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Gary Dean, John Norrish and Chris Cook

Dip transfer gas metal arc welding (GMAW) is used extensively for high productivity welding of thin sheet steel, and is also useful for positional welding of thicker section steels. Unfortunately in the past, the process has gained a reputation for fusion defects, which becomes more apparent when welding traditionally difficult materials such as coated steels. This reputation can be attributed in some instances to the method of control used and the changeable nature of variables crucial to controlling heat transfer during the welding process.

The paper examines the relationship between weld fusion, heat input and current for coated steel welding applications and evaluates the effectiveness of two common control techniques when exposed to variation in welding torch angle.

It is concluded that current control produces more consistent weld penetration and fusion area, irrespective of variations in welding torch angle or whether the base sheet steel is Zn or Zn-Al alloy coated.

Keywords

Dip transfer, GMAW, heat input, fusion, welding torch angle, coated steel.

Introduction

Dip transfer gas metal arc welding (GMAW) is a fusion welding process which is characterised by a continuously fed consumable electrode wire, which alternates between a droplet transfer-weld pool short circuiting state, and an arcing period, re-established once the molten bridge ruptures. Generally two common control techniques have been developed for dip transfer GMAW: constant voltage (CV), where the control system regulates the power source output voltage; and current control (CC), where the output current level is regulated.

For dip transfer GMAW applications control of the filler-wire melting rate is generally a function of the mean current, which for constant voltage control is dependent on the open-circuit voltage, static V/A characteristics, wire feed rate and secondary inductance. The open-circuit voltage is related to the arc voltage and in conjunction with the wire feed rate determines the operating and maximum short circuit current flow. The secondary inductance controls the current rate of change and provides a mechanism for controlling weld spatter and plate fusion[1].

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Using CV control spatter is reduced by limiting the maximum current during the short circuit through the addition of inductance[2]. However this approach tends to decrease the short circuit to arcing period ratio[3] with the longer arcing period providing greater heat input, which may be beneficial in some circumstances but may make the process more difficult to control on thin sheet. Therefore the optimum inductance for some welding applications may depend upon factors other than spatter minimisation[2].

Improved control of the dip transfer GMAW process is possible if the short circuit and arc heating stages can be de-coupled. The rapid development in power electronic technology has made it possible to implement current control waveforms which de-couple the welding process and offer greater control and regularity of the dip transfer GMAW process[4], for enhanced control of heat transfer and work-piece fusion compared to conventional CV control. A number of these current control waveforms have already been applied to dip transfer GMAW applications.

Unfortunately in the past, the process has gained a reputation for fusion defects, which becomes more apparent when welding traditionally difficult materials such as coated steels. This reputation however can be addressed through an evaluation of the above control techniques, but first it is crucial that an understanding of the variables and mechanisms which most influence heat transfer and fusion is attained.

Background

Calculation of heat input and power

It is widely accepted that heat transferred to the workpiece, is a function of the power delivered to the arc, the heat transfer thermal efficiency and the welding travel speed, s. The weldment heat transfer H_n can be calculated using the following equation[5]:

$$H_n = \frac{\eta_t \times P_{av}}{s} \qquad (1)$$

where η_t is the heat transfer thermal efficiency, s is the welding travel speed in mm/s and P_{av} is the arithmetic mean power delivered to the arc which for dip transfer welding is the arc power averaged over the dip cycle as outlined by Equation 2.

$$P_{av} = \frac{1}{(t_3 - t_1)} \sum_{t_2}^{t_3} v_{arc}\, i_{arc} \qquad (2)$$

where v_{arc} is the arc voltage, t_1 is the start time of the short circuit period, t_2 is the start of the arcing period and t_3 is the end of the arcing period and the start of the next short circuit. In practice it is not always possible to measure the true arc voltage. However the characteristic short circuit behaviour of the dip transfer process lends itself to an indirect approach, which measures the short circuit resistance, r, during the droplet transfer and when incorporated into the following equation, facilitates the calculation of an estimated arc voltage.

$$v_{arc} = v_{supply} - i_{arc}\, r \qquad (3)$$

Mechanisms that control heat input

Heat transfer to the work-piece has a significant influence on weld fusion with the control of heat input achieved through a variety of means. In particular through the regulation of welding process parameters such as mean current, which for a range of welding processes including GMAW[6-8] has been demonstrated to have a linear correlation to the measured work-piece heat input. This observation is supported by the plate fusion model for pulsed GMAW proposed by Allum and Quintino[9], where for given material factors (plate, wire and shielding gas), the dilution behaviour is reported to be a function of the product of current I and travel speed s. The arcing current logically has the greatest influence when the deposition rate and travel speed remain constant.

Previous work[10] with dip transfer GMAW also reports a linear correlation between the weld fusion area and the average cycle arcing current, as defined by Equation 4. Based on the premise that arcing current is the principal variable in controlling heat input for dip transfer GMAW, Westendorp[11] developed a servo adjusted MIG control technique that was implemented in an inverter power source. The concept of the control technique was to regulate the average cycle arcing current during the dip transfer process to satisfy the following equation:

$$I_A = \frac{1}{(t_3 - t_1)} \int_{t_2}^{t_3} i\, dt \qquad (4)$$

I_A is controlled to a predetermined value for each arcing period, the value of which is dependent on the required work-piece heat input. The basis of the equation assumes that negligible energy is transferred to the work-piece during the short circuit period.

As can be seen from previous research, a strong correlation exists between the arcing current and the heat transferred to the work-piece. Therefore, when evaluating welding control methods consideration must be given to the capability of the technique to regulate current flow to the desired level.
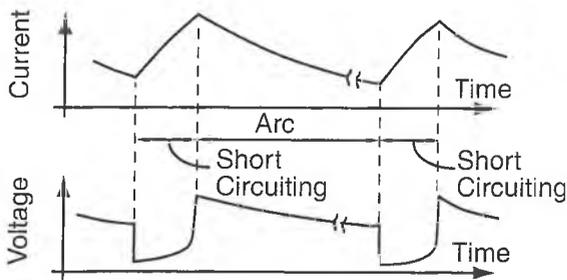

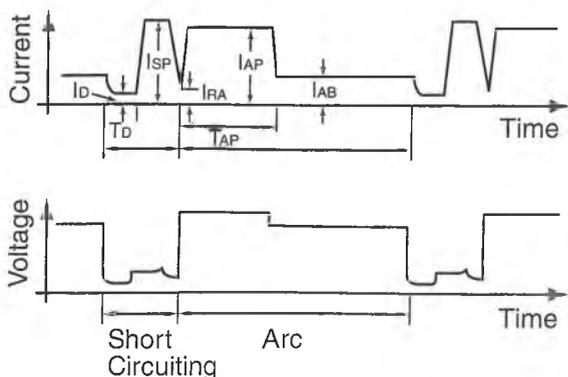*Figure 1. Constant voltage control waveform.*

Figure 2. Current Control Waveform[21].

Dip Transfer Control Techniques

Voltage Control

Conventional GMAW power sources have been designed for constant voltage characteristics, which provide self-adjustment and stabilisation of the arc length. Using this form of control, variations in arc length produce a change in the current flow and burn-off behaviour of the electrode. The response counteracts the arc length variation and therefore provides self-regulation[12]. An example of the transient waveforms typically produced when using a CV power source for dip transfer is illustrated in Figure 1.

At the onset of the short circuit the current increases at a rate governed by the welding circuit inductance. This rate of rise in current must be sufficient to enable the molten bridge to "clear" and re-establish the arc[1]. For small values of inductance the current rise is rapid resulting in high current and spatter at the molten bridge rupture. Conversely excessively high values of inductance can cause arc failure during re-ignition or instability at low arcing currents[13].

For the arcing period the level of inductance impacts significantly on the current and heat transferred to the work-piece. The higher the inductance the longer the arcing period and greater the heat transferred to the work-piece.

Current Control

As stated earlier the rapid development in power electronic technology has made it possible to implement current control waveforms for dip transfer GMAW. The use of these waveforms has been proposed by a number of authors[13-19], with many of these approaches already applied to practical welding applications.

A common characteristic of each current control waveform has been the control philosophy applied at the start of each short circuit period. During the initial contact between the droplet and the weld pool, the current flow is reduced and held at a low level to minimise the magnetic repulsive forces that exist during the wetting-in period. Once the wetting-in period has expired, the current is increased to produce an electromagnetic pinch force to promote the molten bridge rupture and droplet transfer.

On re-establishment of the arc a pre-determined current pulse is applied to produce rapid droplet burn-back and weld pool depression, which significantly reduces the incidence of incipient short circuits[20]. The arcing current is subsequently reduced to a background level. A typical current control waveform is shown in Figure 2.

The short circuit cycle can be easily identified due to the rapid rise in voltage that occurs with the arc ignition and the rapid drop in voltage as the arc extinguishes with the short circuit[22]. A review of the waveform characteristics of Figures 1
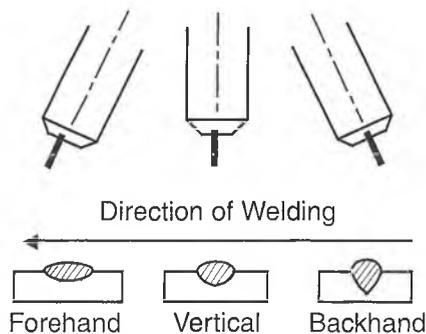

Figure 3. Impact of torch angle welding thick cross-section material[23].
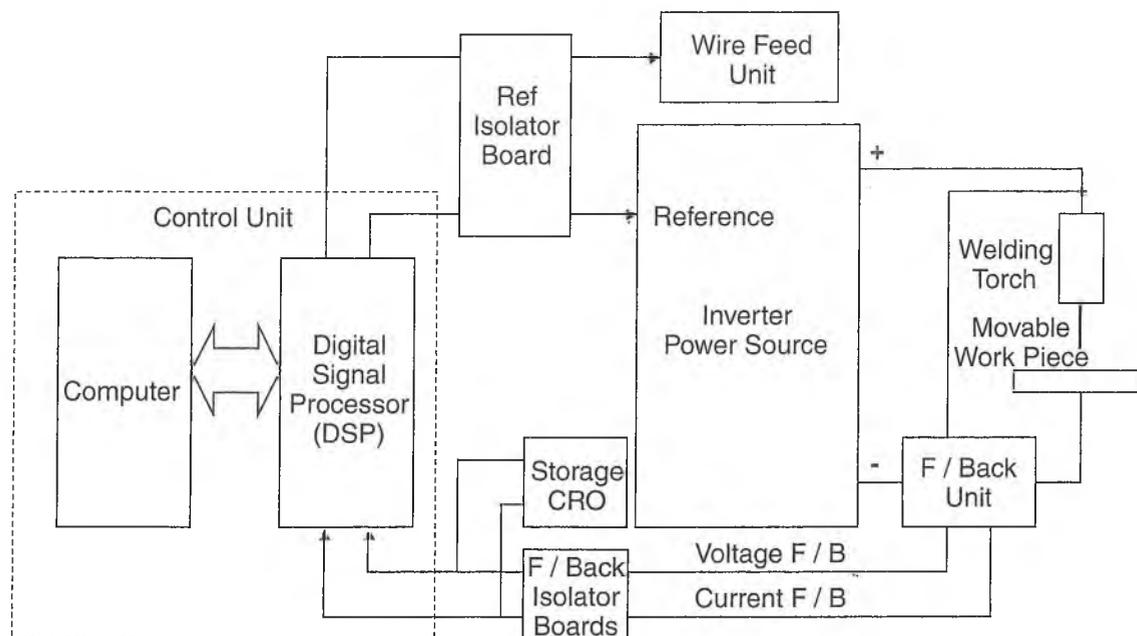
Figure 4. Schematic representation of the experimental setup.

and 2 reveals obvious dissimilarities with regards to the effective voltage and current during the short circuit and arcing periods. Identifying and understanding these dissimilarities is pivotal when developing an understanding of heat transfer in dip transfer GMAW.

Welding Torch Angle

Generally with all arc welding processes the electrode position, which can be defined as the relationship of the electrode axis with respect to travel direction, travel angle and the adjacent work surface (work angle) will impact on the weld bead shape and penetration. Figure 3 illustrates three common welding torch orientations with results, which are commonly observed when using conventional constant voltage control techniques.

When the torch orientation changes from the perpendicular to a forehand angle, the molten metal is pushed towards the leading edge of the weld pool, with a decrease in penetration, along with a wider and flatter weld bead often observed when using this torch orientation to weld thicker material. This technique, even though undesirable for some welding applications, is very useful for vertical welds to assist in holding the metal in place.

Conversely with a backhand torch angle the molten metal is pushed away from the leading edge, towards the back of the weld pool where additional weld reinforcement is formed. This torch orientation tends to produce a more convex, narrower and larger bead. The heat source is concentrated back towards the weld bead where the thermal energy is likely to slow the cooling rate of the weldment and effectively increase the heat input. A shorter arc length results when using this torch orientation which is inclined to affect the absolute values of current and voltage, with a slightly lower voltage setpoint required to achieve a given welding current[24].

Experimental procedure

Welding trials were carried out in dip transfer GMAW using both current control and conventional constant voltage control techniques with the experimental setup shown in Figure 4. The current control welding trials were performed with a 400 A inverter power source developed at the UOW for welding research, while the corresponding welding trials using constant voltage control were performed with a Thermadyne 600GMS inverter power source. Control of the power sources was through a programmable DSP computer system using customised software for the implementation of the respective control waveform. The customised control software offering the flexibility to control the various stages of the dip transfer process as required.

Close square butt welds of 100 mm length were produced on 1 mm thick sheet steel coated steels: Zinc-HI-TEN™, G550, Z275 galvanized; and G550, A2150 Zincalume™ (Zn-55 wt%Al), using an Ar-3%O-5%CO$_2$ shielding gas at 18 litres/min. The electrode wire was 0.9 mm diameter mild steel, which conformed to ER70S-6 AWS specification. Welding parameters were maintained for both constant voltage and current control trials. The welding torch was stationary and fixed in a vertical, 15° forehand or 15° backhand angle for a 10 mm CTWD. The work-piece, which was secured to a movable bed travelled at a speed of 500 mm/min, while the wire feed rate was set to 2.56 m/min for the galvanized and 2.36 m/min for the Zincalume™ sheet steel welds.

Welding current and voltage signals were sampled and recorded with a Nicolet 490 storage oscilloscope at 20 kSa/s over a 1 second sampling period. At approximately the midpoint of each weld the oscilloscope was triggered, recording a 1 second interval of the welding process. An analysis of the transient voltage and current waveforms was performed using customised software in a Matlab environment, with extracted data providing details of heat input and the average cycle arcing current.

Weld samples were cross-sectioned, polished with varying abrasive disc grades and etched using a 2.5% Nital etchant, which comprises 97.5% ethanol + 2.5% nitric acid. Digital images of the macro-sections were recorded for analysis after etching, with image processing software later used to extract weld fusion characteristics relating to the weld fusion area and reinforcement. Digital images were also recorded of the welded sheet steel surface to assess the respective control techniques for coated surface damage attributable to generated weld spatter.

TM: Trade marked coated steel products of Bluescope Steel Ltd, Port Kembla, NSW, Australia

Results and discussion

Welding data and analysis

Using the above equations which define weldment heat input, arc power, arc voltage and average cycle arcing current (Equations 1-4), sampled waveforms were analyzed and data extracted. A thermal efficiency of 0.85 for dip transfer welding was chosen based on previous work[7,25,26]. The resultant data were correlated and utilised for analysis within this section.

Table 1. Heat transfer process variables.

Base Material	WFR W m/min	Travel Speed s mm/s	Heat Thermal Efficiency η_t
Galvanized 1mm	2.56	8.33	0.85
Zincalume 1mm	2.36	8.33	0.85

Welding trials on the galvanized and Zincalume™ sheet steels were performed under a variety of welding conditions, which are described in the experimental procedure.

Fusion area verses heat input – galvanized sheet steel

Welding trials were carried out using both constant voltage and current control techniques with an Ar-3%O-5%CO_2 shielding gas to produce a close square butt weld on 1 mm thick galvanized sheet steel. The control techniques were applied with forehand, backhand and vertical torch angles and a CTWD of 10 mm.

The relationship between the fusion area and weldment heat input was examined along with the relationship between the measured fusion area and the average cycle arcing current. The measured fusion area is plotted as a function of the weldment heat input and average cycle arcing current. The method of least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 5 (a) and (b).

An evaluation of the limited data points of Figure 5 (a) and (b) suggests a strong linear correlation exits between the weld fusion area and weldment heat input or average cycle arcing current irrespective of the control technique or torch angle when welding galvanized sheet steel. The standard deviation in fusion area for either relationship is no greater than 0.1 mm², as shown in Table 2.
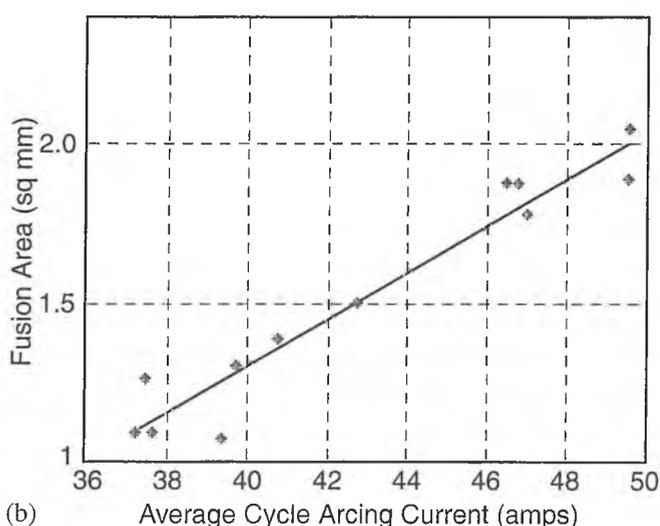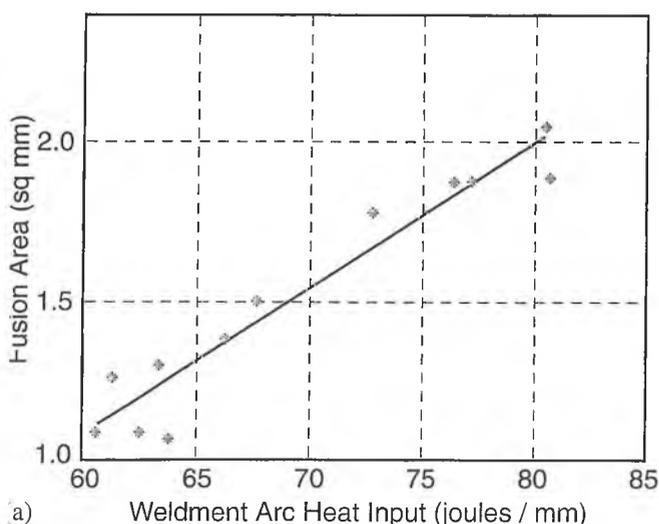

Figure 5. Weld bead fusion area AF for galvanized sheet welds as a function of (a) calculated heat input; and (b) average cycle arcing current.
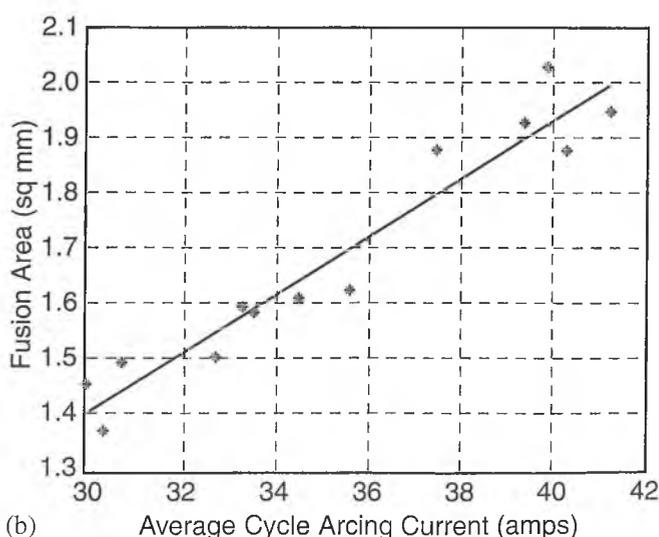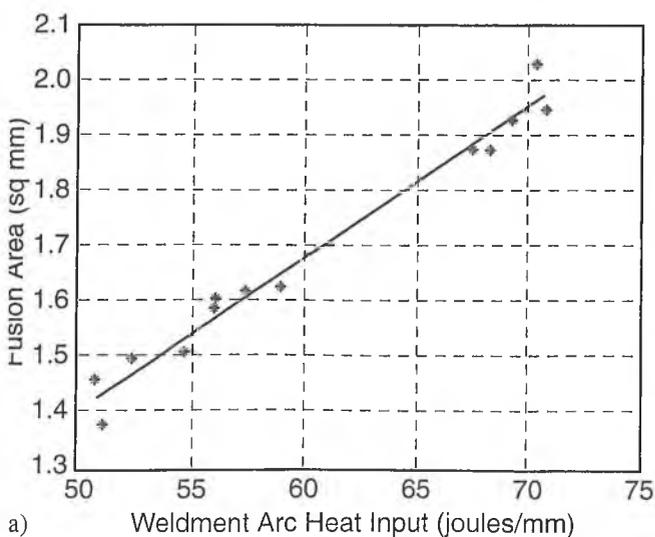

Figure 6. Weld bead fusion area AF for Zincalume™ sheet welds as a function of (a) calculated heat input; and (b) average cycle arcing current.

Measured Variable	Standard Deviation in Fusion Area
Weldment Heat Input	0.1 mm^2
Average Cycle Arcing Current	0.09 mm^2

Fusion area verses heat input – Zincalume™ sheet steel

Using an identical approach to that described in the previous section, welding trials were carried out to produce a close square butt weld on 1 mm thick Zincalume™ sheet steel. The measured fusion area was plotted as a function of the weldment heat input and average cycle arcing current. The method of least squares was applied to the data points, with lines of best fit drawn to illustrate the respective relationships which are shown in Figure 6.

An evaluation of the data points of Figure 6 (a) and (b), suggests as also reported for galvanized sheet steel welds, a strong linear correlation between the weld fusion area and weldment heat input or average cycle arcing current. This is irrespective of the control technique or torch angle when welding Zincalume™ sheet steel. The standard deviation in fusion area for either relationship is no greater than 0.06 mm^2, as shown in Table 3.

Table 3. Standard deviation in fusion area – Zincalume ™ sheet welds

Measured Variable	Standard Deviation in Fusion Area
Weldment Heat Input	0.03 mm^2
Average Cycle Arcing Current	0.06 mm^2

The experimental results presented here and in the previous section suggests the weld fusion area has a strong linear correla-

tion to the weldment heat input and average cycle arc current for dip transfer GMAW, with the results valid irrespective of the control technique used. However even though this relationship is easily recognised there is no certainty that control of the fusion area is maintained once the welding process is exposed to variations in the welding torch angle.

Effect of torch angle – galvanized sheet

The electrode orientation as discussed earlier is generally recognised to have an impact on the welds bead shape and penetration. Therefore the initial investigation evaluated the consistency in penetration, fusion area, heat input and the average cycle arcing current produced by the respective control techniques when exposed to variations in torch angle for galvanized sheet steel welds. The macro-sections of welds produced using the current control technique with variable welding torch angle are displayed in Figure 7.

The macro-sections in Figure 7 are typical of the results achieved when using the current control technique to weld galvanized sheet steel. The welding parameters were identical for each weld, with comparable heat input and average cycle arcing current producing consistent weld penetration and fusion area irrespective of the torch orientation which is emphasised by the images of Figure 7 (a), (b) and (c). The only observed variation is the measured output voltage, which changed with torch orientation. It was noted that the measured output voltage was generally higher with a forehand torch and conversely lower for backhand torch angles. These results can be compared to welds produced using a constant voltage control technique.

It was noted when welding with CV control the average cycle arcing current varied significantly when exposed to variations in torch angle. A backhand torch angle produced a larger weld fusion area and higher average cycle arcing current, while a forehand torch angle tended to produce a lower value of average cycle arcing current, with a correspondingly smaller penetration and fusion area. The macro-sections of welds produced using this technique are displayed in Figure 8.
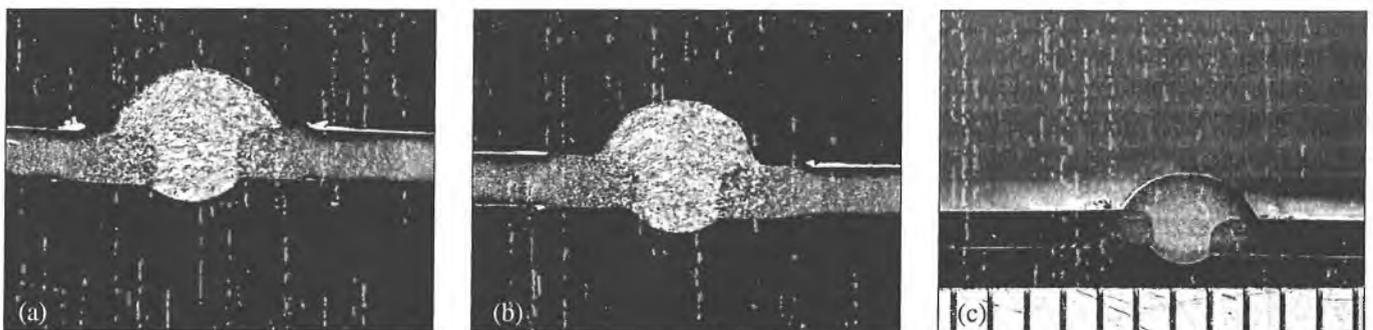

Figure 7. Macrographs of traverse sections of weld beads produced using current control (CC) in 1 mm thick galvanized sheet, as a function of torch angle: (a) backhand; (b) vertical; (c) forehand.
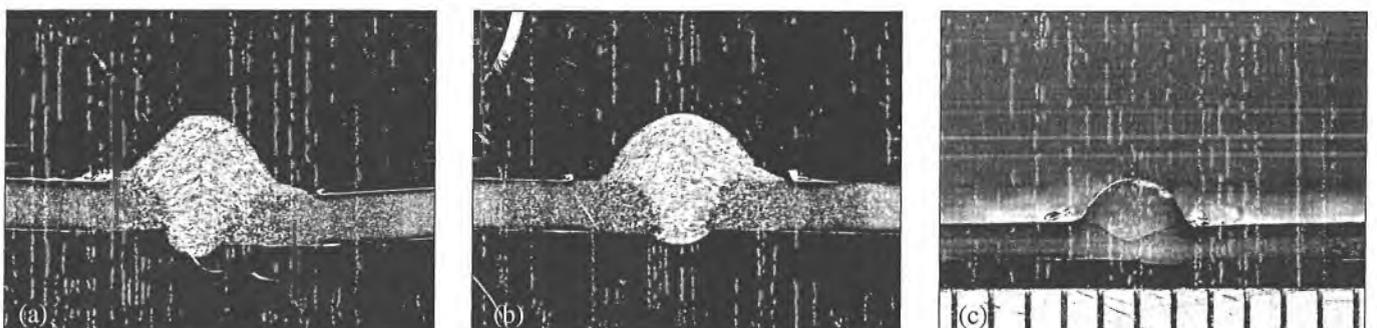

Figure 8. Macrographs of traverse sections of weld beads produced using CV control in 1mm thick galvanized sheet, as a function of torch angle: (a) backhand – 14 V; (b) vertical – 14.4 V; (c) forehand – 14.4 V.

The macro-sections shown in Figure 8 are typical of results achieved using a constant voltage control technique to weld galvanized sheet steel with a power source inductance setting of 50%. The images of Figure 8 (a), (b) and (c) clearly illustrate differences in bead penetration and fusion area. For CV control, the forehand torch orientation results in lower weld bead penetration.

Even though the analysis revealed the backhand and vertical torch positions produced similar heat input and fusion area as can be seen in Figures 8 (a) and (b), it should be emphasised that the voltage setpoint used for the backhand torch angle was lower and if altered to the setpoint value used for the vertical torch an increase in heat input and fusion area should be observed. Conversely inadequate penetration and fusion area was noted when the torch orientation was changed from the vertical to a forehand angle.

The lower weld penetration for the 15° forehand torch angle orientation is also illustrated by the images in Figure 9. A comparison of these images demonstrates the differences in weld penetration, uniformity and continuity for the constant voltage and current control techniques.

The weld penetration produced by using current control, Figure 9(b), is clearly more consistent over the length of the weld compared to that produced using the voltage control technique, Figure 9(a), for the same torch orientation. However, an increase in weld penetration can be obtained when using constant voltage control through an increase of the voltage setpoint.

The effect of torch angle on penetration and fusion area highlights irregularities in weld quality obtained for some voltage control techniques, that are not seen when using current control to weld galvanized sheet steel.

Effect of torch angle – Zincalume™ Sheet

The impact of torch angle on weld fusion characteristics when welding Zincalume™ sheet steel was also examined with the performance of the control techniques assessed. As described in the previous section the investigation initially focused on evaluating the consistency in penetration, fusion area, heat input and average cycle arcing current for the respective control techniques when exposed to variations in torch angle. The macro-sections of welds produced using the current control technique with variable welding torch angle are displayed in Figure 10.

The macro-sections shown in Figure 10 are typical of the consistency in penetration and fusion area achieved when using the current control technique. The welding parameters were identical for each weld, with comparable heat input and average cycle arcing current producing relatively consistent penetration and fusion area irrespective of the torch angle. This can be compared with welds produced using the constant voltage control technique which are shown in Figure 11.

The macro-sections shown in Figure 11 are typical of the consistency in penetration and fusion area achieved. The voltage setpoint was 15 V with the power source inductance set to 50%.

It can be seen from the above results that the penetration and fusion area did not vary significantly with variations in welding torch angle, as was observed for welding of galvanized sheet steel. Rather, the average cycle arcing current was seen to decrease slightly with a backhand torch angle, resulting in a corresponding decrease in fusion area. The consistent weld penetration achieved over the length of the weld when using either control technique is also highlighted in Figure 12.

As can be seen in Figure 12 (a) and (b) relatively consistent weld penetration was achieved irrespective of torch angle or control technique when welding the Zincalume™ sheet steel.

Spatter and coated surface damage

The weld spatter generated while welding coated steels can significantly damage the surface coating. Therefore when welding such materials the selection of process parameters should not only achieve the desired heat input but also minimise weld spatter and potential coated surface damage. A comparison of the coated surfaces when using the two control techniques to weld galvanized sheet steel is shown in Figure 13.
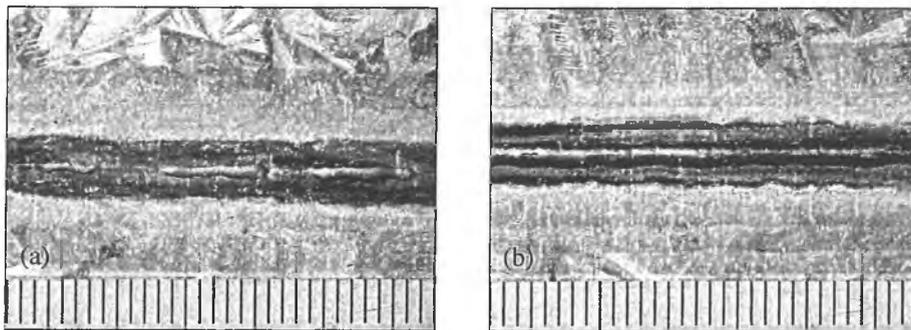

Figure 9. Weld penetration bead in galvanized sheet produced by welding with a 15° forehand torch angle under (a) CV and (b) CC conditions.
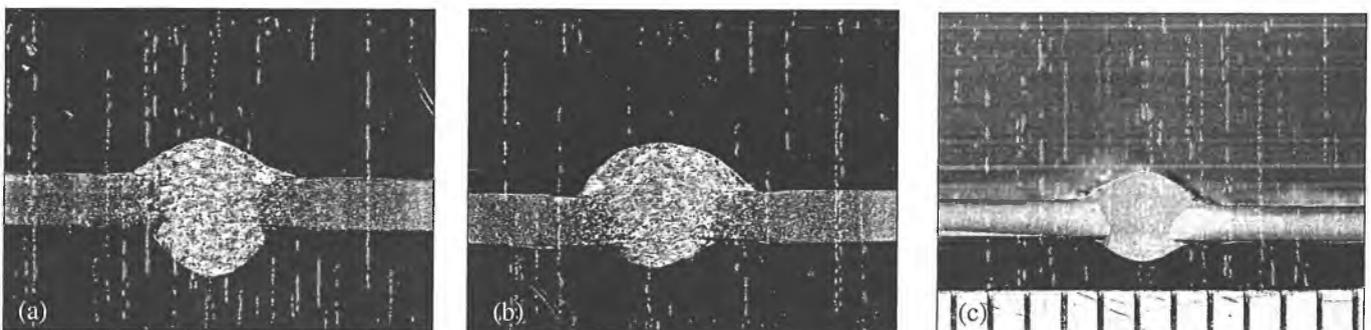

Figure 10. Macrographs of traverse sections of weld beads produced using current control (CC) in 1mm thick Zincalume™ sheet, as a function of torch angle: (a) backhand; (b) vertical; (c) forehand.

Based on the limited experimental work with coated steels the current control technique was noted to produce significantly less weld spatter and coated surface damage than that observed when using constant voltage control. As can be seen in Figure 13(a) the damage to the coated surface is significantly worse when using constant voltage control compared to current control, Figure 13(b), for which coated surface damage by weld spatter is minimal. Similar observations were noted for welding of both galvanized and Zincalume™ sheet steels.

Experimental Errors

Sampled voltage and current waveforms are unlikely to be captured at the same instant of time that the sampled weld bead section was produced. The macro-section and waveforms are indicative of the conditions present at the time of welding and will account for some variations in the correlated data.

Conclusions

This paper deals with some of the conditions that govern fusion control in dip transfer GMAW and reviews some of the control dissimilarities inherent with constant voltage and current control techniques. Experiments were set up to investigate the relationship that exists between weld fusion, weldment heat input and average cycle arcing current, and to compare the performance of constant voltage control and current control welding techniques when welding coated steels. The following conclusions are drawn.

1. Current control techniques produce more consistent weld penetration and fusion area, irrespective of variations in welding torch angle or work-piece base material.

2. Consistent weld penetration and fusion area can be achieved using constant voltage control techniques; however inconsistent results can be experienced when the welding process is exposed to variations in welding setup, torch angle and base material.

3. A strong linear correlation exists between fusion area and weldment heat input when welding galvanized and Zincalume™ coated sheet steels if the arc power is calculated as a function of the instantaneous arc voltage and current.

4. A strong linear correlation exists between fusion area and the average cycle arcing current when welding galvanized and Zincalume™ coated sheet steels if the average arcing current is calculated as a function of the dip cycle.

5. Weld spatter and any resulting coated surface damage can be significantly reduced using a current control technique.
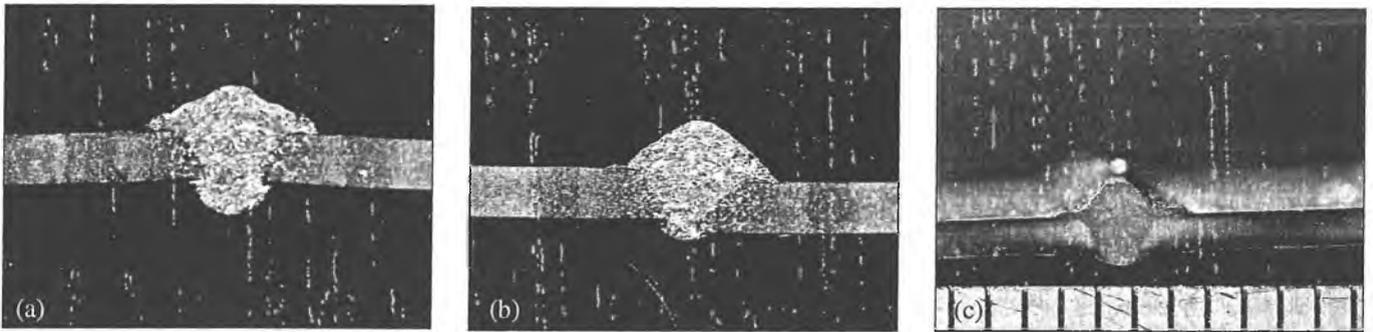

Figure 11. Macrographs of traverse sections of weld beads produced using CV control at 15 V in 1mm thick Zincalume™ sheet, as a function of torch angle: (a) backhand; (b) vertical; (c) forehand.
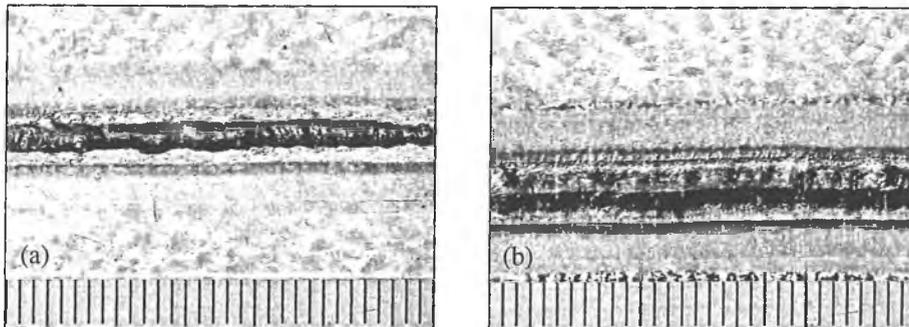

Figure 12. Weld penetration bead in Zincalume™ sheet produced by welding with a 15° forehand torch angle under (a) CV and (b) CC conditions.
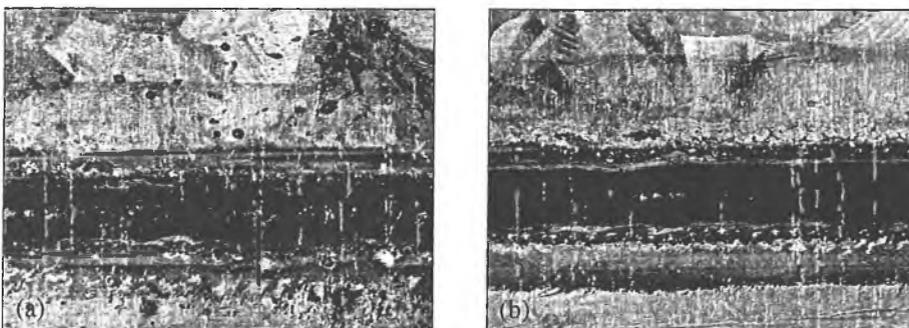

Figure 13. Coated surface damage for welding of galvanized sheet steel under (a) voltage control; and (b) current control.

With the use of microprocessor control in inverter based ...ding power sources, it is now possible with dip transfer IAW to accurately control the average cycle arcing current therefore heat transfer to the work-piece. Further work is ...ired to ascertain the usefulness of an on-line control strategy ...ed on controlling the average cycle arcing current.

...knowledgements

...ferences

...A. Smith: CO_2 welding of steel, The Welding Institute, Cambridge UK, ...970.

... D. Lewis, D. N. A. Bax: "Effect of Inductance on Spatter Loss in the ...O_2 Shielded Welding of Mild Steel", *British Welding Journal*, 1964, 11 ...4), pp.157-162.

...A. Smith: BWRA Members Report No. A1/24/62.

... Middleton: "A comparison of conventional dip transfer welding using a ...V.I power source and controlled dip transfer welding using a transistorised ...ower source", MSc Thesis, Cranfield Institute of Technology, 1987.

... F. Lancaster: Metallurgy of Welding, 3rd Ed., George Allen & Unwin ...td, London, 1980.

...V. G. Essers and R. Walter: "Heat Transfer and Penetration Mechanisms ...ith GMA and Plasma-GMA Welding", *Welding Journal*, 1981, 60 (2), ...p.37s-42s.

...I. R. Bosworth: "Effective Heat Input in Pulsed Current Gas Metal Arc ...elding with Solid Wire Electrodes", *Welding Journal*, 1991, 70 (5), ...111s-117s.

... L. Apps and D.R. Milner: "Heat flow in argon-arc welding", *British ...elding Journal*, 1955, 2 (No. 10), pp.475-485.

... J. Allum, L. Quintino: 'Control of fusion characteristics in pulsed cur...nt GMAW', IIW Doc. 212-582-84.

... Dean, J. Norrish and C. Cook: 'Fusion control in dip transfer gas metal ...c welding', Proc. WTIA 48th Annual & IIW Asian Pacific International ...onference, Paper 28, Melbourne Australia, October 2000.

... F. Westendorp: "Pulsed MIG/MAG and Servo Adjusted MIG (SAM) ...urce using transistor inverter at 40 kHz", Philips Netherlands Internal ...port.

12. J. Norrish: Advanced Welding Processes, IOP Publishing Ltd, Bristol, 1992, ISBN 0-85274-326-2.

13. T. Mita: "Developments in Power Source Technology for the Gas-Shielded Arc Welding of Thin Plates", International trade publications for Hitachi Europe.

14. T. Ogasawara, T. Maruyama, T. Saito, M. Sato and Y. Hida: "A Power Source of Gas Shielded Arc Welding with New Current Waveforms", *Welding Journal*, 1987, 66 (3), pp.57-63.

15. P. Boughton and G.J. MacGregor: "Control of short circuiting in MIG-welding", *Welding Research International*, 1974, 4 (2), pp.31-53.

16. E. K. Stava: "A New, Low-Spatter Arc Welding Machine", *Welding Journal*, 1993, 72 (1), pp.25-29.

17. E. K. Stava: "Low spatter welding", *Australasian Welding Journal*, 1995, 40, Fourth Quarter, pp.21-24.

18. T. Maruyama, M. Okada, Y. Hida, M. Honma and T. Minato: "Current Waveform Control in Gas Shielded Arc Welding for Robotic Systems", Kobelco Technology Review, No.18, April 1995.

19. Z. Ou, Y. Wuang, M. Ushio and M. Tanaka: "New Concept for the Characteristic of an Arc Welding Power Source (Report II)", *Trans. JWRI*, 1999, 28 (1).

20. H. Yamamoto, S. Harada and T. Yasuda: "The development of welding current control systems for spatter reduction", *Welding International*, 1990, 4 (5), pp.398-407.

21. T. Ogasawara, T. Maruyama, M. Sato, Y. Hida and T. Saito: Output control of short circuit welding power source, US Patent No. 4,546,234.

22. S. Liu and T. A. Siewert: "Metal transfer in gas metal arc welding: Droplet rate", *Welding Journal*, 1989, 68 (2), pp.52s-58s.

23. American Welding Society Welding Handbook, 7th Ed. Volume 2, Welding Processes – Arc and Gas Welding and Cutting, Brazing and Soldering, Editor W. H. Kearns, The MacMillan Press Ltd, London, 1978, Chap. 4 Gas Metal Arc Welding.

24. Y. W. Chen, D. P. Dunne and J. Norrish: "Effect of Electrode Orientation on Structure and Properties of GMA Butt Welds of High Strength Zinc Alloy Coated Sheet Steel", The WTIA 50th Annual Conference, Sydney Australia, August 2002, paper 33.

25. A. D. Watkins, H. B. Smartt and C. J. Einerson: 'Heat Transfer in Gas Metal Arc Welding', Proceedings of the 2nd International Conference on Trends in Welding Research, May 1989, Gatlinburg USA, ASM International, pp.19-23.

26. P. W. Fuerschbach: "Melt efficiency in fusion welding", The Metal Science of Joining, edited by M. J. Cieslak, J. H. Perepezko, S. Kang and M. E. Glicksman, The Minerals, Metals and Materials Society, 1992.