TENSILE PROPERTIES OF GAS METAL ARC AND COLD METAL TRANSFERRED ARC WELDED AA6061-T6 ALUMINIUM ALLOY JOINTS

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Abstract: *Heat treatable aluminium alloy such as AA6061 finding wide applications especially in the fabrication of door, hood and trunk components in automobile sector. These components are made up of thin sheets of aluminium alloys due to the low density, high strength to weight ratio, excellent weld ability and better corrosion resistance characteristics. Gas metal arc welding (GMAW) process is one of the most widely used welding technologies in the automobile industry, because of its higher productivity. Cold metal transfer (CMT) welding technique, the most advanced variant of GMAW process attracts the automobile manufacturers because of its capabilities such as stable arc, higher welding speed, less spatter and minimum distortion. This paper focuses on the welding of thin sheets of AA6061-T6 aluminium alloys by constant current-gas metal arc welding (CC-GMAW) and cold metal transfer-gas metal arc welding (CMT-GMAW) processes and highlights its tensile properties. The micro hardness variation across the weld joint was recorded by Vickers micro hardness tester. A soft zone is observed in the HAZ region in both the cases, but the relative softening with respect to the base material is less in case of CMT-GMAW joint compared with the CC-GMAW joint. It is also observed that the width of the soft zone in CMT-GMAW joint is less compared with the CC-GMAW joint. It is concluded that the mechanical properties of CMT-GMAW joint are improved compared with the CC-GMAW joint due to the better refinement of grain structure with narrow soft zone formation.*

Keywords: *Aluminium alloy, Gas metal arc welding, Cold metal transfer arc welding, Tensile properties, Micro hardness*

1. INTRODUCTION

Aluminium alloy being the lighter alloy has attracted the automobile manufacturers because of the advantages such as high strength to weight ratio, excellent formability and weld ability characteristics. Aluminium alloys especially 6xxx series are mainly used in door, hood and trunk components in the automobile sector, because of its characteristics such as better weld ability and superior corrosion resistance. Among the aluminium alloys, AA6061-T6 is a heat treatable aluminium alloy that is widely employed in the automobile sector owing to the better weld ability and higher corrosion resistance characteristics [1]. Joining of thin sheets of aluminium alloys by fusion welding processes poses lot of problems such as distortion, burn through and hot cracking. These problems arise because of the high heat generation during the welding process. In order to overcome the issues, choosing a low heat input process is beneficial. Gas metal arc welding (GMAW) in short circuiting mode which comes under a low heat input can be able to control the above mentioned problems. But the problems such as spatter and unstable arc exist due to the repeated short circuits. Cold metal transfer (CMT) welding, the advanced variant of GMAW is well suited for welding of thin aluminium sheets, because of the wire retraction capability during the short circuiting mode that controls the spatter and distortion. So in this investigation, cold metal transfer (CMT) welding which also comes under short circuiting mode was chosen along with the gas metal arc welding process to study its beneficial effects on mechanical properties.

Peng Wanga et. al [2] claimed that increase in the short circuiting current results in the increase in dilution ratio and grain size of weld metal even though the whole energy input is kept constant. They further stated that by adjusting the characteristic parameters the energy input and metal transfer behaviour can be controlled. John Norrish and Dominic Cuiuri [3] briefly explained the principles, advantages and limitations of short circuiting transfer mode in GMAW process. They suggested that this process can ensure good positional performance and can be suitable to thin sheet welding with mean currents in the range of 40 to 180 A. They also pointed out that CMT-GMAW comes under current and dynamic wire feed controlled short circuiting transfer that achieves low heat input, less spatter high speed on thin ferrous and non-ferrous materials. Abdullah Wagiman et.al [4] stated that CMT-GMAW process has the capability to produce spatter free and crack free weld bead. Javier A. Vargas et.al [5]coined that the transformation of precipitates is the main reason for the reduction in mechanical properties of GMA welded aluminium alloy joints. Ying Liang et.al [6] studied the microstructural and mechanical properties of 6061-T6 aluminium alloy joints by GTAW–CMT hybrid welding and stated that the hardness recorded in the softened zone was approximately 50 % less than the base material. They observed that the joints undergone necking (i.e plastically deformed) before failure. Moreover they concluded that there was a reduction in strength and elongation of the joints by 40 % and 50 % respectively.

Giovanna Cornacchia et. al [7] compared the mechanical properties of CC-GMAW, CMT-GMAW and fiber laser-GMAW hybrid welds of AA6005 aluminium alloy joints and suggested that the CC-GMAW joint has a larger HAZ than CMT-GMAW joint. The reduction in the thermal cycling minimizes the over aging phenomenon of the base material. Finally they concluded that the CMT-GMAW joints exhibited higher strength values compared to the other joints. H. Pinto et. al [8] reported that the porosity is lesser for the CMT-GMAW joint than for the PC-GMAW joint. Moreover they stated that CMT-GMAW joint is characterized by narrow HAZ than the laser-GMAW and PC-GMAW joints. They compared the residual stresses among the following joints i.e., PC-GMAW, CMT-GMAW and laser-GMAW joints and found that the residual stresses in CMT-GMAW joints are lesser compared to the other joints. This is due to the lower heat input of the CMT-GMAW process. Y.M. Zhang et.al [9]\\n6061 aluminum alloy was selected as a test material for the newly\\ndeveloped double-sided arc welding (DSAW stated that weld metal zone with columnar grains form elongated porosity whereas little amount of dispersed porosity occurs in columnar grains in double sided arc welded aluminium alloy joints. They found that the shape and size of the porosity is dependent on the solidification structure. R.R. Ambriz et.al [10]the indirect electric arc (IEA pointed out that the phase transformations that are occurring in the HAZ region of GMA welded aluminium alloy joints can be minimized due to the low heat input.

From the published literature available, it was found that very few investigations have been carried out on comparing the tensile properties of conventional GMAW and CMT-GMAW of AA6061-T6 aluminium alloy. Hence the present investigation is aimed to evaluate the tensile properties of GMA and CMT welded AA6061-T6 aluminium alloy joints.

2. EXPERIMENTAL DETAILS

An AA6061-T6 aluminium alloy sheet of 3 mm thickness was chosen as the base material. AA4043 of 1.2 mm diameter was chosen as the filler wire. Joint dimensions of 300 mm length and 75 mm width were sectioned with the help of hacksaw. The included groove angle was kept as 60˚ with a root gap of 1.2 mm between the plates. The chemical composition of the base metal and the filler metal are presented in the Table 1. The mechanical properties of the base material and filler metal are presented in table 2. Argon (99.99 wt %) was used as a shielding gas. Before welding the surfaces of the base material were initially wire brushed and then cleaned with acetone. The welding setup used was CMT advanced 4000R to fabricate the joints in the following variants (i.e constant current gas metal arc welding (CC-GMAW), and cold metal transfer-gas metal arc welding

(CMT-GMAW)). The joints were fabricated using the optimized welding parameters as listed in Table 3. The photograph of the welded joints is shown in the figure 1.

Table 1: Chemical Composition (wt %) of the Base Metal and Filler Metal

Material	Si	Cu	Fe	Mn	Mg	Cr	Zn	Ti	Al
AA6061-T6	0.56	0.31	0.28	0.052	0.98	-	0.024	0.018	Bal.
ER4043	5.6	0.3	0.8	0.05	0.05	0.05	0.1	0.02	Bal.

Table 2: Mechanical Properties of the Base Metal and Filler Metal

	0.2% Yield strength (MPa)	Ultimate Tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Hardness ($HV_{0.1}$)
AA6061-T6	275	318	16	120
AA4043	164	190	-	-

Table 3: Optimized Welding Parameters used to Fabricate the Joints

Variants	Welding current (A)	Arc voltage (V)	Arc length correction (%)	Wire feed speed (mm/min)	Welding speed (mm/min)	Heat input (kJ/mm)
CC-GMAW	125	16.1	-	5600	400	0.242
CMT-GMAW	116	14	15	5600	480	0.177

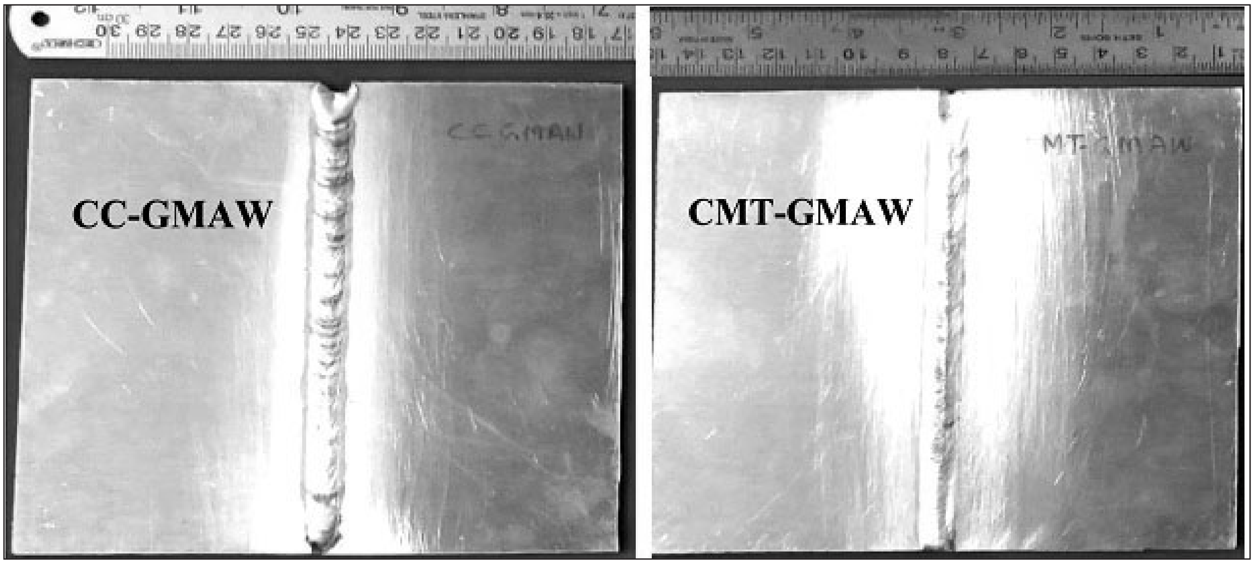


Fig 1. Photographs of the CC-GMAW and CMT-GMAW Joints

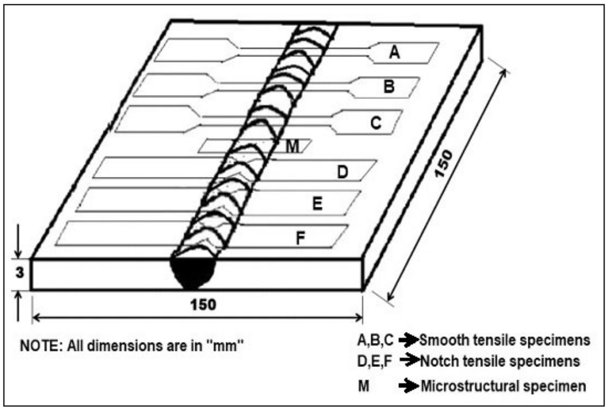
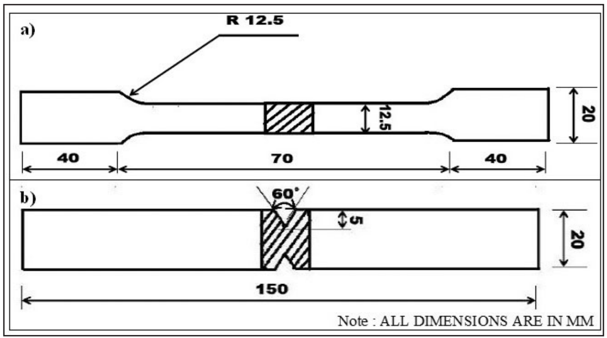
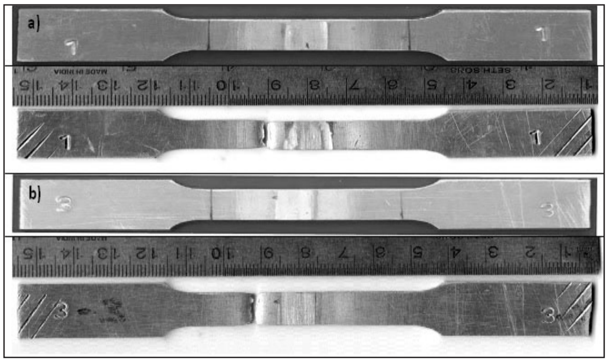


Fig 2. Scheme of Extraction of the Tensile Specimens



a) Smooth Tensile Specimen **b) Notch Tensile Specimen**

Fig 3. Dimensions of the Tensile Specimens



a) CC-GMAW **b) CMT-GMAW**

Fig 4. Photograph of the Tensile Specimens Before and After Test

Scheme of extraction of the tensile specimens from the welded joint is shown in the figure 2. Smooth and notch tensile specimens were prepared (shown in figure 3) as per the ASTM E8-04 standard. Cross weld tensile test was performed using a universal testing machine (UTM) with a cross head displacement of 2 mm/min and strain rate of 1.3 × 10^{-3} s^{-1}. Micro hardness survey across the cross section of the joint was done with a load of 100 gms and dwell time of 15 seconds. The samples were etched with Keller's reagent to reveal the microstructures of the welded joints. The fracture surfaces were initially cleaned with acetone and then they are examined by scanning electron microscopy (SEM).

3. RESULTS

3.1 Tensile Properties

Figure 4 shows the fracture location of the tensile tested specimens. The stress-strain graph is shown in figure 5. Transverse tensile properties of the CC-GMAW and CMT-GMAW joints are presented in table 4. The results are taken as the average of three tested specimens. All the specimens failed in the HAZ region and the

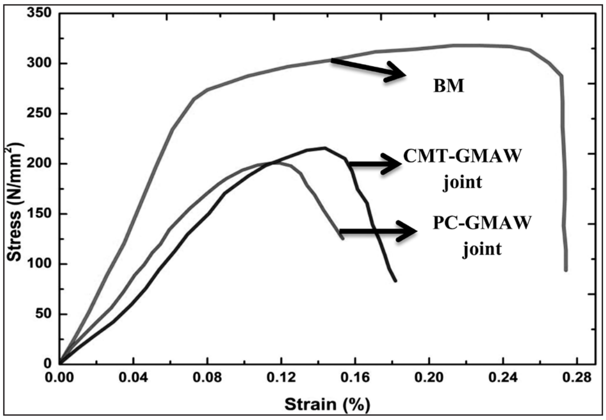
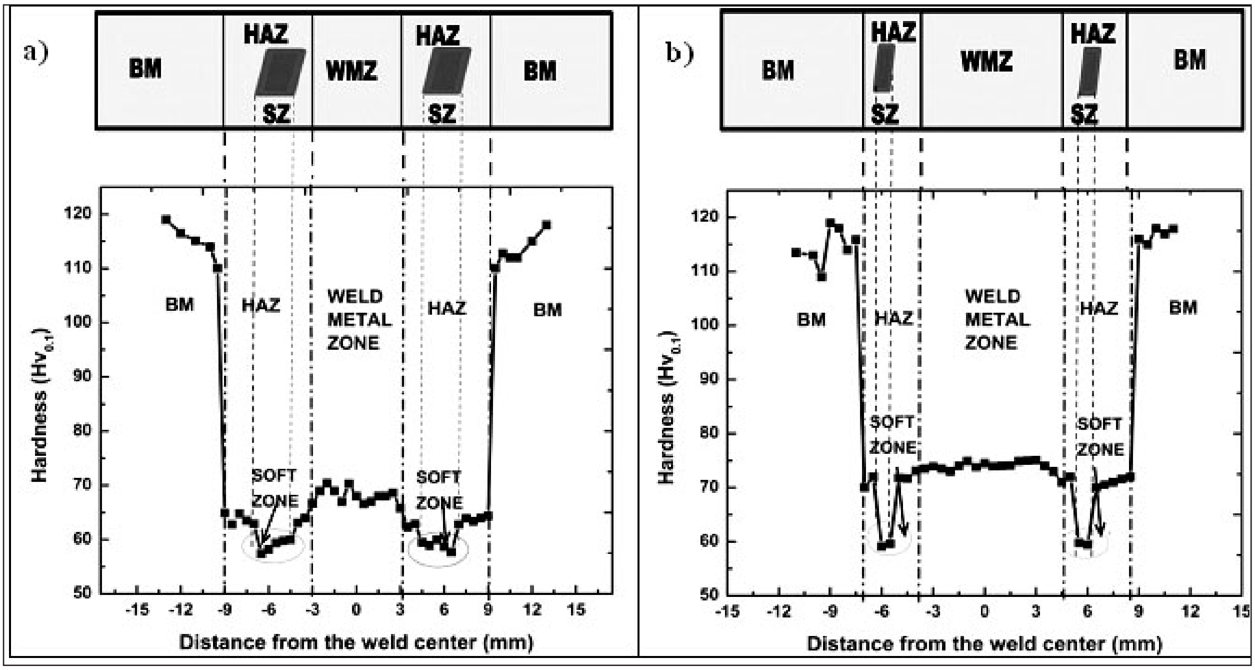


Fig 5. Engineering Stress - Strain Graphs for Base Metal and Welded Joints

Table 4: Transverse Tensile Properties of the Welded Joints

Joint type	0.2% Yield strength (MPa)	Ultimate Tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Reduction in c.s.a, %	Notch tensile strength (MPa)	Notch strength ratio	Joint efficiency (%)	Fracture location
CC-GMAW	177	195	7.08	26.6	196	1.005	61.3	HAZ
CMT-GMAW	175	215	9.02	58	220	1.02	67.6	HAZ



a) CC-GMAW b) CMT-GMAW

Fig 6. Microhardness Distribution Along the Cross Section of the Welded Joints

Table 5: Grain Size (µm) of Various Zones of Both CC-GMAW and CMT-GMAW Joints

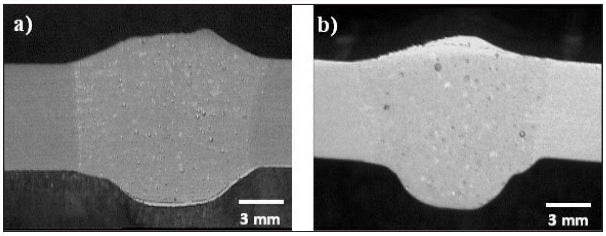
Variant	Average grain size (µm) in WM	Average grain size (µm) in HAZ	Average grain size (µm) in PMZ
CC-GMAW	27.4	63.9	59.2
CMT-GMAW	20.3	47.4	41.7

fracture location is about 10 mm and 12 mm from the weld center for CC-GMAW and CMT-GMAW joints respectively due to the presence of softer zone. The base material (BM) exhibits a tensile strength (TS) of 318 MPa and elongation of 16 %. Whereas the CC-GMAW joint records a UTS of 195 MPa and elongation of 7.08 % while CMT-GMAW joints yields a TS of 215 MPa. Even though CMT-GMAW joints records lower TS than base material, these joints are 9.3 % higher TS than the CC-GMAW joints. The reduction in cross-sectional area (c.s.a) of the base material is 60.11 %. However the reduction in cross sectional area for the CC-GMAW joints is 26.6 % which indicates that the reduction in cross sectional area is 55.7 % lower than the BM. The reduction in cross sectional area for the CMT-GMAW joints is 58 % which is 118 % higher than the CC-GMAW joints and 3.5 % lower than the base material.

Notch tensile strength (NTS) of the base material is 325 MPa whereas CC-GMAW and CMT-GMAW joints exhibits relatively lower NTS of 196 MPa and 220 MPa respectively. This suggests that the reduction in NTS values are 40 % for CC-GMAW joints and 32 % for CMT-GMAW joints compared with the base material .Of the two welded joints, the joints fabricated by CMT-GMAW joints yields higher NTS and the increase is 12.2 % higher than the CC-GMAW joints. Notch strength ratio (NSR) for the base material is 1.02 while the NSR for CC-GMAW and CMT-GMAW joints are 1.005 and 1.02 respectively. Invariably all the joints fall in the notch ductile materials category, since the NSR is greater than one. Therefore it is clearly evident that these joints are insensitive to notches. But the sensitivity to notch is less in CMT-GMAW joints.

3.2 Micro Hardness Survey

Micro hardness distribution profile for CC-GMAW and CMT-GMAW joints are shown in figure 6. T.Y. Kuo and H.C. Lin. C [11]aluminum is increasingly employed in the fabrication of automotive body panels. This study performs butt welding without filler metal on two frequently used automotive body panel aluminum alloys, 5754-O and 6022-



a) CC-GMAW b) CMT-GMAW

Fig 7. Macrographs of the Welded Joints

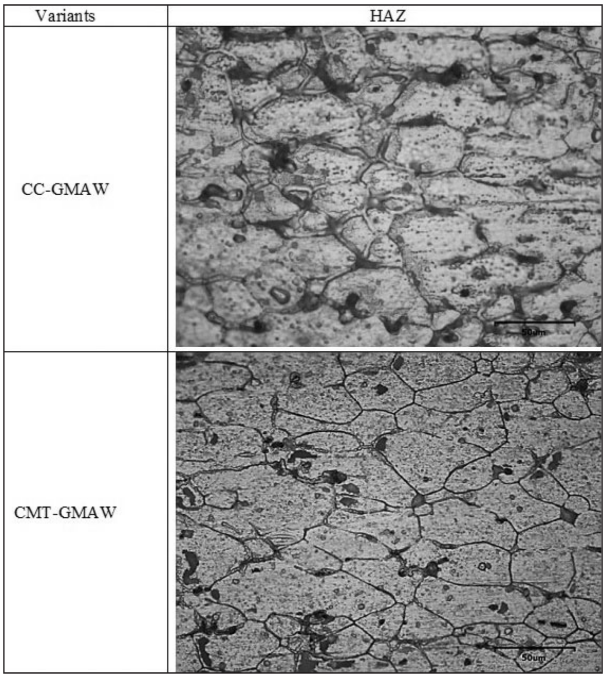


Fig 8. Optical Micrographs of the HAZ region CC-GMAW and CMT-GMAW Joints

T4E29. Welding is conducted using a Nd-YAG laser with a rectangular wave form having various pulse levels (ΔP claimed that the hardness profile for the CC-GMAW joint looks similar to that of CMT-GMAW joint except that the width of the HAZ is larger than that of CMT-GMAW joint. The width of the HAZ region for CC-GMAW and CMT-GMAW joints are 6 mm and 4 mm respectively. This is due to relatively higher heat generation in CC-GMAW process compared to the CMT-GMAW process. The hardness recorded in the HAZ is lower compared to the weld metal and base material regions. A hardness of 68 HV in the weld metal, 63 HV in the HAZ region is recorded for the CC-GMAW joint. Whereas a hardness of 75 HV in the weld metal, 70 HV in the HAZ region are noted for the CMT-GMAW joint. This suggests that the hardness in the WM region for CMT-GMAW joint is 10.2 % higher than the CC-GMAW joint. A low hardness region (called as soft zone) was observed in the HAZ region for both the CC-GMAW and CMT-GMAW joints. This zone is commonly took place only when the hardness in the HAZ is 50% lower than the base material. The value of hardness in the softer zone for CC-GMAW joint is 56 HV whereas for the CMT-GMAW joint, it is 59 HV.

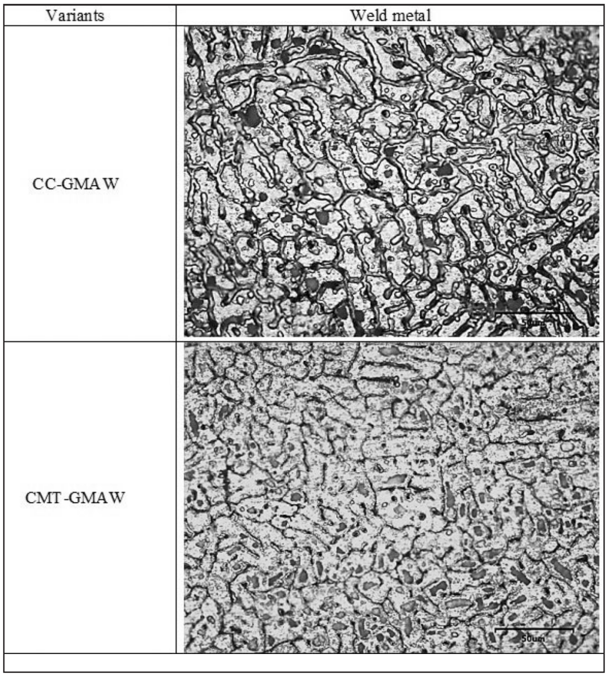


Fig 9. Optical Micrographs of the Weld Metal Region of CC-GMAW and CMT-GMAW Joints

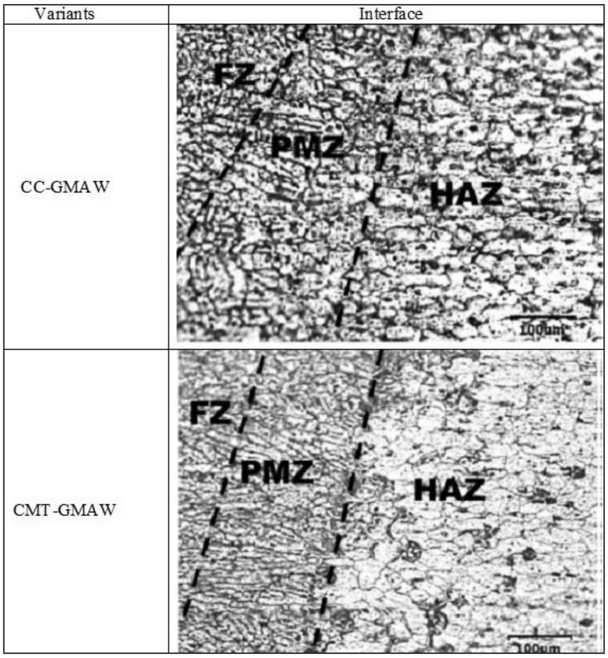


Fig 10. Optical Micrographs of the Interface Region of CC-GMAW and CMT-GMAW Joints

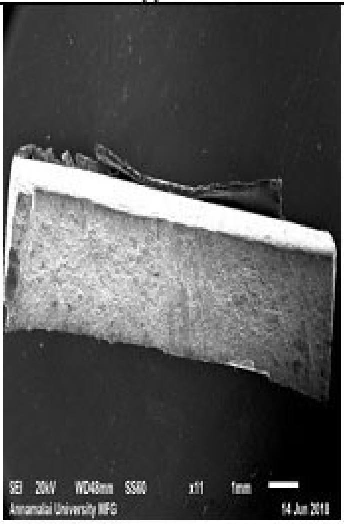
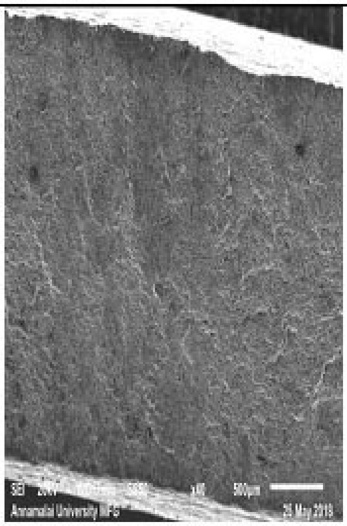
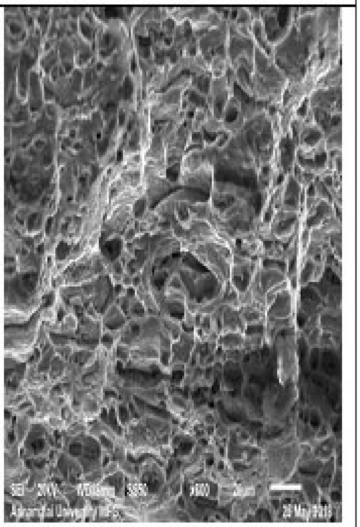
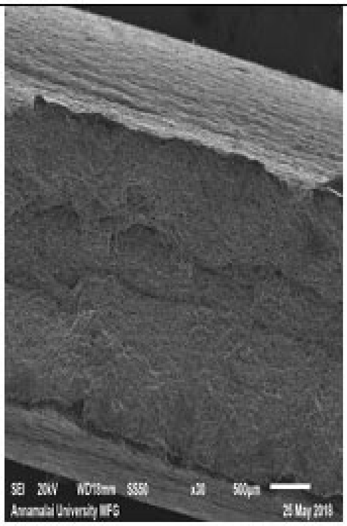
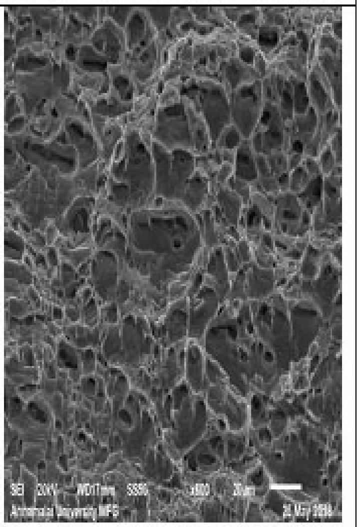
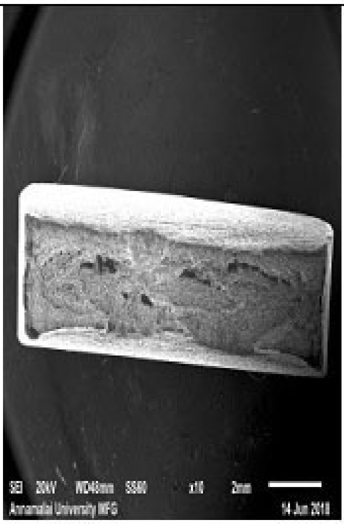
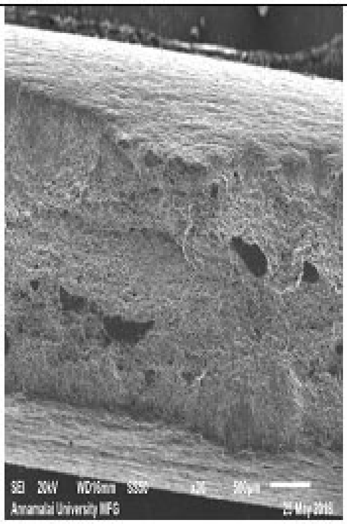
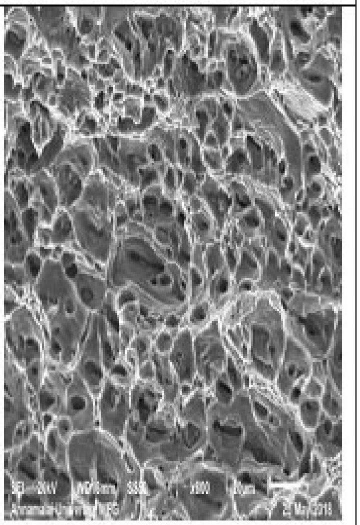
	Close up view of failed specimen normal to loading direction	SEM images at lower magnification	SEM images at higher magnification
BM			
CC-GMAW			
CMT-GMAW			

Fig 11. SEM Fractographs of the Smooth Tensile Specimens

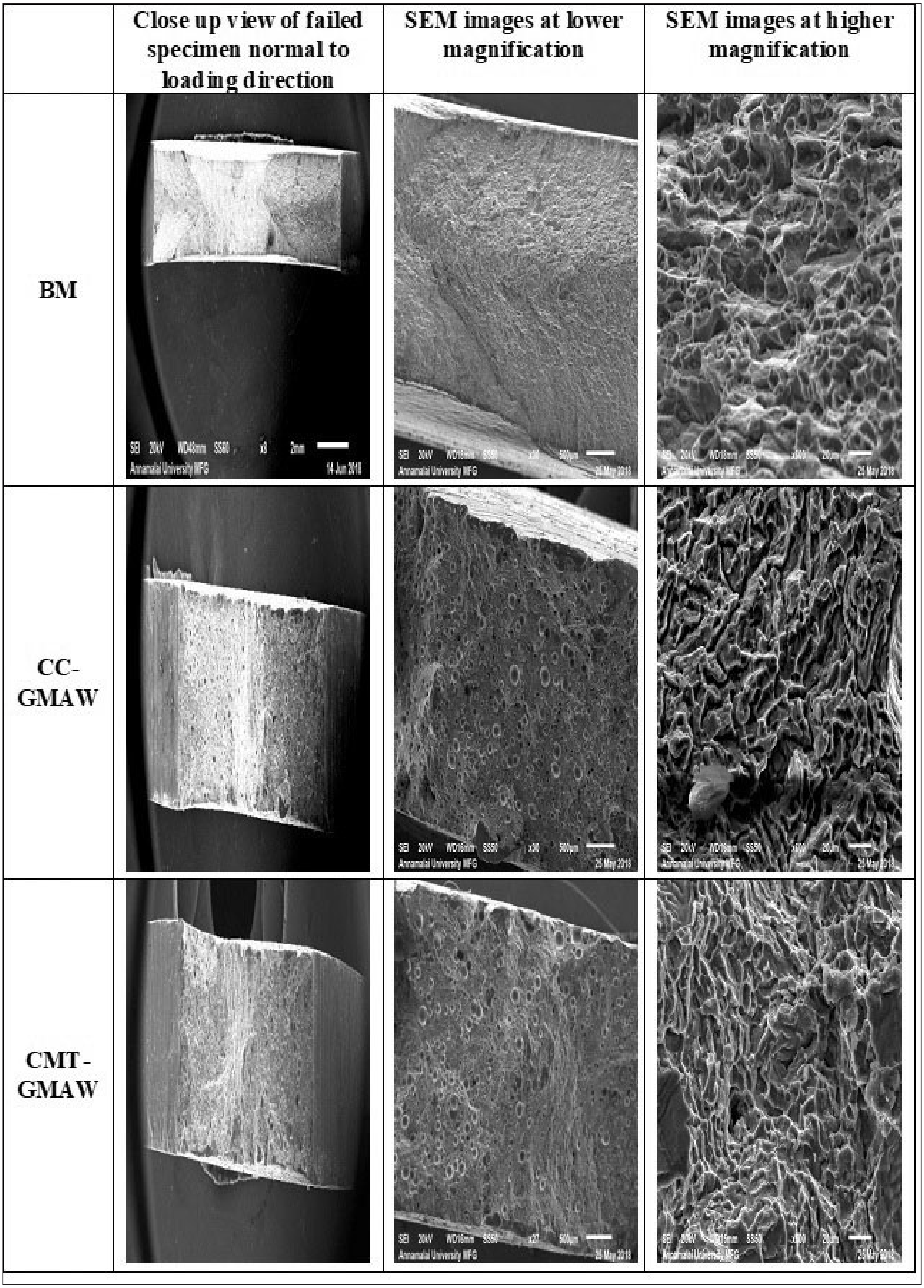


Fig 12. SEM Factographs of the Notched Tensile Specimens

3.3 Macro and Microstructure

Figure 7 shows the macrographs of both CC-GMAW and CMT-GMAW joints. From the macrographs it can be revealed that no macro level defects like liquation cracks or solidification cracks which are common in welding of aluminium alloys were found. This is because of the faster cooling rates associated with the low heat input. The micrographs of HAZ, Interface and WM regions are shown in figures 8, 9 and 10. Elongated grain structure was observed in the microstructure of the base material. The weld metal area consists of Al solid solution and Al-Si eutectic structure in dendritic form. F.Nie et. al [12] evidenced the segregation phase with low melting point eutectics which consists of a lamellar, aggregate or discrete morphology along the grain boundary in an Al-Si eutectic structure. A fine columnar dendritic microstructure was found in the weld metal region of CMT-GMAW joints due to the high solidification rates that helps to regain the strength of the solidified aluminium alloys. The HAZ region consists of coarser equiaxed grain structure in both the cases. From the figure it is clear that the PMZ consists of equiaxed to columnar grain structure. But the width of the PMZ differs in each case. The width of the PMZ is more for CC-GMAW joint compared with the CMT-GMAW joint due to the high heat input associated with the CC-GMAW process.

3.4 Fracture Surface Analysis

From the macroscopic observation of the fracture surface as shown in figures 11and 12, it is clear that both the CC-GMAW and CMT-GMAW joints shows ductile shear fracture with a shear angle of 45° . Most of the fracture surface consists of coarse dimples bounded by small dimples in CC-GMAW and CMT-GMAW joints as shown in figure 11 and 12. But in case of base material, the fracture surface with vertabration zones was observed. The close up view of the fracture surface consists of dimples with fine distribution of spherical second shaped particles. The SEM fractographs of CC-GMAW joints contains a lot of pores. But the fracture surface of CMT-GMAW joint consists of shallow dimples and pores with the absence of second phase particles, whereas the base material consists of deep dimples.

4. DISCUSSION

The loss of tensile strength after welding AA6061-T6 aluminium alloy is well understood and described by means of the precipitation sequence. The general sequence of precipitation in Al-Mg-Si alloys is as follows proposed by Dutta and Allen [13] :

SSSS ➔solute clusters ➔ GP zones (Spherical) ➔ β"(needle) ➔β' (rod) ➔β

Where SSSS is the super saturated solid solution and β is the equilibrium phase Mg_2Si. The T6 treatment of AA6061 aluminium alloy contains a matrix α, where the fine precipitates (β″) in needle shape are homogeneously spread. Presence of β″ precipitates is responsible for the highest tensile strength of the base material. But after welding, the material losses its strength as it is subjected to high temperatures caused by the weld thermal cycle. Since the β″ precipitates are thermodynamically unstable, transformation of β″ to β′ precipitate is observed in a welding process. Therefore a softer zone is formed in the HAZ region where the reduction in hardness is occurred due to the incoherence of β′. This leads to a reduction of tensile strength of the joint. This soft zone phenomena is observed in both the cases i.e., in CC-GMAW and CMT-GMAW joints. But the width of the soft zone and degree of softening are varied for each case. A narrow soft zone with relatively less degree of softening is observed in CMT-GMAW joint compared with the CC-GMAW joint. This is because of the low heat input process that controls the transformations in the microstructure of the HAZ region and leads to higher strength compared with the CC-GMAW joints. CMT-GMA welded joint showed higher ductility than the CCGMAW joint. This is because of the reduced porosity content in the joint madewith CMT-GMAW process. This phenomenon is due to the low heat input associated with the faster cooling rate.This faster cooling rate, in turn, causes relatively narrow columnar dendritic spacing in the weld metal zone. These microstructures usually offer higher resistance to deformation and indentation. Perhaps this might be one of the reasons for higher hardness and superior tensile properties of CMT-GMAW joints.

It is well clear that if precipitation occurs from a super saturated solid solution is observed in a microstructure, then the strength and hardness of the alloy increases. CMT-GMAW joints yield higher hardness in the weld metal zone although the hardening precipitates are dissolved. This is due to the solid solution gets enriched with Mg and Si in the weld metal zone. While the low hardness was observed in the HAZ region because of the dissolution of hardening precipitates. This dissolution of precipitates happens mainly because of the vaporization of strengthening elements or segregation of Mg along the grain boundary. A soft zone was observed in the HAZ region where the fracture took place because the low hardness value is observed at this location. Due to the strong constitutional super cooling and heterogeneous nuclei in CMT-GMAW process, the microstructure of the joint becomes finer by breaking the primary and secondary dendritic arm spacing.

5. CONCLUSIONS

1. The transverse tensile properties of the CMT-GMAW joints are relatively higher than the CC-GMAW joints. These results show that CMT-GMAW process could be the potentially suitable welding process in joining of thin AA6061-T6 aluminium alloy sheets without any metallurgical defects.
2. A soft zone is formed in the HAZ region due to the dissolution or coarsening of precipitates. The relative softening is less in the CMT-GMAW joints compared with the CC-GMAW joints. It is also observed that the width of the soft zone and HAZ is less in CMT-GMAW joints compared with the CC-GMAW joints.
3. Lower current and shorter duration of CMT-GMAW process led to stronger constitutional super cooling and more heterogeneous nuclei in the weld pool and this may be the reason for the formation of fine columnar dendritic structure in the weld metal region of CMT-GMAW joint compared to the CC-GMAW joint.

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