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Characterisation of the cold metal transfer (CMT) process and its application for low dilution cladding

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ABSTRACT

The process characteristics of the synergic cold metal transfer (CMT) process have been examined for welding aluminium alloy. Utilising a simple backlighting system and through the arc monitoring the droplet transfer modes were identified. Whilst the modified short circuit mode was evident for the lower parameter range, a two part transfer mode based upon a combination of spray and short circuit transfer was observed for the mid to upper parameter range. The technology was also explored as a cladding process for applying to ternary alloyed (Al–Cu–Mg) aluminium plate. This alloy system is known to be susceptible to solidification cracking when MIG welded using the binary Al-2319 (Al–Cu) filler wire, this being due to the wide element freezing range of the weld resulting from mixing with the base material. Utilising this filler, weld dilution ratios for both CMT and pulsed welding were identified across the examined parameter range. The CMT process exhibited greater control of dilution that enabled deposition of a quasi-binary (Al–Cu) layer exhibiting a less crack susceptible composition. Onto this layer conventional MIG welding could be applied which could potentially eradicate cracking using a binary filler wire.

1. Introduction

Arc welding of thin sheet aluminium alloys pose unique challenges. Due to comparatively high coefficients of thermal expansion and thermal conductivity when compared to steel, control of heat input to the weldment is a major prerequisite. Traditionally the pulsed mode of operation is used for this application, with spray transfer being discounted as being suitable only for thicker section due to the associated higher heat inputs. In contrast to the welding of thin steel sheet, traditional short circuit/dip transfer is rarely used. Houldcroft and John (1988) highlighted the occurrence of poor material transfer and ensuing fusion defects when applying this process due to the low resistance of aluminium filler wires. Although developments in power source technology have seen advances in the control of this transfer mode (Lincoln STT; Kemppi Fastroot) these process are essentially variants of the traditional dip transfer process and as such are generally not considered suitable for aluminium. Cold metal transfer (CMT) welding is a relatively new technology that partially decouples the arc electrical transients from the filler wire feed rate. Although the process relies on a filler wire short circuit for material transfer, by controlling both the cycle arcing phase and the wire feed rate sufficient energy can be realised to melt both the base material and a molten globule of filler wire. The result is that material transfer can be realised at the point of short circuit with low arc energy and hence reduced heat input to the weldment.

The basic operating principles of the process were previously reported by Pickin and Young (2006). The controlled method of material deposition and higher melting coefficient when compared to conventional arc welding processes highlighted the suitability of CMT for welding thin aluminium alloy sheets. This work has been expanded with similar findings being reported by Feng et al. (2009) for welding aluminium sheets and of Wang et al. (2008) for welding dissimilar alloys. Additional studies by Agudo et al. (2008) and Zhang et al. (2007) have reported the potential of the process to join steel to aluminium due to the reduced heat input which results in control over the formation of brittle inter metallics. However it is notable that these studies have generally focused upon the properties of the deposited weld bead based upon the process operating principles as defined by the system manufacturer. No exhaustive works examining the characteristics of the process across the available parameter range have yet been reported. The objective of this work is to fully characterise the operation of the process when operating in synergic mode for the welding of aluminium and explore the potential of the technology as a cladding process. In particular control of weld dilution was examined when welding ternary high strength aluminium (Al-2024) plate using the binary Al-2319 (6% Cu) filler wire. Pickin et al. (2009) have previously shown that severe solidification cracking resulted when using this filler to MIG weld constrained fillet test pieces. Thermo-

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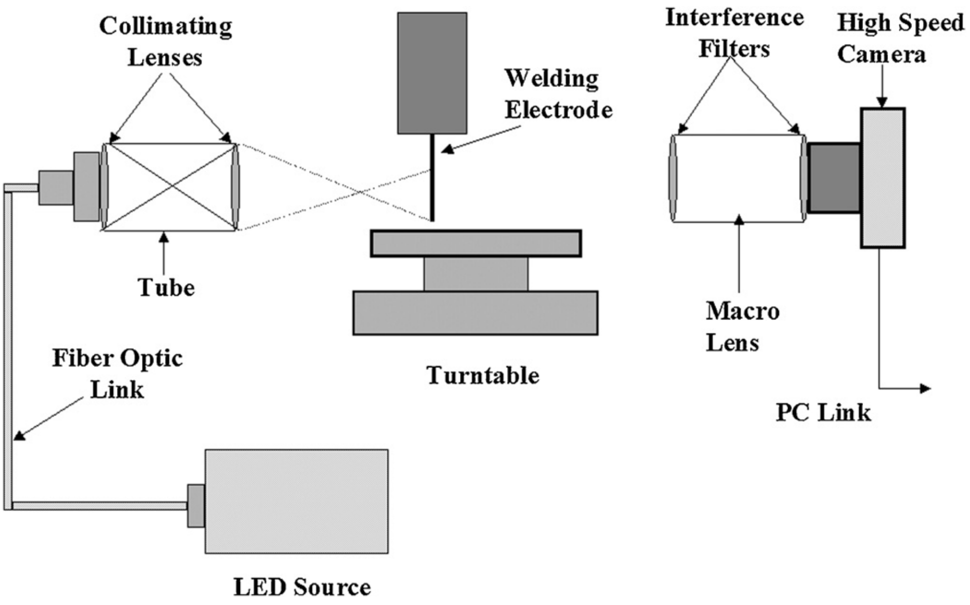

Fig. 1. High-speed camera and LED backlighting configuration.

dynamic modelling illustrated that suppression of cracking could be realised by controlling the terminal eutectic reactions in the weld bead with validation showing that this was possible by utilising a ternary filler composition (Al–Cu–Mg). However only binary fillers are commercially available with the result that the full potential of many high strength alloy systems cannot be fully exploited. By controlling weld bead dilution using a binary filler wire a clad layer could be deposited onto the ternary base material surface that was essentially quasi-binary (Al–Cu) i.e. the composition was not in a crack susceptible composition range. Onto this quasi-binary layer conventional MIG welding could then be employed using the same binary filler wire to join the component. Lorenzin and Rutili (2009) previously reported a similar approach for cladding Inconel 625 onto carbon–manganese steel for corrosion resistant applications. Controlling weld dilution minimised mixing of the filler wire material with potentially corrosion susceptible elements in the base material. However these results were determined within a narrow parameter range and similar to the previously reported research, little characterisation of the process was conducted.

2. Experimental

A simple backlighting system was developed for capturing high-speed images of material transfer. A 60 W (electrical power) green light emitting diode (LED) was employed emitting a wavelength of 530 nm. This was directed via a fiber optic link to two collimating focusing lenses to backlight the arc plasma. The camera used was a Phantom Miro-4M employing a macro lens containing two interference filters (FWHM = 10 nm). Frame capture rate was set at 2900 frames/s. This configuration is shown in Fig. 1. Analysis of optical data was by vision software and MATLAB processing. In addition a high-speed storage oscilloscope was used to capture both electrical arc transients and wire feed rates via mechanical tachometer readings.

Utilised base material, filler wires and specified composition ranges are detailed in Table 1. Filler wire diameter was maintained at 1.2 mm for all experiments. For process characterisation sheet base material thickness of 3.2 mm was used and for cladding experiments plate of 12.7 mm thickness was employed.

Instantaneous values were derived from captured electrical waveform transients. The instantaneous power value was calculated using Eq. (1), this being derived from the product of the measured instantaneous current (I_i) and instantaneous voltage (V_i) values. Work by Joseph et al. (2003) and Koiotynskii et al. (2005) have shown this approach to have a greater accuracy than that based upon average values when investigating pulsed welding. As the CMT cycle is modulated between two phases with wide differences in process values, greater accuracy will be realised by adopting this approach than using the cycle average values.

$$P_{ai} = I_i V_i \tag{1}$$

Cross-sections taken from the weld bead were prepared and measured using standard metallographic techniques. Weld bead dilution ($R\%$)was determined using Eq. (2) where Ab is the area of weld penetration and Af is the area of weld reinforcement.

$$R\% \quad \text{Weld} = \frac{Ab}{Ab + Af} \tag{2}$$

Element composition of the weld ($E\%$) at a given dilution ratio was determined using Eq. (3). This has previously been shown by the authors to provide a close fit with EDX measured values.

$$E\% \quad \text{Weld} = (E\% \quad \text{Base}) \times \left[\frac{Ab}{Ab + Af}\right] + (E\% \quad \text{Filler}) \times \left[\frac{Af}{Ab + Af}\right] \tag{3}$$

All welding trials were conducted using a 500 Amp Fronius CMT power source that had the facility to operate in additional transfer modes (spray, pulse, etc.). Pure Argon shielding gas was used with a flow rate of 18 l min^{-1}. Contact tip to work (CTTW) distance was maintained at 17 mm for all welding experiments regardless of transfer mode.

Table 1
Material and filler wire specified composition values.

Material	Mn	Si	Ti	Mg	Zn	Cr	Fe	Cu
Filler 4043	0.05	4.5–6.0	0.20	0.05	0.1	–	0.8	0.30
Filler 2319	0.3	0.2	0.15	0.02	0.1	–	0.3	5.8–6.3
Alloy 2024	–	0.5	0.20	1.2–1.8	0.2	0.1	0.5	3.8–4.9

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3. Principle of operation

The basic operation mode of CMT is characterised by an arcing phase during which a molten droplet is formed on the end of the wire electrode and a weld pool created. After a set duration the wire electrode is fed forward to make contact with the weld pool/base material creating a short circuit. During this phase material transfer is initiated and the arcing current substantially reduced. After a defined period the electrode is mechanically retracted, this rearward motion aiding in pinching the molten globule into the weld pool. The arc is then reignited and the cycle repeats. The process is unique in that not only is deposition controlled by the forward and rearward motion of the electrode, the electrical characteristics are also controlled with the result that material transfer takes place at both low current and low voltage. A typical CMT transient waveform and definition of cycle instantaneous values is shown in Fig. 2.

Partially decoupling the wire feed from the process electrical transients results in an increased electrode melting coefficient when compared to the pulsed mode of welding. This phenomenon was reinvestigated for both CMT and synergic pulsed welding utilising the Al-4043 filler. Instantaneous power was calculated for a corresponding electrode melting rate using Eq. (1). Reference to Fig. 3 shows that compared to pulsed welding, CMT exhibits in the region of 15% greater electrode deposition for similar measured power across the investigated parameter range.

Whilst the melting trend for pulse welding is essentially linear, some deviation is evident for the CMT values, this principally occurring mid range of the investigated parameters shown in the circled area in Fig. 3. Analysis of high-speed film footage of welds deposited using these values show that the process deviated from the previously defined mode of operation shown in Fig. 2. with droplet detachment being observed during the arcing phase. This is shown in Fig. 4a. were one droplet was observed detaching for a feed rate setting of 5.5 m min^{-1} and Fig. 4b. were three droplets were observed for a feed rate setting of 6 m min^{-1}. In the current example a diminished arc is shown at the end of the arcing phase. The arc continues to diminish and fully extinguishes at the point of short circuit (when welding aluminium).

Captured transient signals for the weld shown in Fig. 4b are illustrated in Fig. 5a–c. Reference to the current trace shows little discernable deviation during the arcing phase for droplet transfer. Due to the modified constant current operating mode of the process the system maintains the applied current during the relatively small arc length change caused by droplet transfer. In contrast the current spikes at points ‘A’ and ‘B’ indicate where the filler electrode is fed forward and retracted during the short circuit phase, respectively. This results in a rapid change in arc length and hence arc voltage with a corresponding rapid change in arc current. However in contrast to a conventional constant current process the microprocessor control of the system limits and cuts this change in current. Fig. 5b shows the transient arc voltage trace where the identified points clearly represent droplet transfer. Calculation of

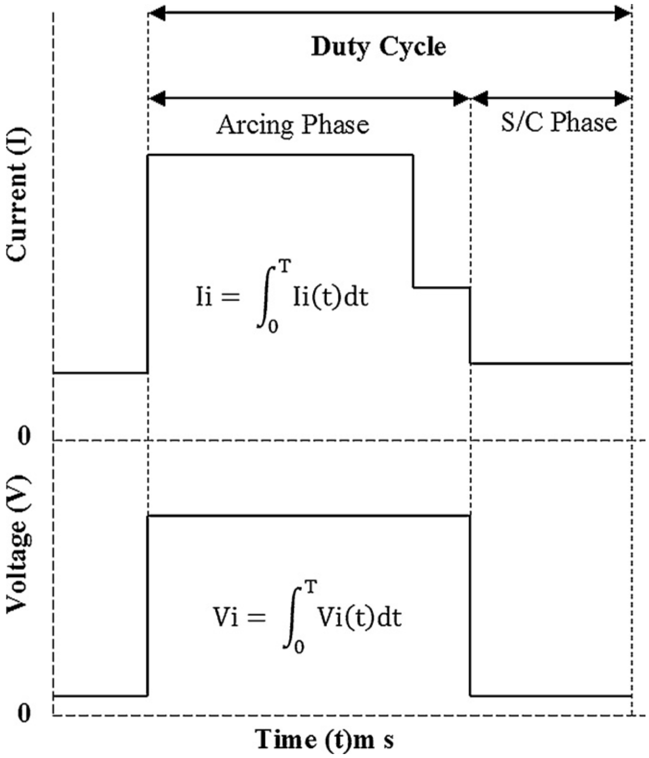

Fig. 2. CMT cycle instantaneous current and voltage values based on electrical transients.

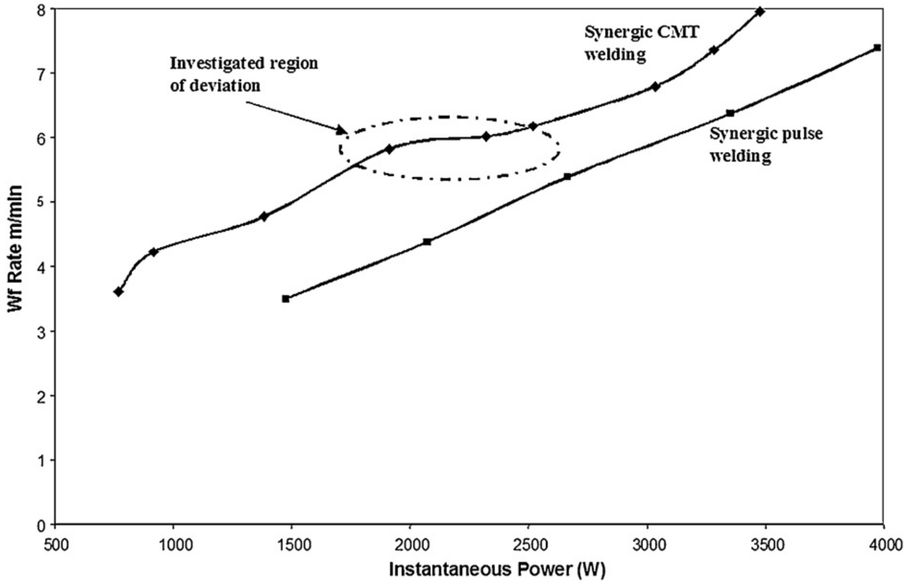

Fig. 3. Comparative deposition–synergic CMT vs. pulse welding using 1.2 mm Al-4043 filler.

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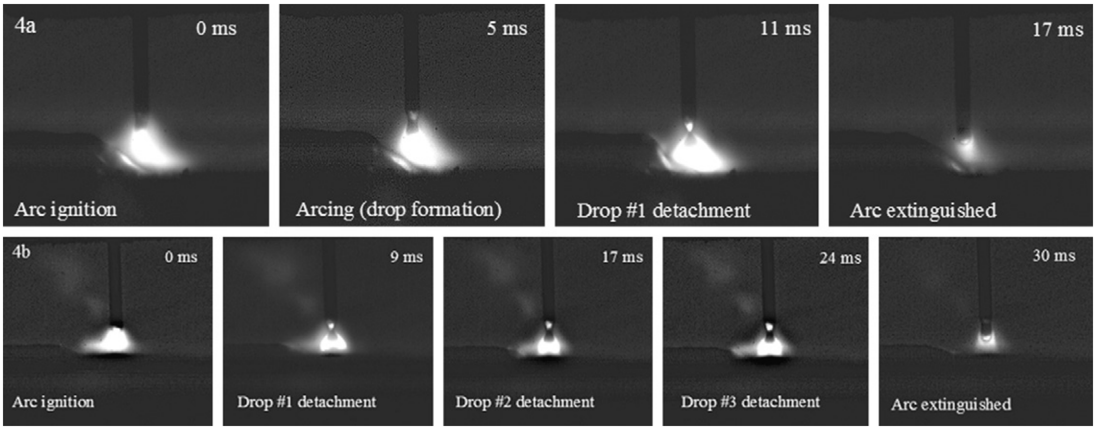

Fig. 4. Arcing phase droplet detachment. (a) W_f 5.5 m min^{-1}, 1 droplet; (b) W_f 6 m min^{-1}, 3 droplets.

instantaneous power values for each droplet detachment show that these values are within the spray transfer region. However stability is maintained by controlling the arcing phase parameters (peak values and duration) with the result that repeatable transfer rates are realised during this phase with deposition additionally occurring at the point of short circuit. Increasing the wire feed rate results in increased cycle power and a greater number of droplets being detached during the arcing phase. Fig. 5c shows analysis of arc intensity and is included for comparison, analysis of these values complimenting the captured electrical transients. Changes in intensity are clearly shown for each droplet detached. In addition arc ignition is visible as is the rapid decrease in intensity as the arc is extinguished during the short circuit. Based upon these findings the operation characteristics of the CMT process are based upon controlled short circuit deposition at the lower parameter range and a combined spray/short circuit transfer mode of operation at the mid to upper parameter range.

A further additional feature of the process is the facility to control heat input by varying the short circuit duration. By maintaining the arcing phase duration (although this can be adjusted) increasing the short circuit duration results in an incremental increase in duty cycle and a corresponding decrease cycle arc power. Whilst the frequency of deposition will also reduce the effect on deposition has previously been shown to be minor. This is illustrated in Fig. 6 (NB. Control of s/c duration is initiated by the machine arc length control feature; arc length control of the CMT process is however fixed). Adjustment of this parameter from +10% to −30% results in a change in s/c duration from ∼5 ms to ∼10 ms, respectively.

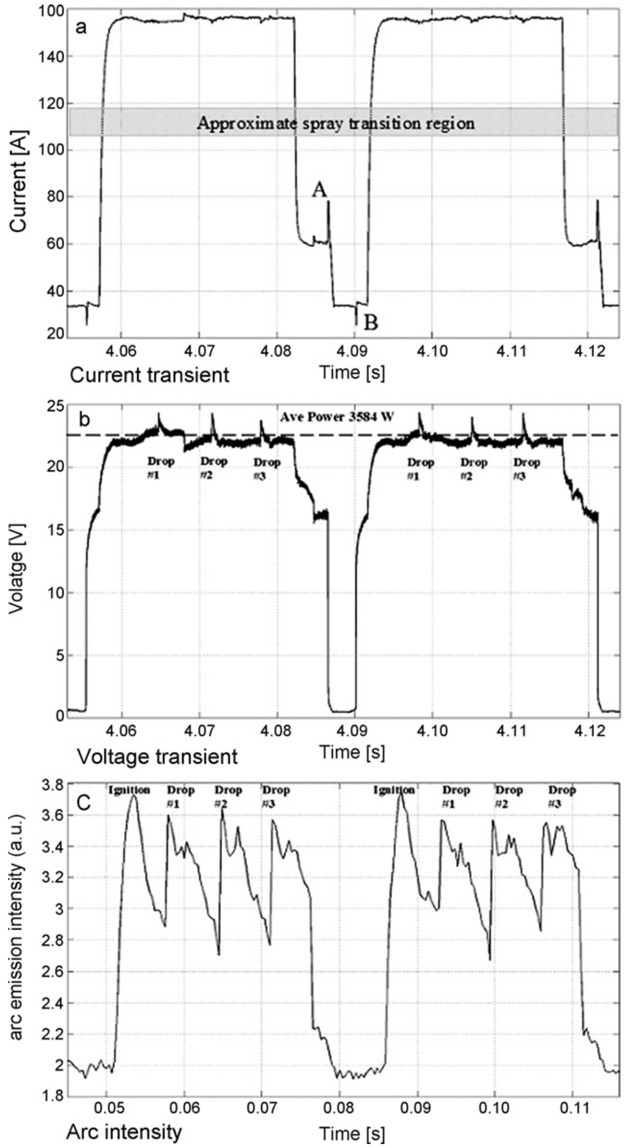

Fig. 5. CMT transients (W_f 6 m min^{-1}) (a) current trace; (b) voltage trace; (c) arc plasma intensity (arbitrary values).

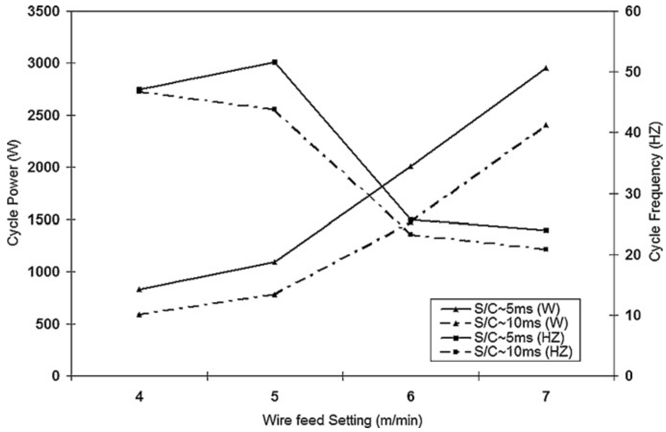

Fig. 6. Effect of changes to short circuit duration on power and frequency.

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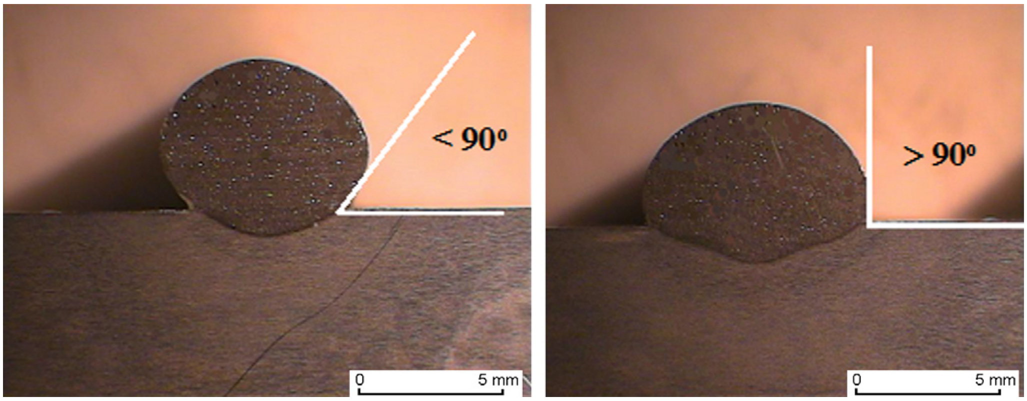

Fig. 7. Weld contact angle definition.

4. Control of weld dilution

For examining cladding dilution ratio the Al-4043 filler was substituted for the Al-2319 filler. As this wire is not in common use no synergic CMT welding program was available. As a result welds were conducted using the Al-4043 synergic program. Although adopting this approach parameters were not fully optimised for this filler, the spray transfer linear regression relationship between the wire feed rate (W_f) and the applied mean current (I_m) exhibited similar melting coefficients for the Al-4043 filler ($W_f = 0.0426I_m - 0.973$) and the Al-2319 filler ($W_f = 0.0463I_m - 0.428$) suggesting similar melting behaviour will be evident when applying the CMT process. Bead on plate welds were deposited on the Al-2024 base material for wire feed settings from 4.5 m min^{-1} to 7.5 m min^{-1}. Travel speed was set at 5 mm s $^{-1}$ with CMT short circuit duration being maintained at ~5 ms as previously discussed. Each weld exhibited good stability with no spatter. Analysis of high-speed images showed similar behaviour to the previous Al-4043 welds with respect to arcing phase droplet detachment. Comparative trials were conducted using synergic pulsed welding with similar deposition. Cross sections were taken from each sample and the dilution ratio determined using Eq. (2). Limits for cladding for both processes were defined by the weld bead contact angle with the base material. An angle of less than 90° not only resulted in non-uniform bead shape deposition, potentially voids could occur between each successive cladding weld pass. This is shown in Fig. 7.

The relationship between feed rate and dilution ratio based upon this limitation is shown in Fig. 8 . Not only does CMT exhibit a wider process window, when compared to pulse welding, dilution is reduced by ~20% for similar deposition across much of the investigated range. In addition as the objective was to maintain a quasi-binary (Al–Cu) composition Mg content was calculated for each weld using Eq. (3). This was based upon an average base material composition of 1.5%Mg (Wt%). An increased dilution ratio clearly results in greater mixing with the base material and an increased Mg content in the weld bead. By reducing the dilution ratio greater control of the final clad composition could be realised resulting in a potentially less crack susceptible composition range.

The Al-2024 plate was then clad using the two processes. Wire feed was set to 6.5 m min^{-1} with a travel speed of 5 mm s^{-1}. A slight overlap of 6 mm from the previous weld was used for both processes. Weld interpass temperature was maintained at ambient to ensure consistency of bead shape geometry. Fig. 9a and b illustrates

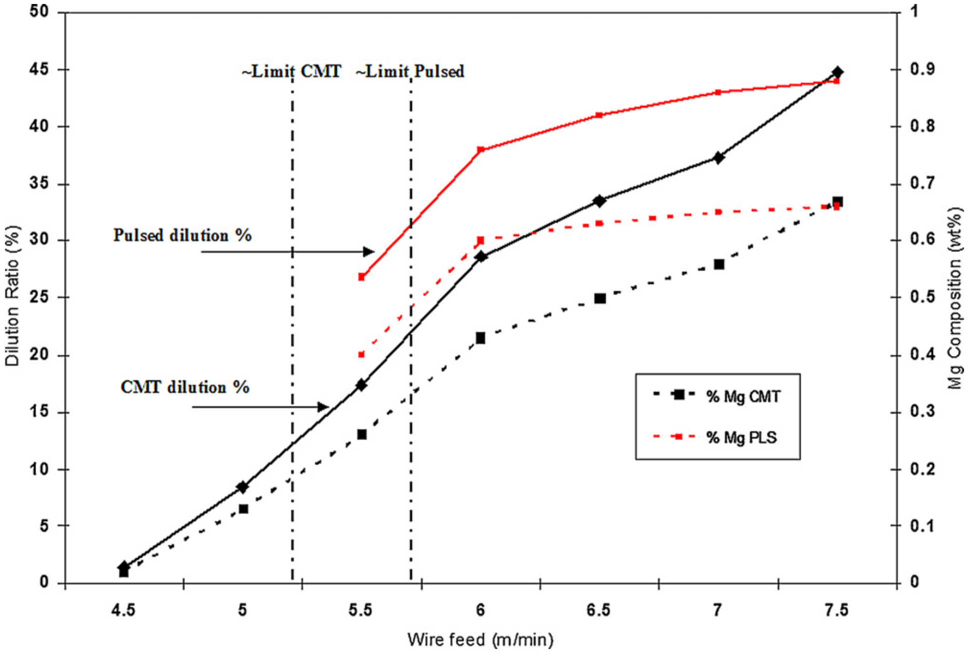

Fig. 8. Comparative dilution ratio and Mg composition between CMT and pulsed welding.

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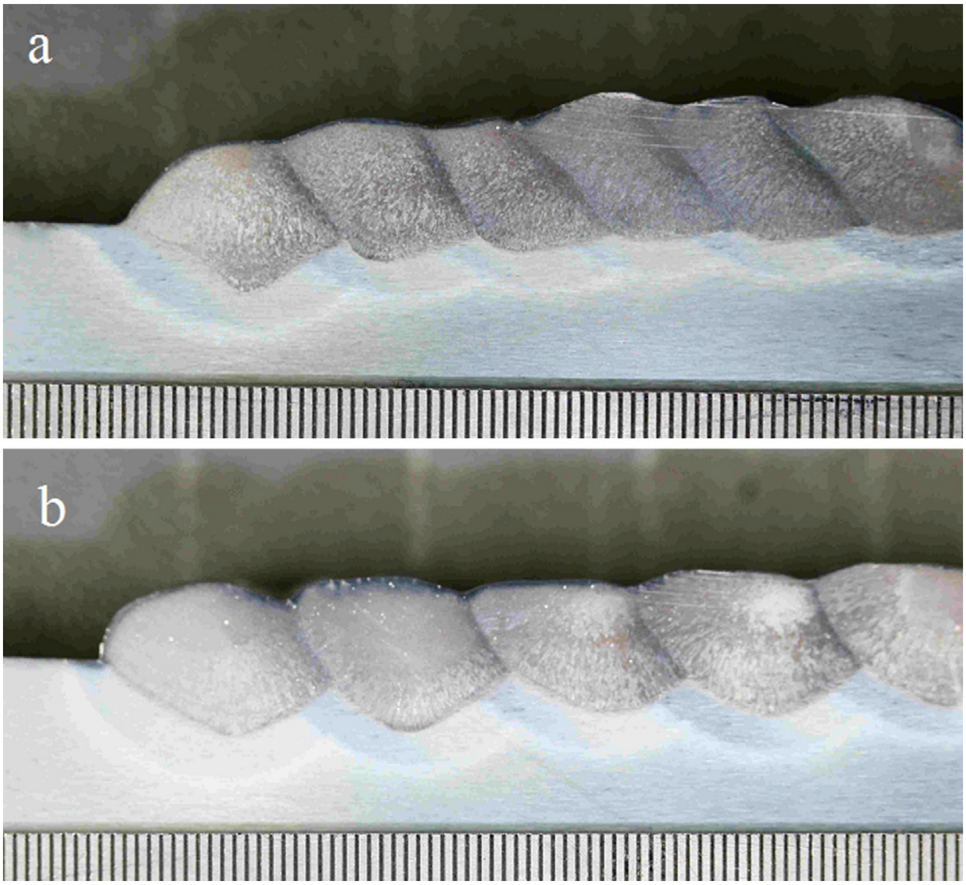

Fig. 9. (a) CMT cladding (I_i 144 A, V_i 16 V, W_f 6.5 m min^{-1}), (b) pulse cladding (I_i 152 A, V_i 19.5 V, W_f 6.8 m min^{-1}).

the results from both trials. Although similar measured average values were recorded clear differences in deposition are evident for both processes. The CMT welds exhibit a diminishing dilution ratio and increased reinforcement height with each successive weld pass. In contrast the pulse weld results show both greater and more uniform weld dilution with a reduced reinforcement height.

5. Further discussion

Whilst the differences in weld dilution between the two processes are clear, a more elaborate test framework is required for full validation of the concept, this being outside the remit of this study. Although welding this particular alloy system using conventional MIG welding processes produces solidification cracking at dilution ratios of ~40–50% using the Al-2319 filler, the exact dilution ratio were cracking is eradicated is currently unknown. Also the effect of a reduced dilution ratio on joint performance, notably the strength of the clad weld/base material interface, must be determined when MIG welding onto the clad layer to form a structural joint. Additionally performing multi pass weld cladding full parameter optimisation of the system will be required to produce consistent and uniform clad bead geometry.

6. Conclusions

- The CMT transfer mode is based on short circuit transfer at the lower power range and a combination of both spray and short circuit transfer at the mid to upper range. Any droplet transfer during the arcing phase is dependent upon the applied instantaneous power values and is regular and controlled.
- The technology can be used as a cladding process due to precise control of weld bead dilution. A lower dilution ratio is possible than that realised with pulsed MIG welding.
- For cladding ternary aluminium systems using a binary filler wire a layer of weld can be deposited exhibiting a quasi-binary composition. This composition is potentially less susceptible to solidification cracking due to control of the terminal ternary eutectic reactions. Onto this layer conventional MIG welding could be applied using the same binary based welding wire.

Acknowledgments

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