Microstructure and Mechanical Properties of Cold Metal Transfer Welding Similar and Dissimilar Aluminum Alloys

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Abstract Integrating structures made from aluminum alloys in automotive industry requires a large amount of joining. As a consequence, the properties of the joints have a significant influence on the overall performance of the whole structure. Robot cold metal transfer welding is a relatively new joining technique and has been used in this work to join 6082-T4 and 5182-O aluminum alloy sheets by using ER5356 and ER4043 filler metals. Microstructure characterization was performed by optical microscopy and energy dispersive X-ray spectroscopy, and the mechanical properties were measured by tensile and hardness tests. A correlation is made between welding variables, mechanical properties and the microstructure of welded joints. Results indicate that robot cold metal transfer welding provides good joint efficiency with high welding speed, good tensile strength, and ductility. Owing to the low heat input of robot cold metal transfer welding process, the heat affected zone microstructure was quite similar to base metals, and weld metal microstructure was the controlling factor of joint efficiency. The best performing were the 5182/5182 joints welded with ER5356 and these had mechanical property coefficients of 100%, 98%, and 85% for yield strength, ultimate tensile strength, and elongation, respectively.

KEY WORDS: Aluminum; CMT; Welding; Microstructure; Tensile property

1 Introduction

Transportation is one of the largest energy-consuming sectors, using about 19% of the world's energy demand. Nowadays, 96% of the world's transportation systems depend on petroleum-based fuels and products, with global transportation systems accounting for about 40% of the world's oil consumption of nearly 75 million barrels of oil per day [1]. Use of aluminum helps to reduce the weight of cars, buses, trucks, planes, trains and boats. When the weight is reduced, energy consumption during transport is reduced. Thus, the extra energy and extra greenhouse gas

emissions related to the production of aluminum compared to alternative materials may be paid back many times through the life cycle of the product. Additionally, the strength and corrosion-resistance of aluminum alloys guarantee durability, reliability and security, coupled with cost-effectiveness. Finally, its total recyclability allows the aluminum industry to fulfill its commitment to the principles of sustainable development and its pledge to future generations. So, it is not surprising that the use of aluminum is increasing across the whole range of transport applications. At present over 130 kg of aluminum goes into the average European car, and this is rising steadily [2, 3]. Of particular interest are the 5000-series alloys used for inner body panels, heat shields, and structural and weldable parts; and the 6000-series alloys for body components, outer and inner body panels, and structural and weldable parts [4–7].

A perpetual challenge to the designer is determining the joining process needed to create an assembly made from a variation of grades of dissimilar materials. Additionally,

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automakers are constantly searching for innovative means of reducing vehicle weight and manufacturing costs in order to meet ever-restricting fuel economy standards while remaining economically competitive. Thus, the automotive industry is interested in more than just the type of metal being used. A promising opportunity to meet these seemingly conflicting requirements is through the use of tailor welded blanks (TWBs). These are blanks made from multiple sheets of material welded together prior to the forming process. The differences in the materials within a TWB can be in the thicknesses and/or grades of the materials [8]. Consequently, the mechanical properties of the welded joints are important because the TWBs must stand up to the subsequent forming processes.

Cold metal transfer (CMT) technology is a likely innovative welding process for joining aluminum parts of similar and dissimilar alloys, and offers versatility, environmental friendliness, and energy efficiency [9, 10]. CMT utilizes an innovative wire feed system integrated with high-speed digital control in order to control not only the arc length during welding, but also the method of material transfer and amount of thermal input transferred to the work piece. The process is based upon dip transfer welding insofar as material transfer is initiated at the point of short circuit of the wire electrode into the weld pool and operates in a similar power range. However, whereas material transfer in dip transfer welding is controlled electrically in the CMT process control of the material transfer, short circuit initiation and short circuit duration is by mechanically extending and retracting the wire electrode into and out of the weld pool for defined durations. By incorporating this mechanical process into the electrical process control, the point of short circuit can be detected and the current cut, thus greatly reducing the thermal input to the work piece [11]. Owing to the lower thermal heat input, gap-bridging ability, low dilution, fast operation and low spatter offered by CMT welding compared to other welding techniques, it is considered very attractive and promising for joining similar and dissimilar aluminum alloys.

Reported studies on CMT welding are rather scarce since the process is relatively new. Most of the studies focus on welding aluminum to steel alloys since the heat input can be controlled, and consequently, this controls the volume fraction of intermetallic compounds; thereby enabling optimization of the joint strength [12–14]. For the same reason, aluminum to magnesium CMT welding has attracted the attention of some researchers, but intermetallic compounds have been difficult to avoid even with the low heat input process [15, 16]. Some reports have presented a successful application of the CMT process—that is, low spatter and good gap bridging ability—in welding parts made from similar aluminum alloys [11, 17]. However, little work has been done in the area of CMT

welding of Al sheets of dissimilar alloys. As far as we know, only one study has been reported on CMT welding of 6-mm-thick 5083-H111 and 6082-T651 aluminum alloys. Good joint efficiency with high welding speed, good tensile, and fatigue performance has been achieved [18].

The choice of CMT welding wire is of fundamental importance. While no aluminum filler metal fits all needs, ER5356 and ER4043 are the two most common and make up the majority of aluminum filler metal applications. They can be used with the most widely used aluminum alloy base metals. Therefore, these two filler metals were evaluated in this study.

A detailed investigation of the characteristic microstructural features and mechanical properties is important to many industrial fields. The current study explores the relationship between the aluminum alloy with respect to the original microstructure and mechanical properties, and their comparable characteristics after welding. However, to achieve this and produce a weld metal with specific characteristics, proper control is required of the factors that interact during welding. The relationship between the welding parameters, microstructure features, and the mechanical properties of the joints will then be characterized and evaluated.

2 Experimental Procedure

2.1 Material and Welding Procedure

The base metals for this study were 2-mm-thick 5182-O and 6082-T4 aluminum alloy sheets. Coupons were cut with dimension of 250 mm × 100 mm and placed in a butt joint configuration without a gap between the plates. Chemical compositions for the base and filler metals [19] are shown in Table 1. Each coupon was cleaned with acetone and steel brush to remove the oxide layer and other contaminants from the surface of the samples. After cleaning, the coupons were clamped and argon shielding gas, at a flow rate of 15 L/min, was switched on 3 s before the arc was struck. A torch angle of 10° from the perpendicular axes was used, and welding was carried out using the robotic CMT technique.

A matrix of welding parameters providing different heat inputs to the work piece was selected and is given in Table 2. Figure 1 shows the CMT robot head and welding assembly. Heat input is a relative measure of the energy transferred per unit length of weld. It is an important characteristic because it influences the cooling rate, and this in turn has an effect on the microstructure of the weld metal and the heat affected zone (HAZ) and consequently on the mechanical properties. Heat input (J) is calculated using the equation:

Table 1 Chemical composition (wt%) of the aluminum alloys and filler metals

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
6082-T4	0.7–1.3	0.5	0.1	0.4–1.0	0.6–1.2	0.25	0.2	0.1	0.15	Bal.
5182-O	0.2	0.35	0.15	0.2–0.5	4.0–5.0	0.1	0.25	0.1	0.15	Bal.
ER5356	0.25	0.4	0.1	0.05	4.5	0.05	0.1	0.06	0.06	Bal.
ER4043	5.6	0.8	0.3	0.05	0.05	0.05	0.1	0.02	0.08	Bal.

Table 2 Welding parameters

Filler	Base metal combinations	No.	Current (A)	Voltage (V)	Welding speed (mm/s)	Wire feed rate (m/min)	Heat input (kJ/mm)
ER5356	6082/6082	1	69	14.3	10	4.3	0.089
		2	93	15.1	15	5.5	0.084
		3	104	15.4	20	6.2	0.072
	6082/5182	4	69	15.7	10	4.3	0.098
		5	93	14.9	15	5.5	0.083
		6	104	16.2	20	5.7	0.076
	5182/5182	7	69	13.9	10	4.3	0.086
		8	93	14.9	15	5.5	0.083
		9	96	15.0	20	5.7	0.065
ER4043	6082/6082	10	55	15.1	10	2.9	0.075
		11	82	15.5	15	3.4	0.076
		12	90	16.6	20	3.7	0.067
	6082/5182	13	55	14.9	10	2.9	0.074
		14	82	16.1	15	3.4	0.079
		15	90	16.7	20	3.7	0.068
	5182/5182	16	55	15.8	10	2.9	0.078
		17	78	16.7	15	3.2	0.078
		18	86	16.4	20	3.5	0.065

$$J = \eta(60 \times VI)/v. \quad (1)$$

where V is the mean welding voltage, I is the mean welding current, v is the welding speed, and η is the efficiency

factor for the welding process. For the CMT process, η is 0.9 [20, 21].

2.2 Metallography

Cross-sectioning of the welds was performed in plane and perpendicular to the welding direction for metallographic analysis to identify the different weld zones and check for the presence of welding defects such as porosity and lack of fusion. The samples were prepared according to standard metallographic practice ASTM E3-11, and etched with Barker's reagent (5 mL HBF₄ (48%) in 200 mL water). The microstructures of different zones of interest, such as base metal (BM), HAZ and weld metal (WM) under different welding speed combinations, were analyzed on an Olympus BX60 M microscope fitted with an Olympus UC30 camera using polarized and unpolarized light. Images were analyzed using the Olympus Stream Motion 1.8 image analyzing software. Porosity percentages and imperfections were studied and evaluated from the cross section of the bead. Additionally, a JEOL JSM 7001F scanning electron microscope (SEM) equipped with an

Fig. 1 Robot head and sample clamping before welding

energy dispersive X-ray (EDX) spectrometer was employed to investigate the intermetallic phases.

2.3 Tensile and Hardness Testing

The weld bead was ground flat, and tensile samples were prepared in accordance with DIN 50125 [22]. Tensile specimens were machined from four locations from the welded joints, as shown in Fig. 2: (1) base material in the rolling or parallel direction (H specimen); (2) base material in the transverse or vertical direction (V specimen); (3) transverse specimens containing the weld in the center of the gauge length (T specimen); and (4) longitudinal specimens machined along the weld metal (L specimen). Six samples were used to calculate the average yield strength, tensile strength, and ductility for each combination of the welding parameters. It is worth noting that transverse weld specimens provide a measure of joint efficiency in terms of strength, but do not provide an accurate ductility measurement of the weld. However, the longitudinal weld specimens are more representative of the weld metal properties and joint formability [23]. The tests were carried out by Zwick Z100 tensile machine at room temperature with a displacement speed was 0.5 mm/s.

Hardness measurement was taken with the help of a Vickers hardness testing machine type (Leco LM700) according to ASTM E384-11e1 with a 1.0 N load, 0.35 mm between indentations in the weld and adjacent areas, and

0.5 mm between indentations in the base metals. Measurements were conducted through the center of welded joints across the BM, HAZ, and WM.

3 Results and Discussion

3.1 Microstructure

Characteristic microstructures of the base metals are shown in Fig. 3. The presence of silicon in the 6082 alloy results in the formation of Mg_2Si in addition to other phases, see Fig. 3a. Most 6082 commercial alloys also contain iron as an impurity. As a result, the $\alpha-Al + Al_6(Fe, Mn)$ are formed in addition to Al-Fe, Al-Mg, and Al-Mg-Mn intermetallic phases [24–26]. In contrast, the 5182 alloy has coarse insoluble intermetallic phases. These were identified by EDX as Mg_2Al_3 and other precipitates containing quite high contents of Fe, Mn, Al, and Si, see Fig. 3b. This result is in agreement with other reported studies [27, 28].

The visual appearance of the joints with regard to surface roughness and bead shape appeared to be very uniform for all joints. Figure 4 shows the bead profiles and cross-sectional macrostructures of representative joints. Consistent, tight, and uniform ripples indicate a strong weld, free from contamination or cracks. This observation is typical for automated welding processes. The distance between weld ripples is larger in joints No. 3 and No. 12 compared to joints No. 1 and No. 10 owing to the higher welding speed. Owing to the high content of silicon in ER4043 (Table 1), this alloy has a lower melting point and more fluidity than ER5356. Therefore, joints welded with ER5356 filler metal have much less spatter than the joints welded with ER4043 filler metal, and weld spatter from the latter is very low. This phenomenon has been reported by other researchers [29, 30]. This confirms the ability of the CMT process to produce joints with virtually no weld spatter. Lastly, a visual observation of the joints found an absence of obvious surface flaws such as lack of fusion, undercuts, overlaps, and cracks.

Influence of heat input on welded metal area is clearly shown in Fig. 4. Weld size and mechanical properties are both influenced by the heat input. Heat input is usually chosen to be high enough to achieve full penetration and sufficient fusion to base metals, but also as low as possible to decrease weld distortion and phase transformation in the fusion and heat affected zones [31, 32]. The welded areas in the high heat input joints (joints No. 1 and No. 10) are almost 25% larger than the welded area in joints welded with low heat input (joints No. 3 and No. 12). Furthermore, full and continuous penetration of the welded beads is present in the high heat input joints (Fig. 4b and h) in contrast to the interrupted penetration in low heat input joints (Fig. 4e and k).

Fig. 2 Schematic view of the welded joint showing the locations of test samples (unit: mm)

Fig. 3 Polarized (*bottom*) and unpolarized (*top*) light images showing the microstructure of the base metals: **a** 6082 alloy; **b** 5182 alloy

Representative macrostructures of the joints welded with ER5356 and ER4043 are shown in Fig. 5a and e, respectively. During the weld thermal cycle, the BM in the fusion zone partially melts. The weld microstructures appear dendritic and owing to the temperature gradient the edge of the weld has more columnar dendrites in contrast to the equiaxed dendrites found at the center of the weld. For both filler metals, the weld metal is characterized by an Al-rich matrix and secondary eutectic phases. In the case of the ER5356 filler metal, the secondary eutectic phases are present as spherical precipitates (Fig. 5b), and as an interdendritic network in the case of ER4043 (Fig. 5f).

Comparing the WM grain sizes of the two filler metals, the grains are larger when ER5356 is used. The average WM grain size in the cases of joints welded with ER5356 and ER4043 are 217 and 164 μm, respectively. In general, the higher heat input into the welded area needed for this filler metal promotes grain growth and results in larger grain sizes. This phenomenon is limited only to WM since the HAZ close to the weld metal showed almost no change in grain size of HAZ compared to the BM (Fig. 5e, d, g and h). Surprisingly, while no observed change in precipitates types and shape in 6082 HAZ, the 5182 HAZ close to WM contains fine precipitates in the aluminum matrix and next to this area, to the direction of the BM, coarsening of the Mg_2Al_3 precipitates can be seen in Fig. 5e and g. This coarsening has been reported in other studies [6, 33].

Figure 6 shows SEM micrographs of the WM, 6082 HAZ, and 5182 HAZ from sample No. 6. The excess of Mg in the filler metal promotes the formation of spherical precipitates identified by EDX as Mg_2Si . Additionally, the light intermetallic Mg–Al phases scattered in the aluminum matrix also contain Si, Mn and Fe. These elements constitute phases such as Al_3Mg_2 , Al_3Fe and $AlMg_2Mn$, see Fig. 6a. The Mg_2Si precipitates are clearly visible in the 6082 HAZ, see Fig. 6b. Meanwhile in the 5182 HAZ, there is a transition zone containing some

coarse particles of Al_3Mg_2 and very fine precipitates which could not be identified accurately by EDX analysis, as shown in Fig. 6c. It is proposed that the Al_3Mg_2 precipitates close to the WM dissolved during the heating cycle and re-precipitated again during cooling depending on the cooling rate.

Maps of elements present in the weld metal, sample No. 6, are shown in Fig. 7. The distribution of elements shows concentrations of Si and Mn at the grain boundaries and a uniform distribution of Mg in all areas. Also, a depletion of aluminum is obviously seen at the grain boundaries where the precipitates formed. The EDX analyses revealed lower concentrations of Si and Mg in the joints welded with ER5356 filler metal than in the joints welded with ER4043. As shown in Fig. 7b, the WM produced from ER5356 filler contains low contents of Si and Mg. There is an increase in the Si content with respect to the filler metal composition (0.2–0.98 wt%), and this will be due to dilution from the 6082 sheet. Mg content is reduced (4.5–1.22 wt%) because it is prone to evaporation during welding [34, 35]. In contrast, the ER4043 filler produced WM with high Si content (9.6 wt%) and the Mg concentration (0.92 wt%) have increased by dilution from the base metals, especially when at least one of the base metals is the 5182 alloy (the spectrum of the weld metal is not shown). Changes in the alloying elements in the weld metal area will certainly affect the mechanical properties of the joints.

3.2 Mechanical Properties

Micro-hardness profiles across the welded joints produced by the different welding parameters are shown in Fig. 8. It is observed that the lowest hardness values are measured in the WM area of the joints welded with ER5356 filler, especially when at least one of the base metals is 6082 alloy. In contrast to ER5356 filler, joints welded with ER4043 filler show higher hardness in the weld metal when at least one of base

Fig. 4 Bead profiles and cross-sectional macrostructures of representative joints: **a, b, c** sample No. 1; **d, e, f** sample No. 3; **g, h, i** sample No. 10; **j, k, l** sample No. 12

metals is 5182 alloy. In fact, several factors are controlling the hardness of the weld area. The main factors are the alloying elements in solid solution; precipitate volume fraction, morphology and size and grain size. During welding, the elements in the WM are a combination of the filler metal and the dilution from the base metal. When at least one of the base metals is 6082 alloy, which contains low Mg and Si, the amount of alloying elements and precipitates is lower in the weld metal area, see Fig. 5b and f. This results in the decrease of WM hardness, as shown in Fig. 8a, c and e.

Due to the higher heat input required for the ER5356 filler metal, it can also be concluded that these joints experience a slower cooling rate than the ER4043 filler metal

joints, and hence have a coarser-grained WM microstructure. Furthermore, after experiencing a melting process, the solidified alloy was expected to be in the form of supersaturated solution, and few particles precipitate from the supersaturated solid solution. Thus, the lower micro-hardness in the WM of the joints welded with ER5356 is due to the action of grain coarsening and weak precipitation strengthening. On the other hand, when using ER4043 filler metal, the concentrations of alloying elements and precipitates in the WM increases when at least one of base metals is 5182 alloy. The filler metal is already high in Si and becomes richer in Mg due to the dilution of the base metal. The increase in alloying elements and precipitates

Fig. 5 Typical microstructures of the dissimilar joints No. 6 **a**, No. 15 **e**, polarized (*bottom*) and unpolarized (*top*) optical light images showing the microstructures of the WM of joints No. 6 **b**, No. 15 **f**, 5182 HAZ/WM interface of joints No. 6 **c**, No. 15 **g** 6082 HAZ/WM interface of joints No. 6 **d**, No. 15 **h**

Fig. 6 SEM images showing the microstructure of sample No. 6: **a** WM; **b** WM/6082 HAZ; **c** WM/5182HAZ

causes the WM hardness to proportionally increase, as shown in Fig. 8b, d and f.

It is worth noting that the hardness of the 6082 HAZ is slightly affected by weld thermal cycle. Despite the unclear change in the HAZ microstructure, a small drop in hardness in HAZ is observed compared with the BM. It is reported that the strength losses in the 6000 alloys are less in the naturally aged metal than in the artificially aged alloys [6]. On the other hand, the 5182 HAZ showed similar hardness values to the base metal.

The yield strength, tensile strength, and elongation for all joints are shown in Fig. 9. Table 3 shows the average mechanical properties of the base metals for comparison. In the case of joints welded with ER5356 filler, the 5182/5182 joints have the highest ultimate tensile strength (UTS), and in most cases also the highest elongation. Since there is homogeneity between the base and weld area, this combination achieved good mechanical properties. The mechanical property coefficients of the 5182/5182 joints (known as the ratio between the mechanical properties of a welded joint and that of base metal) are 100%, 98%, and 85% for YS, UTS, and elongation, respectively. The

corresponding ratios with respect to the 6082/6082 joints are 83%, 79%, and 66%. It is interesting to note that there is little variation in YS for all joints and L samples were higher in UTS and elongation than T samples in all joints which have low hardness in weld metal area. In T welded joints, since the weld is weaker than the surrounding transverse areas, it possesses all plastic deformation and the fracture took place at a low tensile load. On the other hand, L welded joints display entirely different tensile behavior. The different zones have different resistance to deformation due to difference in microstructure, grain size, precipitate size and distribution. The increase in strength properties compared to T joints is due to the presence of the stronger HAZ and BM longitudinal to WM and resisting the deformation [36, 37].

With a much higher elongation than all other joints, the 6082/6082 joints welded with both filler metals show a good combination of properties. The high elongation of these joints is owing to the low hardness level in the weld metal area, as clearly shown in Fig. 8a and b. High hardness in the case of 5182/5182 joints and 5182/6082 joints resulted in a lower elongation of these joints, but with no

Fig. 7 SEM image **a**, EDS spectrum of the weld metal area **b**, EDX maps of elements in the weld metal of sample No. 6 **c–f**

apparent effect on the UTS or YS. The YS and UTS of the ER4043 welded joints are comparable to joints welded with ER5356 filler metal.

Visual examination of the tensile samples after fracture indicated that the fracture always occurred within the weld area for the 6082/6082 joints and in the majority of 5182/6082 and 5182/5182 joints welded with ER5356 filler. Meanwhile, the fracture path shifted mainly to the 5182 base metal in case of 5182/5182 and 5182/6082 joints welded with ER4043 filler. This result indicates that the HAZ is not the weakest location for these latter joints. These observations are in agreement with the hardness results. Failure occurs in the WM when the hardness of the WM is less than the BM hardness and vice versa. Failure of the joint in the 5182 alloy BM when the WM has the highest hardness is to be expected because the 5182 alloy

has the lowest YS of the two BMs (Table 3). This clearly shows the welded joint properties and fracture paths are controlled to a large extent by the WM microstructure and composition.

For the 6082/6082 joints, the best combination of mechanical properties was achieved using ER5356 filler since the composition of WM contained less amount of alloying elements, compared to joint welded with ER4043, which improve the ductility of the joints in addition to keeping the strength at an optimum level. Since the softest part of the joints is in WM up to the hardness measurements, the fracture originated and propagated in this area. ER4043 showed less compatibility with 5182 alloy due to the high alloying elements and consequently the high hardness of the produced WM. In spite of achieving good YS and UTS by using ER4043 filler metal, the joints ductility sharply

Fig. 8 Micro-hardness profiles across the welded joints produced under different welding parameters, the 0 mm position is taken as the left-most edge of the weld metal: **a** samples No. 1 and No.3; **b** samples No.10 and No. 12; **c** samples No. 4 and No. 6; **d** samples No.13 and No.15; **e** samples No. 7 and No. 9; **f** samples No.16 and No.18

degrade. The fracture path in joints welded with ER4043, except 6082/6082 joints, is mainly in 5182 BM since it is the softest area in the joints.

4 Conclusions

5182 and 6082 aluminum sheets were successfully joined using different CMT welding parameters. The following results were obtained:

1. The 6082 HAZ showed almost no change in shape and size of precipitates compared to the BM. However, in the 5182 sheets, the HAZ microstructure showed fine precipitates of second phases and coarsening of the Mg_2Al_3 precipitates in the aluminum matrix.
2. Mechanical property coefficients for 5182/5182 joints welded with ER5356 are 100%, 98%, and 85% for YS, UTS, and elongation, respectively. The corresponding ratios for 6082/6082 joints are 83%, 79%, and 66%. In general, joining 5182 to 6082 alloy did not show worse mechanical properties compared to the other joints.
3. The welded joints mechanical properties are controlled by the weld metal microstructure and composition.
4. Use of ER5356 filler metal in welding 5182 alloy sheet is better than ER4043 since it produces a weld metal with low Mg and Si content. The corresponding joints are characterized by low hardness, high ductility, and high strength. However, for the 6082 alloy, both filler metals are compatible.

Fig. 9 Mechanical properties of different weld joints made with ER5356 **a**, ER4043 **b** filler metals

Table 3 Properties of the aluminum substrates at room temperature

Material	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
6082-T4	296	180	28.3
5182-O	297	143	24.1

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