Investigations on weld bead geometry and microstructure in CMT, MIG pulse synergic and MIG welding of AA6061-T6

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Abstract

This research paper focuses on a comparative study on weld bead geometries of three different welding techniques: Cold Metal Transfer (CMT), Metal Inert Gas Pulse Synergic (MIG P) and MIG Manual Standard (MIG M). Bead-on-plate tests were performed using ER4043 (AlSi5%) as a filler material on the 3.18 mm thick plates of AA6061-T6. Current (80 A, 100 A and 120 A) and welding speed (7.5, 10.5 and 13.5 mm sec−1) were used as input process parameters while shielding gas flow rate and contact tip to workpiece distance (CTWD) were maintained constant as 15 l min−1 and 10 mm respectively. The weld beads processed by all the three techniques are compared by analysing the weld bead geometry. Microstructural characterization is carried out using optical microscopy and Field Emission Scanning Electron Microscope (FESEM). CMT has high dilution and penetration with low heat input. Compared to MIG Pulse Synergic and MIG Manual, CMT shows a drastic reduction in residual stresses. A good amount of penetration and dilution with low heat input is necessitated for better joint efficiency.

1. Introduction

In the present scenario, industries are moving towards a lighter material, which can significantly reduce the cost of transportation or energy consumption during transportation. Aluminium alloys have eventually managed to replace steel in most of the applications, such as aeronautical and aerospace components, automotive vehicle body parts, external and internal body panels, railcars, shipbuilding, boiler manufacturing, structural and weldable components, etc, due to their high strength, low weight and excellent corrosion resistance [1–8]. AA6061–T6 consists of Mg and Si as the most important alloying elements. A high strength Al–Mg(0.84%)-Si(0.665%) alloy contains 0.067% of manganese to increase ductility and toughness. AA6061–T6, which is a heat treatable alloy being obtained through artificial aging at a low temperature of approximately 180 °C for 2 h until it reaches a stable condition. This increases strength to a greater level after solution heat-treating quicker than natural aging.

Cold Metal Transfer (CMT) is an upgraded technology of Gas Metal Arc Welding (GMAW) method, which is based on conventional short-circuiting (CSC) transfer process established via ‘Fronius of Austria’ [9–12]. In CMT welding, 1/4th of the total time will be in a short-circuit phase where the magnitude of current tends to almost zero. It greatly reduces the cost of welding and energy consumption by 30%–40% [8]. It is unlike from the conventional short-circuiting (CSC) method given by GMAW. The major difference between CSC and CMT is the mode of liquid droplet detachment from the filler wire. In CSC, Lorentz forces are responsible for droplet detachment whereas in CMT, wire retraction motion is responsible. CMT welding gives the flexibility to weld thin sheets without deformation because of low thermal heat input due to very low non-zero current [13]. It is possible to weld extremely thin sheets like aluminum foil (0.3 mm) using CMT. It has a high gap bridging ability and provides spatter-free welds.

Weld parameters directly influence the bead dimensions that in turn dictate the quality of weld [14, 15]. There are many factors that can be taken as welding process parameters like current (I), voltage (V), wire feed
rate (WFR), welding speed (S), contact tip to workpiece distance (CTWD), stick-out distance and flow rate of shielding gas. From an extensive literature survey and preliminary tests conducted, the notable thing is that ‘I’ and ‘S’ are the most dominant factors that influence bead dimensions and shape relationships [16]. Current, voltage and WFR are the dependent process parameters in CMT and MIG pulse synergic (MIG P). Figure 1 demonstrates the schematic diagram of weld geometry. In this, the shaded portion ‘A’ is reinforcement area and ‘B’ is penetrated area. Dilution is the ratio of molten base metal (BM) volume/area to the volume/area of the total fusion zone (FZ). It can also expressed as the ratio of penetrated area (B) to the area of total weld metal (A + B) as shown in equation (1). The absolute importance of dilution is that the final weld metal’s chemical composition is totally distinct from the substrate and filler components, creating a fresh intermediate alloy between the two [17–19]. Dilution enhances the mechanical properties of the weld bead by introducing a suitable filler material to the BM. Like in chemistry, it is stated that dilution is the method of reducing the concentration of solute in a solution by merely adding some amount of solvent like adding water to a solution. Similarly, in welding, some amount of filler wire is fused to the BM, which is calculated by equation (1).

Dilution is expressed as the fraction of the parent metal in the subsequent weld metal (WM) and, for a solitary weldment deposit [20]. Analysis of the weld parameters by grey relational analysis (GRA) on MIG welding of high-strength stainless steel determined that welding current had a major effect on the fusing process. Current, voltage and flow rate of gas are 130 A, 27 V and 17 l min\(^{-1}\) respectively with a 0.8 mm electrode wire diameter are optimum parameters [21]. Welding on AA2012 plate which indicates the impact of current (I), voltage (V) and flow rate of shielding gas increase the weld penetration (P), weld width (W), and reduces the height of weld reinforcement (R) [22]. Impact of welding voltage (V), welding current (I), flow rate of gas and welding speed (S) on tensile strength of st-37 low alloy steel material on MIG welding. The tests use L9 orthogonal array, and the findings showed that current and voltage have an important impact on UTS [23]. Development of mathematical model in MIG welding of SS409M for predicting the weld bead dimensions using central composite rotatable design technique. It is found to be a powerful tool for finding optimal results with lesser number of trials [24, 25]. The ANN indicates the combination of processing parameters that lead to appropriate or better joints while working under different conditions. It makes it possible to trace defects and the quality index maps in the whole domain [26].

Results showed that all bead dimensions are increasing by raising the current and reducing the welding speed. Weld reinforcement form factor (WRFF) is the ratio of bead width (W) to reinforcement height (R) and calculated by equation (2). Weld penetration shape factor (WPSF) is ratio of bead width (W) to penetration (P) which is calculated by equation (3). Heat input is very important term in context to the material thickness and is calculated using equation (4). It is a comparative measure of the transfer of energy per unit weld length. A more effective method needs less thermal input for the same joint, ensuing in stronger weld bead [27]. Heat input has a remarkable influence on the shape factors such as bead width, WRFF and WPSF [19].

\[
\text{Dilution (D)} = \frac{\text{Area B}}{\text{Area A + Area B}} \times 100 \quad (1)
\]

\[
\text{WRFF} = \frac{W}{R} \quad (2)
\]

\[
\text{WPSF} = \frac{W}{P} \quad (3)
\]

\[
\text{Heat Input} (Q) = \frac{\eta VI}{s} \quad (4)
\]

Where Q, V, I, S, \(\eta\) are heat input (J/mm), voltage (V), current (A), welding speed (mm/sec) and efficiency (%) respectively. The thermal efficiency for welding is approximately 80%.

CMT being a low heat input arc welding technique that welds thin plates with lesser energy consumption. The weld bead dimensions between CMT, MIG P and MIG manual (MIG M) welding techniques are to be compared. The variation in penetration, dilution, heat input, residual stress and microhardness between these
three welding techniques are analyzed. Microstructural characterization of these three welding techniques at the bead and fusion zone were scrutinized.

2. Experiment

2.1. Material and methods
AA6061-T6 is chosen as a substrate material of thickness 3.18 mm and ER4043 (AlSi5%) is used as the filler material of 1.2 mm diameter. Chemical compositions of substrate materials and filler material (wt%), are tested by chemical spectroscopy method as per ASTM E 1251:2011 and the same is presented in table 1. Mechanical tests were performed on substrate material (AA6061-T6). Microstructural images captured by optical
microscope at 200× and 500× magnification are shown in figures 2(a) and (b). Tensile strength of 284 MPa and total elongation of 24.5% is clearly shown in figure 2(c). Average microhardness of 116.1 HV is measured by Vicker’s microhardness. Substrate is having 97.76 GPa modulus of elasticity. Brinell hardness is measured with a 5 mm diamond indenter giving 93 HB of hardness. XRD plot for substrate material is shown in figure 2(d). It clearly shows the primary elements (Al and Si) at various peaks with varying intensity, which constitutes the material. Figure 2(e) shows the histogram plot for grain size of parent material with an average grain size of 28 μm.

CMT welding machine (TPS400i) by Fronius (as shown in figure 3) is used for performing the experiments, as per the design of experiment (DOE) given in table 2. Taguchi L9 design matrix is used for experiments, which helps in finding the optimal parameters while performing minimum number of trials, which are presented in table 3. It gives the best weld bead in terms of penetration, overall appearance of the bead, high strength with low HAZ, less amount of residual stresses, negligible deformation of the substrate material for thin sheets and high gap bridging ability. Current, voltage and WFR are the dependent parameters in CMT and MIG P. Changing the value of one-parameter leads to change in the other as well due to synergetic lines.

Schematic diagram of fixture containing AA6061-T6 plate of dimension 100 mm × 60 mm × 3.18 mm is shown in figure 4. Before welding, each plate is cleansed with acetone (CH₃₂CO). In order to eliminate the surface films and various other impurities, metal surface is subsequently cleaned with steel wire brush. After cleaning the surface, sample was fastened in a fixture as displayed in figure 4, with torch angle placed at 90°, CTWD is 10 mm, stick-out is 5 mm and argon (99.99% purity) as a shielding gas at flow rate of 15 l min⁻¹ are kept constant.

Table 1. Chemical compositions (wt. %) of parent materials and filler metal as per ASTM E 1251:2011.

| Composition       | Al   | Si   | Fe  | Zn  | Cu  | Ti  | Mg  | Mn  | Cr  |
|-------------------|------|------|-----|-----|-----|-----|-----|-----|-----|
| AA6061-T6         | 97.75| 0.665| 0.233| 0.0226| 0.153| 0.0225| 0.840| 0.0676| 0.178|
| ER4043            | Bal. | 5.6  | 0.8 | 0.10 | 0.3 | 0.02 | 0.05 | 0.05 | 0.05 |

Table 2. Process parameters for CMT, MIG P and MIG M with their levels.

| Welding Process Parameters | Units | Symbol | Levels |
|---------------------------|-------|--------|--------|
| Current                   | A     | I      | −1     | 0     | 1     |
| Welding speed             | mm/sec| S      | 80     | 100   | 120   |

Figure 3. Experimental setup for CMT machine.
Table 3. Design matrix.

| S.No. | I (A) | S (mm/sec) |
|-------|-------|------------|
| 1.    | 80    | 7.5        |
| 2.    | 80    | 10.5       |
| 3.    | 80    | 13.5       |
| 4.    | 100   | 7.5        |
| 5.    | 100   | 10.5       |
| 6.    | 100   | 13.5       |
| 7.    | 120   | 7.5        |
| 8.    | 120   | 10.5       |
| 9.    | 120   | 13.5       |

Table 4. Macro-images of CMT weld bead.

![Macro-images of CMT weld bead](image)

Figure 4. Schematic diagram of fixture containing AA6061-T6 plate of dimension 100 mm × 60 mm × 3.18 mm.
The standard bead-on-plate procedure was used to lay the weld beads on AA6061-T6 plates by using a wire of Ø1.2 mm of ER4043 (AlSi5%). For every process parameters listed in Table 2; five such beads were laid on the substrate material.

After making the weld bead, each plate was cut from the middle parallel to the length. It was then dry polished with the use of different grades of emery paper (320, 400, 600, 800, 1000, 1200, 1500, 2000 and 2500) and etched using Keller’s reagent (1 ml HF, 1.5 ml HCl, 2.5 ml HNO₃ and 95 ml of water for 20 s). The bead profiles were then captured at 10X magnification, bead dimensions and bead areas were measured by using a sipcon multi sensor CNC inspection system (SVI-5300-CNC-VT). FisherScope (HM2000S) was used to measure the micro-hardness at various position (bead, BM and FZ). It has a micro indenter which indents with force 300 mN for 20 s having 5 s of creep time. Pulstec μ-X360n Full 2D High-Resolution x-ray Diffraction (HR-XRD) machine is used for measurement of residual stresses at various position of the weldment. Device specification contains a standard Cr x-ray tube (30 kV and 1 mA) with a collimator size of $\varphi$ 1 mm and measurement conditions. It is based on Cos$\alpha$ method, which acquire a full Debye–Schererrer ring (reveals grain orientation (texture) & grain coarsening, etc); by a single short duration x-ray exposure from a 2-D detector [28]. It is a faster process because it does not require sample tilts at multiple angles as compared to traditional sin$^2\psi$.
technique. In this method, x-ray exposure is up to 1 μm into the material and measure the fundamental atomic plane spacing and difference in spacing as a result of processing. This measured lattice spacing is collected by Debye ring with a single measurement using a 2D detector.

3. Results and discussion

3.1. Weld bead dimensions
Weld bead dimensions give the overall view of the bead geometry. In weld bead geometry, reinforcement height (R), penetrated depth (P), weld width (W) and angle of contact (θ) are measured and percentage dilution (D) is calculated with the help of sipcon multi sensor CNC inspection system. Weld bead dimensions is important to be measured to understand the insight view of the bead geometry that helps in the overall cost of the welding. Good and economical weld joint needs deeper penetration for higher tensile strength; lower HAZ, weld width and weld reinforcement for lesser consumption of filler wire [15].

3.2. Macrostructure of weld bead in cross-sectional direction
Macrostructure in the cross-sectional direction of the weldment clearly shows the amount of pores that are present in the weld, depth of penetration, reinforcement, HAZ and BM. Tables 4, 5 and 6 shows the macro-images of cross-section of CMT, MIG pulse synergic and MIG manual weld bead respectively. It can be seen that MIG P and MIG M is having high number of pores, which is formed due to gases entrapment when bead undergoes fusion. At such high heat inputs in MIG M and MIG P, aluminium alloys are susceptible to solubility of gases, majorly hydrogen which creates porosity. In contrast to heat input, alloying element is also responsible for hydrogen solubility. Mg element in aluminium alloys has high hydrogen affinity because the interactions between the Mg atoms and hydrogen atoms are stronger than those between aluminium and hydrogen [29]. Different welding zones are also visible after polishing and etching of the samples. Welding process parameters has variable effect on the weld bead, as current increases while keeping welding speed constant all the weld geometry increases due to high amount of high input. As welding speed increases while keeping current constant, penetration, weld width and dilution is decreased due to high heat input. Figures 5 (B) and (C), shows the crack formation on the plates of MIG P and MIG M. When heat input is 249.45 J mm⁻¹ (120 A, 7.5 mm sec⁻¹) for MIG P and 271.64 J mm⁻¹ (120 A, 7.5 mm sec⁻¹) & 194.74 (120 A, 10.5 mm sec⁻¹) for MIG M, cracks are seen on the surface of the bead with high amount of deposition. This elevated heat input and rapid cooling of the molten pool produces high amount of tensile residual stresses, which leads to formation of cracks on the surface of the bead. CMT is a welding process of low heat input is able to produce beads free from cracks with the same process parameters as shown in figure 5(A). It is noticed that the oxide layer deposition (aluminium oxide) i.e. white layer adjacent to the weld bead, is having more thickness in MIG P and MIG M as

Figure 5. (A) No crack on CMT 120 A; Crack formation on bead on plate (B) MIG P (120 A) (C) MIG M (120 A).
compared to CMT. Black soot, which is highly shown in MIG P and MIG M plates of 120 A, is magnesium oxide, which is formed by vaporized magnesium due to arc’s heat.

The samples were subjected to x-ray diffraction for the identification of the formation of intermetallic phases. As the parent material and filler material majorly constituting aluminum and silicon so primary peaks depicts the same as the major elements as shown in figure 6, which is confirmed by EDX plots. XRD plots shows lesser amount of intermetallic in CMT as compared to MIG P and MIG M owing to its low heat input. XRD plot of CMT depicts only Mg2Si and Al12Mg17 binary phases, which exists at lower temperature of 580 °C and 450 °C respectively. Fe2Si binary phase is formed in both MIG P and MIG M, which exists at a temperature of about 1100 °C—1200 °C due to their high thermal heat input. More amount of intermetallic phases causes lower mechanical properties which results in strength degradation.

3.3. Microstructure of weld bead

Olympus GX41 compact inverted metallurgical microscope is used for microstructural images. Figures 7–9 shows the microstructural images from optical microscope for CMT, MIG P and MIG M respectively. Three samples were taken for examining the microstructure from each welding processes. Microstructure is taken at the (a) Base Metal (BM), (b & c) Fusion Zone (FZ) and (d) Weld Zone (WZ). Image (b) clearly shows the fusion
line where AA6061-T6 substrate material and ER4043 filler metal fuses. It can be clearly noticed from figures 7(b), 8(b) and 9(b) the difference in the microstructure of parent metal and weldment, which is separated by fusion line (shown in black dashes). Grain boundaries and grain structure is clearly shown in figures 7(a), 8(a) and 9(a) which is representing parent metal. At higher current (i.e. 120 A) values it is noticed that high amount of black spot is seen in the parent metal and bead region, which is due to high heat input. It causes non-uniformity.
in cooling rate, which results in high amount of brittle compounds (Mg$_2$Si) that is seen as the black spots. Mg$_2$Si dissolves in FZ of the weld bead and results in large precipitation and coarsening of grains [30, 31]. These black spots deteriorates the mechanical properties and surface profile of the bead. It is more in MIG M process as compared to CMT and MIG P. High amount of pores are present in MIG P (figure 8) and MIG M (figure 9) as compared to CMT, which weakens the joint, and results in reduced tensile strength. CMT is showing better microstructures as compared to MIG M and MIG P owing to its spatter free welds even at high current inputs.
and better bead aesthetics. FESEM help us examine the morphology and microstructure. Figure 10 shows the FESEM images of fusion zone of CMT at 100 A current with 10.5 mm sec$^{-1}$ of welding speed. Figure 10(b) shows large precipitates of dissolved Mg$_2$Si in FZ.

FESEM clearly shows the difference among the grain structure that is formed due to non-uniformity in temperature. This is majorly seen in the weld bead and fusion zone where high heat input is experienced.
3.4. Effect on dilution (D) and heat input (H)

Dilution (D) and heat input (H) are directly proportional to each other, as heat input on the substrate material increases, more volume being melted, causing increase in dilution and vice versa. As mentioned above, dilution is the fraction of penetration area (B) to the area of total weld metal (A + B) as shown in equation (1). It is the factor, which is influenced by primary dimensions of the weld bead. Figure 11 shows the heat input curve and figure 12 shows the dilution curve between CMT, MIG P and MIG M respectively w.r.t. welding speed (S). Heat input is calculated with the help of equation (4). It is an important response in terms of influencing various factors like plate deformation, thickness of HAZ, arc stability, etc.

With increase in welding speed causes less dilution, which can be attributed to the lower heat input with increased weld speed. From figure 12, dilution (D) experiences a decreasing trend with increase in the value of welding speed (S) for all the processes, because as S increases 7.5-13.5 mm sec\(^{-1}\), heat input on the weld decreased as shown in figure 11, and less amount of substrate material melted thereby decreasing the penetration area as shown by macro-images. Similarly, by lowering down the value of S, heat input on the substrate material increases and more amount of substrate material melted which cause deeper penetration resulting in high percentage of dilution. As current increases from 80 A to 120 A, Dilution increases for all the welding processes. Higher current produces high heat input (as shown in figure 11) causes melting of substrate material for deeper penetration resulting in increment in percentage of dilution. It can be seen from figure 12, as current increases from 80 A to 100 A, D increases to about 40% for CMT, 50% for MIG P and 60% for MIG M in comparison to
10% for CMT, 12% for MIG P and 16% for MIG M when current is increased from 100 A to 120 A w.r.t welding speed. So, for a current period of 80-100 A, D is showing higher values as compared with current period of 100-120 A because heat input for current period 80-100 A is more as compared with 100-120 A as shown in figure 11. Figure 13 clearly depicts that the trend for dilution w.r.t heat input. This graph shows, as the current increases from 80-100 A for all the processes, there is significant change in the dilution due to variable change in heat input. Comparatively, CMT is having less amount of dilution and heat input on various process parameters from MIG P and MIG M. It is a much stable process in terms of dilution and heat input, as it is not showing any variable change in the output. Lower amount of dilution and heat input is needed for fabricating a good joint, which is having high strength by minimizing the HAZ.

3.5. Effect on penetration
Penetration is an important factor for having a good joint efficiency, deeper penetration results in higher joint efficiency due to filler material fusing into the substrate material. Deeper penetration with higher tensile strength is required for a good quality joint provided its HAZ, weld reinforcement and width are lower to reduce weld...
metal consumption are vital requirement for all types of welding [15]. It is usually noted that, as is obvious in figure 14, penetration is positively influenced by an increase in current and a decrease in welding speed. CMT process exhibits steeper decrement of 60%, 45% and 35% in 80 A, 100 A and 120 A respectively as welding speed increases from 7.5 to 10.5 mm sec$^{-1}$. In comparison to MIG P and MIG M, it is 40%, 16% and 14% in 80 A, 100 A and 120 A respectively. MIG P and MIG M shows deeper penetration of about 45% in comparison to only 20% in CMT when current increases from 80 to 100 A for speed of 7.5 mm sec$^{-1}$ owing to high amount of heat input at higher current and lower welding speed. Wire feed rate (WFR) too plays an imperative role in increasing the penetration. With increase in WFR, current increases, which helps in raising the heat input for a weld duration, leading in high amount of melting of substrate material. In CMT, the oscillatory movement of the wire helps in controlling the penetration by maintaining the arc length. With higher WFR in CMT, the current increases which helps in more droplet detachments, results in higher penetration. It is observed from figure 15, CMT is achieving similar amount of penetration as compared to MIG P and MIG M with lesser amount of heat input, which ultimately results in saving of energy.

Figure 14. Comparison of penetration (mm) between CMT, MIG P and MIG M.

Figure 15. Penetration (mm) vs heat input (J/mm) between CMT, MIG P and MIG M.
Figure 16. Residual stresses induced on different position of the specimen.

Figure 17. Residual stress profile vs alpha angle for CMT, MIG P and MIG M at different positions for 100 A and 10.5 mm sec$^{-1}$ process parameters.
3.6. Effect of residual stress

Residual stress magnitude depends on several factors such as deposited weld bead size, weld sequence, total deposited weld metal volume, weld geometry, deposited weld metal and adjacent BM strength, and cooling rate. As shown in the figure 16, CMT shows less residual stress compared to MIG P and MIG M. Due to high heat input and cooling rate, FZ has higher compressive stress for all the fusion welding process (CMT, MIG P and MIG M) compared to the weld bead. CMT is showing 6%–12% and 21%–29% decrement at the beads compared with MIG P and MIG M respectively. At FZ, CMT is experiencing, 11%–14% and 17%–25% decrement as compared with MIG P and MIG M respectively [32]. Weld bead and fusion zone has compressive stress, which has a positive impact on the tensile and fatigue strength. The top and bottom surfaces of the weld joint experiences a greater cooling rate during welding than the middle part of the weld and HAZ. This creates differential expansion and contraction by welding in the plate’s thickness. Metal contraction near the surface begins even if the middle portion of the material is still in solidus form. This contributes to the growth of the residual compressive stress at the top surface and the residual tensile stress at the middle of the weld bead. Therefore, compressive residual stresses are deliberately caused to improve the fatigue behavior of mechanical parts, while attempts are made to decrease residual tensile stresses using multiple methods such as post-weld heat treatment, shot peening; spot heating, etc. As tensile residual stress, causes crack nucleation and further crack propagation under tensile load condition, which results in tensile failure etc. As the current level increases and the welding speed decreases, residual stress increases, resulting in the crack propagation and base plate distortion.

Figure 17 shows the residual stress profile with respect to alpha angle for CMT, MIG P and MIG M welding process at different positions for 100 A and 10.5 mm sec^{-1} process parameters. The residual stress peaks for all the samples are in between 155 ° to 160 °. Red shade peaks are seen in fusion zone and weld bead, which indicated higher concentration of residual stresses. Blue shade peaks means negligible amount of residual stresses. From these residual profile peaks, FWHM is measured at different position of the weld bead by the machine. Thicker the residual peaks, higher will be the value of FWHM that results in finer grain structure (i.e. higher micro-hardness) as shown is figure 18. It is seen that, FWHM and micro-hardness are linearly related and directly proportional to each other. The welded samples were segmented and polished with various grades of waterproof emery paper (320, 400, 600, 800, 1000, 1200, 1500, 2000 and 2500) and etched using standard keller’s reagent to identify FL and FZ. A diamond micron indenter determines and presents the hardness values and evaluates them with the help of a microscope. The indenter indents for 20 s, 5 s for creep and 20 s for returning the indenter. As shown in figure 18, weld bead is having low hardness w.r.t BM and FZ. Compared to MIG P and MIG M, CMT has higher hardness values. It shows a 17.5% increase in FZ compared to BM. Compared to MIG P and MIG M, CMT has higher hardness values. It shows a 17.5% increase in FZ compared to BM. CMT shows an increase in FZ hardness of 5% compared to MIG P and MIG M. Microhardness at weld bead for MIG welding is in the range of 45–65 HV [33]. Obtained microhardness values for CMT are higher than MIG welding. The variation in micro-hardness only depends on the zone of the weld bead. The material generally loses its original strength during solidification in the fusion zone (FZ) owing to the strain hardening effect. Formation of brittle
intermetallic compounds (IMC) in the FZ stimulates an increase in micro-hardness in the case of aluminum alloys.

4. Conclusions

1. Overall, CMT has relatively lower penetration for the same current and welding speeds compared to MIG pulse synergic and MIG manual, which helps to weld thin sheets. A good amount of penetration and dilution with low heat input is required for a better joint efficiency. As current increases from 80 A to 100 A, Dilution increases to about 40% for CMT; 50% for MIG Pulse synergic and 60% for MIG Manual in comparison to 10% for CMT, 12% for MIG P and 16% for MIG M when current increases from 100 A to 120 A w.r.t welding speed due to high input.

2. High heat input and rapid cooling in the molten pool produce high residual stresses that are seen on the bead’s surface in the form of cracks, which ultimately reduces the joint strength. These cracks are experienced by MIG pulse synergic and MIG manual, which CMT prevents due to low heat input. As a result, compared to MIG Pulse and MIG Manual, CMT has low residual stresses.

3. At the beads, CMT shows a decrease in residual stress of 6%-12% and 21%-29% compared to MIG Pulse synergic and MIG Manual respectively and in the fusion zone, CMT is experiencing a decrease of 11%-14% and 17%-25% compared to MIG Pulse synergic and MIG Manual.

4. When FWHM values increase, grain size decreases, resulting in higher hardness values. Compared to MIG P and MIG M, CMT has high hardness values resulting in finer grain structure. It shows a 17.5% increase in FZ compared to BM. CMT shows a 5% increase in FZ hardness compared to MIG P and MIG M.

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References

[1] Efremay A and Ross N G 2015 Microstructure and mechanical properties of cold metal transfer welding similar and dissimilar aluminum alloys Acta Metall. Sin. Engng. 28 715–24
[2] Mceayley J W 2003 Global sustainability and key needs in future automotive design Environ. Sci. Technol. 37 5414–6
[3] Selvamani S T, Govindarajan P, Ajaymohan M, Harirahan S J and Vigneshwar M 2018 Correlation between Micro hardness and Microstructure of CMT Welded AA 7075 Al Alloy In IOP Conf. Series: Materials Science and Engineering 390 012058
[4] Totten G E and MacKenzie D S 2003 Handbook of Aluminum: vol. 1: Physical Metallurgy and Processes (New York: CRC press) (https://books.google.co.in/books?hl=en&lr=&id=Wbvw3nt1gl0C8oi=fnd&pg=PR3&dq=Totten+G+E,+MacKenzie+D+S+2003+Handbook+of+Aluminum:+vol.+1:+Physical+Metal+&f=false)
[5] Kaufman J G 2000 Introduction to Aluminum Alloys and Tempers (United States of America: ASM international) (https://books.google.co.in/books?hl=en&lr=&id=edmZIDcwCycK8oi=fnd&pg=PR7&dq=Kaufman+J+G+2000+Introduction+to+Aluminum+Alloys+and+Tempers&f=false)
[6] Mathers G 2002 The Welding of Aluminum and Its Alloys (England: Woodhead publishing) (https://books.google.co.in/books?hl=en&lr=&id=HEFO8f7yVXPZ0P7wHULfhuN8Ya-B4&f=false)
[7] Moshman M and Lippold J C 2002 Weldability of dissimilar combinations of 5000- and 6000-series aluminum alloys Weld. J. New York:81 188–94 (https://app.aws.org/wj/supplement/W1_2002_09_s188.pdf)
[8] Kumar N P, Chinnadurai T, Vendan S A and Shanmugam N S 2018 Techno economical evaluation for energy analysis in AA6061 during cold metal transfer welding. Materials Today: Proceedings 5 23375–85
[9] Kumar N P, Vendan S A and Shanmugam N S 2016 Investigations on the parametric effects of cold metal transfer process on the macrostructural aspects in AA6061. J. Alloy Compd. 688 255–64
[10] Selvi S, Vishvaksenan A and Rajasekhar E 2018 Cold metal transfer (CMT) technology-an overview. Def. Technol 14 38–44
[11] Zhang H T, Feng J C, He P, Zhang B B, Chen J M and Wang L 2009 The arc characteristics and metal transfer behaviour of cold metal transfer and its use in joining aluminum to zinc-coated steel J. Materials Science & Engineering A 499 111–3
[12] Evangeline A and Satheya P 2019 Cold metal arc transfer (CMT) metal deposition of Inconel 625 superalloy on 316L austenitic stainless steel: microstructural evaluation, corrosion and wear resistance properties. Mater. Res. Express 6 066516
[13] Irizapl A O, Dumruh H, Yüksel N and Türkmen I 2016 Cold metal transfer welding of AA1050 aluminum thin sheets Matéria (Rio de Janeiro) 21 615–22
[14] Kolahan F and Heidari M 2010 A new approach for predicting and optimizing weld bead geometry in GMAW Int. J. Mech. Syst. Sci. Eng. 2 138–42 (https://www.researchgate.net/profile/Mehdi_Heidari12/publication/279301681_A_New_Approach_for_Predicting_
Ishak M, Noordin N F M, Razali A S K, Hakim L and Shah A 2015 The effect of heat-input and cooling-time on bead characteristics in SAW welding of stainless steel 409M.

Sun Y L, Obasi G, Hamelin C J, Vasileiou A N, Flint T F, Balakrishnan J, Smith M C and Francis J A 2019 Effects of dilution on alloy content and microstructure in multi-pass steel welds J. Mater. Process. Tech. 265 71–86

Saha M K, Hazra R, Mondal A and Das S 2019 Effect of heat input on geometry of austenitic stainless steel weld bead on low carbon steel Journal of The Institution of Engineers (India): Series C 100 607–15

DuPont J N and Marder A R 1996 Dilution in single pass arc welds Metall. Mater. Trans. B 27 481–9

Sankar B V, Lawrence I D and Jayabal S 2018 Experimental study and analysis of weld parameters by GRA on MIG welding Materials Today: Proceedings 5 14309–16

Saktivel R, Venkadeshwaran P, Sridevi R, Meenan B A and Chandrasekaran K 2016 Effect of welding current, arc voltage and gas flow rate on depth of penetration during MIG welding of AA2014 plate way 2 30 (https://www.researchgate.net/profile/Kamaraj_Chandrasekaran/publication/279920913_Effect_of_Welding_Current_Arc_Voltage_and_Gas_Flow_Rate_on_Depth_of_Penetration_during_MIG_Welding_of_AA2014_Plate/links/559e3ad108ac76bed0bb7238/Effect-of-Welding-Current-Arc-Voltage-and-Gas-Flow-Rate-On-Depth-of-Penetration-during-MIG-Welding-of-AA2014-Plate.pdf)

Utkarsh S, Neel P, Mahajan M T, Jignesh P and Prajapati R B 2014 Experimental investigation of MIG welding for ST-37 using design of experiment International Journal of Scientific and Research Publications 4 1 (https://s3.amazonaws.com/academia.edu.documents/3627908/ijrj-p2974.pdf?response-content-disposition=inline%3B%20filename%3DExperimental_Investigation_of_MIG_Weldin.pdf?X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIAIWOYYGGY253UL3M%2F20191229%2Fus-east-1%2Fs3%2Faws4_request&X-Amz-Date=20191229T183732Z&X-Amz-Signature=0fbc76e6529753302d3d397ca3d5e75fa62f776c99393e568a2d350d1e1832b7f)

Khanna P and Maheshwari S 2018 Development of mathematical models for prediction and control of weld bead dimensions in MIG welding of stainless steel 409M Materials Today: Proceedings 5 475–88

Sharma S K, Maheshwari S and Singh R K R 2019 Effect of heat-input and cooling-time on bead characteristics in SAW Mater. Manuf. Process 34 208–15

Galantucci L M, Tricarico L and Spina R 2020 A quality evaluation method for laser welding of Al alloys through neural networks CIRP Ann. 49 131–4

Mendez P F and Eagar T W 2001 Welding processes for aeronautics Adv. Mater. Processes 159 39–43 (http://eagar.mit.edu/Publications/Eagar184.pdf)

Kumar S, Grover S and Walia R S 2018 Effect of hybrid wire EDM conditions on generation of residual stresses in machining of HCHCr D2 tool steel under ultrasonic vibration International Journal on Interactive Design and Manufacturing (IJIDeM) 12 1119–37

Anyalebechi P N 1995 Analysis of the effects of alloying elements on hydrogen solubility in liquid aluminum alloys Scr. Metall. Mater. 33 1209–16

Ahmad R and Bakar M A 2011 Effect of post-weld heat treatment on the mechanical and microstructure properties of AA6061 joints welded by the gas metal arc welding cold metal transfer method Mater. Des. 32 5120–6

Maisonnette D, Suery M, Nelia D, Chaudet P and Epicier T 2011 Effects of heat treatments on the microstructure and mechanical properties of a 6061 aluminium alloy Materials Science and Engineering: A 528 2718–24

Pinto H, Pyzalla A, Hackl H and Bruckner J 2006 A comparative study of microstructure and residual stresses of CMIF-, MIG-and laser-hybrid welds In Materials science forum 524 627–32

Ishak M, Noordin N F M, Razali A S K, Hakim L and Shah A 2015 The effect of filler ER4043 and ER5356 on weld metal structure of 6061 aluminium alloy by Metal Inert Gas (MIG) method yield over Bi253/CdS photocatalyst 4 68–75 (https://ijets.ump.edu.my/images/archive/teks_IJETSVol3.pdf?#page=68)