turned off’ the current just before the short circuit rupture occurred. The adaptive control of current was triggered by monitoring the welding voltage as indicated in figure 2,

This technique virtually eliminated spatter and allowed a degree of decoupling between short circuit stability and fusion efficiency. Its only limitations were its reliance on a very costly power source and the use of a fixed threshold voltage to detect the iminent short circuit rupture.

Practical application of the process was made possible by utilising lower cost primary rectifier - inverter power supplies and detection of the rate of rise of voltage during necking for pre-emptive detection of the short circuit completion.

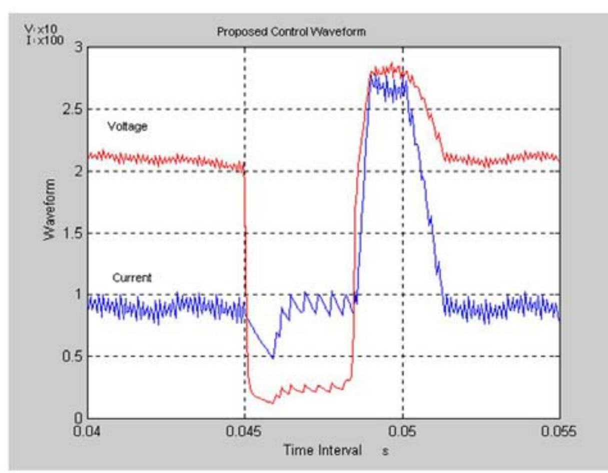

Figure 3 Simplified controlled dip transfer waveform.

Variants of this approach as described by Stava et al. [8] have now become commercially available. A simpler alternative which is illustrated in figure 3 relies on using a current pulse during the arcing period to grow a molten droplet on the end of the wire which is of a suitable size to aid low current separation during the short circuit cicruit under the influence of surface tension alone.

It is interesting to note that in most cases these short circuit control techniques result in lower short circuit frequencies and consequently improved fusion efficiency when compared with conventional dip transfer.

Whilst these techniques rely on current control Huismann [9] has shown that similar effects may be obtained by high speed oscillation of the wire feeding. This approach relies on braking or wire retraction to achieve the initial short circuit initiation without 'stubbing' as well as physically breaking the molten metal bridge. It is particularly beneficial for larger wire diameters.

Combining adaptive wire feed and current modulation has enabled systems to be developed [10] which further enhance the control of the process to enable very low heat input and high welding speeds to be obtained.

All of these controlled dip transfer approaches provide the potential to improve quality, reduce OH&S exposure for operators. In addition benefits such as improved control of root penetration and the ability to produce low dilution deposits have been found to be possible.

The various modes described above have been captured in a proposal for a new classification approach for metal transfer as shown in table 2.

Table 2. Proposed re-classification of metal transfer modes as developed by IIW Comission XII.

	Natural		Sub Mode		Controlled
A	Short Circuit	A1	Short circuit	A1.1	Short circuit
B	Globular	B1	Globular		
		B2	Repelled		
C	Spray	C1	Drop	C1.1	Pulsed
	Streaming	C2	Streaming	C1.2	Pulsed
		C3	Rotating		

Extended GMAW operating modes

Both natural and controlled transfer modes may be further extended to provide a combination of productivity, quality and operability advantages as shown in table 3. The essential mode of transfer remains the same as those listed in table 2 and can be explained by existing physical process models but these extended techniques are based on exploiting existing parameter relationships. For example extending the electrical extension of the wire from the contact point increases the resistive heating which depends on the product of the extension resistance and the square of current (I^2R). Increasing the extension and the mean current will lead to an increase in melting rate in all modes of transfer. For high productivity this high deposition mode [11] is often used in the spray range.

Table 3 Extended GMAW operating modes

Transfer Group	Sub Group	Example - Application	Commercial name or reference
Short Circuiting GMAW	Extended stick out GMAW	High deposition short circuit transfer GMAW	Rapidarc™
	Low frequency pulsed	Pulsed mean current for gap filling	Ref. [27 - 29]
Pulsed transfer GMAW	Multiwire	Multiwire GMAW	Ref. [35]
	Low frequency pulse	Modulated pulsed transfer welding of aluminium	Synchropulse™
	Variable polarity	Welding of thin sections and single sided root runs	Ref. [30 - 31]
Spray transfer GMAW	Rotating spray	High current extended stick out	T.I.M.E™ Rapidmelt™
	Electrode negative	Flux cored wire or special gas mixture	Ref. [32 - 33]
	Extended stick out	High deposition rate welding of steel	Ref [ ]
	AC/ Variable polarity	Root runs in pipe	Ref [30 – 31]

Tandem GMAW

The use of multiwire techniques often used in submerged arc welding is a logical enhancement of the GMAW process. In the high current range this has been achieved with two wires supplied from separate power supplies in what is known as tandem GMAW. Pulsed transfer is often used and to avoid magnetic interference the pulse waveforms may be synchronised to produce pulses on one wire whilst the second arc is in the background phase. This process has been used for fill passes in high strength thickwalled pipe with remarkable gains in productivity and excellent joint mechanical properties [12]. The potential to use the process in low current pulse or controlled short circuiting modes is also under investigation for applications such as high speed root runs in pipe.

Laser hybrid GMAW

Laser hybrid GMAW welding is already employed; notably in the automotive and shippbuilding industries. The development of more efficient diode, fibre and disc lasers has further improved the potential for laser hybrid GMAW processes. It is established that the combination of laser and GMAW heat sources can lead to productivity and quality improvements which are often greater than would be anticipated fom a simple additive model. This is due to factors such as the improved absorption of laser energy in the GMAW weld pool as well as improved arc stability due to laser induced ionisation. In general the combined processes give improved joint tolerance (compared with laser welding) and improved control of fusion in GMAW. Figure 4 shows the effect in trials aimed at producing high speed root runs on closed 'J' pipeline girth welding preparations.

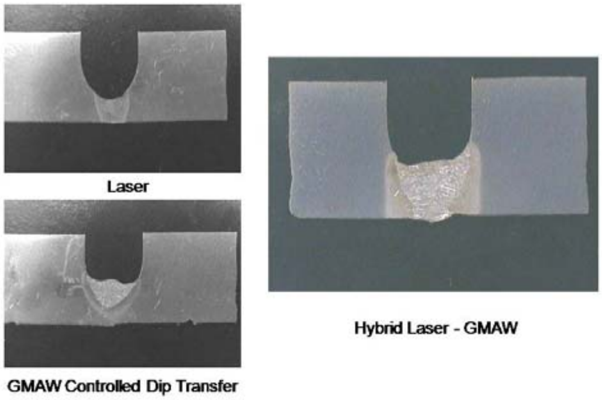

Figure 4. Comparison of root runs made in a closed J butt with a 3kw diode laser, controlled dip transfer and a hybrid combination of the 2. The material was carbon manganese steel, the root face was 1.6mm and the travel speed 1000mm/min.

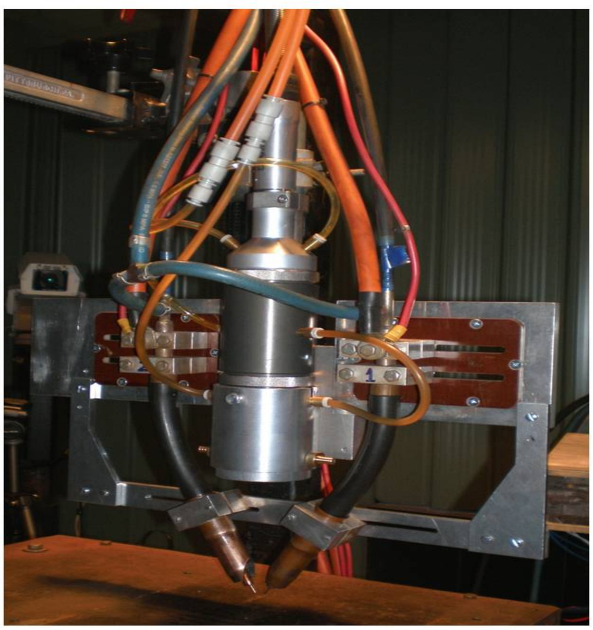

Figure5 . Prototype tandem GMAW system

The authors laboratory is currently investigating the possibility of combining tandem GMAW and laser processes for enhanced control and productivity. The prototype test system is shown in figure 5.

Conventional welding automation

Welding automation has been classified [13] as:

- Simple mechanisation (tractors and manipulators etc.)
- Special purpose systems (orbital welders etc.)
- Dedicated automation (purpose designed)
- Modular automation (component systems)
- Programmable systems (robots, CNC machines etc.)

All of these systems remove elements of human mechanical effort from the welding operation, improve consistency and remove the operator from the welding hazards. Simple mechanisation is often underutilised in the West but has be exploited very effectively in Japan. Dedicated automation is generally only justified for high volume operations although it often completely removes the welding skill element during its operation. The most interesting trend is probably in welding robotics. Standard industrial robot systems have become more afordable and the user and peripherable interfaces have improved to give them greater flexibility. Generic off-line programming systems provide reduced production down time and the possibility of process simulation and optimisation. On line position detection and seam tracking systems add to the potential consistency of the welded joint.

In spite of these advantages the following limitations are often quoted;

- Inability to perform short batch or 'one-off' operations due to the high programming overhead.

- Inability to achieve high accuracy on large workpieces

Novel programming techniques

Repair of worn components by weld build up is often a hardous operation due to use of highly alloyed consumables and high fume levels. Robotic welding is an attractive option in these circumstances but the non-repetitive nature of repairs seems to preclude it on the basis of programming time. This problem has been addressed in the application of robotic repair of earth engaging parts by machining the worn components to a common profile prior to weld build up [14]. A more innovative approach has been to use a vision system to programme the robot. This approach has been sucessfully evaluated for robotic weld repair of cavitation damage in hydro turbines [15] and potential corrosion patch repair of pipelines.

In the case of cavitation damage of large hydro turbine runners as shown in figure 6 it is usually sufficient to use a single camera attached to the robot end effector to capture an image of the worn area.

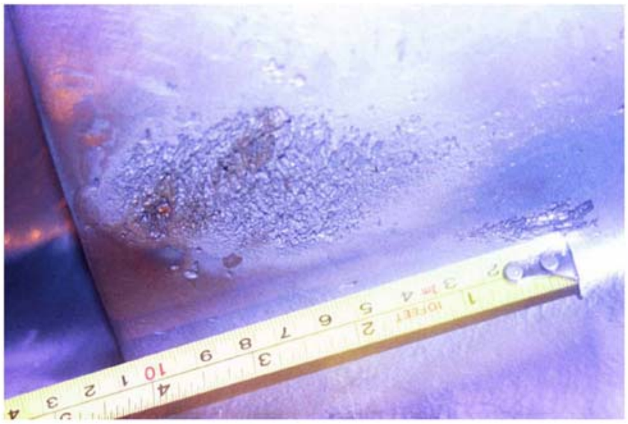

Figure 6. Cavitation damage on a hydro turbine runner

This image is relayed to a computer monitor on which the operator is able to select the repair area with a few mouse 'clicks'.

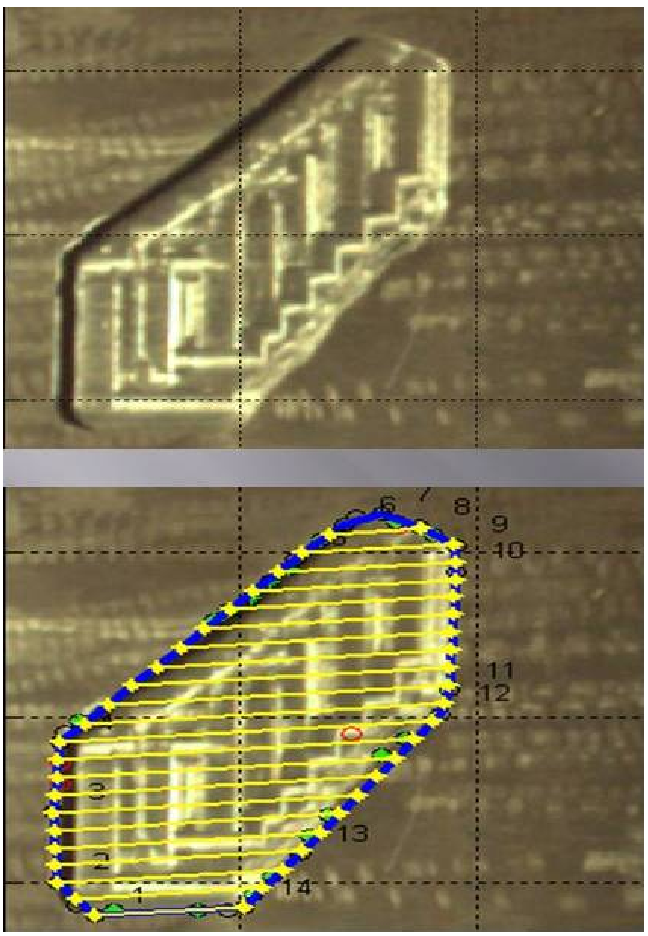

Figure 7top- a simulated wear cavity, bottom – the automatically generated weld paths.

The software used defines the repair area and automatically divides it into weld paths based on a deposition model which calculates weld width from the welding parameters chosen. Figure 7 shows the two stages of this operation. The x and y coordinates of the weld paths are dowloaded directly to the robot whilst in the simple case of an essentially flat plane the z coordinate is obtained by using the robot/power supply touch sensing capability.

The repair patch generated by this operation is shown in figure 8.

Figure 8. repair patch complete

The programming time involved for the complete operation is around 30 seconds for the example shown.

For more complex three dimensional surface repair this technique has been extended using a novel vision system approach which uses two views of the damaged area and a projected laser grid to extract the profile data [16].

High accuracy robotics

Whilst for most welding applications accurate positioning of the robot to within ± 1.0mm is acceptable there are instances where higher accuracy is required over a larger operating envelope. In these situations industry often selects large rigid dedicated systems rather than robots. However by applying a lateral thinking approach very high acuraccy systems have been developed for drilling [17]. In this case a robot end effector with metrology feed back from a laser or infra red global positioning system is used. The robot manipulates the head to a pre-programmed position and the end effector adjusts the final tool position. Accuracies of better than 25µ over 5m traverse distance have been obtained using this approach. There is no reason why a similar technique could not be used for high accuracy welding operations.

Near net manufacture

By combining the advantages of process control and robotic automation it has been shown that direct deposition of metallic components by GMAW welding is possible. Early work in this area dates back to the 1980's when it was demonstrated that quite complex shapes may be fabricated by directly programming a robot from a CAD drawing of an object [18]. For example the object shown in figure 9 was fabricated directly from weld metal using a relatively simple 6 axis robot and a tilting turntable. The object was drawn in an Autocad™ environment, it was then sliced and a robot programme was generated and downloaded automatically.

Figure 9 Complex fabrication formed by direct metal deposition

Due to continuous refinement of previous layers the quality of the final fabrication was excellent. Such techniques have been referred to as; rapid prototyping, direct metal deposition or shape metal deposition. By combining the technologies referred to above it seems that significant developments are likely in this area.

Conclusion

This presentation set out to show that the answer to growing skill shortages, productivity, cost, quality limitations and OH&S concerns was 'smarter' technology. These technologies not only reduce the dependence on skilled welders but they may make welding a more attractive proposition for those workers who are involved.

Underpining these developments is the continued need to better understand the processes and to model their behaviour. It has been shown that a fundamental approach can lead to radical improvements in the control and performance of welding processes as can a more lateral approach to combining seemingly diverse process and automation technologies.

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