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Investigation of PCTIG, CCTIG and MMA Welding on Powder Metallurgy Aluminium Specimen Processed through Equi-Channel Angular Pressing (ECAP)

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Abstract: Present manufacturing processes require welding with adequate strength in the welded joints and excellent weld quality with reduced defects in the samples. To make effective use of this Autogenous TIG welding,arc oscillation technique such as pulsed current TIG welding with optimal current parameters is required to achieve desired weld properties. The experiment involves the study of mechanical properties and fractography of pulsed current TIG(PCTIG), constant current TIG(CCTIG) and Mixed mode TIG(MMA) welded 99.5% pure P/M Aluminium specimens processed through Equi channel angular pressing(ECAP). The specimens were initially processed through powder metallurgy route followed by an intermediary hot extrusion process to achieve a reduction in diameter as well as densification of the compact. The ECAP process was then carried out at optimum die parameters of channel angle 110^0 and corner angle 70^0 through route A for 2 passes. The micro hardness and mechanical properties like tensile strength, yield strength and % elongation of pulsed current, mixed current and constant current welded samples were compared. The factrography study was made on pulsed and constant welded specimens using Scanning Electron Microscope(SEM).Also, X-ray diffraction study for pulsed and constant specimens was taken to study the different phases present after the welding process. The study confirms that properties of pulsed current TIG welding are superior to mixed mode TIG welding and constant current TIG welding. Also, ductile fracture(dimples, cup and cone type) is obtained in the pulsed welded specimen(PCTIG) whereas the combination of brittle fracture(cleavage type) and ductile fracture is observed in the constant welded specimen(CCTIG).
Keywords: Brittle fracture; Constant current TIG; Ductile fracture; ECAP; Pulsed current TIG

I. INTRODUCTION

In recent years, the use of aluminium in manufacturing has become more prevalent because of its light weight and other attributes that make it an attractive alternative to steel. Welding of aluminum is important in today's world for various applications ranging from automobile to aerospace engineering. And because of their high demand and high precision, faster production is necessary to meet them. Autogenous TIG welding process has taken a prominent place in the welding field to achieve those ever increasing demands. Many research works are being carried out to develop new welding methods and gain a greater understanding of weld quality and properties[1].Welding of aluminum and its alloys using arc welding such as Tungsten Inert Gas (TIG) welding is the conventional method adopted. This is because welding is comp.tively cheaper with conventional TIG welding process. But the major challenge of this method is the reduced weld strength[2].Non-pulsed current(constant current) TIG welding on Aluminium causes the weld zones to exhibit coarse-columnar grains due to the thermal stresses in the heat affected zones at the time of welding[3]. This results in reduced weld strength due to higher weld input and lesser solidification rate of the weld pool. So it is necessary to control this solidification rate. The problem of coarse grain microstructure can be rectified by a method like surface nucleation with scandium as nucleation agent, micro cooler additions such silicon and titanium powders or arc oscillation methods like pulsed current welding[4-8].Among these methods, a pulsed current method is widely adopted because of their relative ease of handling and also its direct use in real-time applications[9].Also, fewer research works are being carried out on mixed mode current TIG welding of Aluminium specimens. Pulsed current TIG (PCTIG) welding involves cycling of welding current from a higherlevel(peak current) to lower level(base current) at a particular pulse frequency. This peak current gives adequate penetration and bead contour while the base current helps in maintaining a stable arc throughout the welding process. The pulse frequency helps in giving sufficient time to transfer heat from weld zone and heat affected zone to the base material region. Also optimized PCTIG welding parameters gives reduced heat input and fine grain microstructure. This can increase the weld strength of the aluminum specimen when compared to non-pulsed current(constant current)TIG welding[10]. Mixed current involves the cycle of AC current for one half and DC current for the other half cycle.

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This paper investigates the effect of pulsed current TIG welding(PCTIG), mixed current TIG welding(MMA) and constant current(non-pulsed current) TIG welding(CCTIG) on aluminum which is processed through powder metallurgy route and is equi channel angular pressed(ECAP).The problem is that the processed specimen will often result in decreased strength and ductility. So it is required to increase the properties of the material such as density, tensile strength, ductility and also possibility to get super plasticity at low temperatures. Severe plastic deformation (SPD) is the technique to attain ultra-fine grain refined structures of specimens: in bulk[11] and cylindrical tube alloys[12].Equal channel angular pressing(ECAP) is considered as one of the renowned techniques for producing ultra-fine grain structure through severe plastic deformation. ECAP induces uniform effective strain distribution in the workpiece which results in uniform deformation which in turn contributes to the grain refinement and eventually increases its strength[13].

II. EXPERIMENTAL PROCEDURE

A. Powder Metallurgy process

This first step involves the preparation of samples of pure Aluminium, processed through Powder Metallurgy(P/M) route.

1) *Selection of composition:* The chemical composition of the powder metallurgy samples: Aluminum is 99.74%, Fe is 0.24%,and Si is 0.02%. The composition of the specimens was found out using a portable alloy analyzer at SPF.
2) *Compaction:* The compaction process was carried out in Strength of materials(SOM) lab, SASTRA University. The pure aluminum powders were taken after calculating the amount to be compacted for the preparation of each sample using density and volume relations. The density of final compacted specimen is assumed to be 90%.The compaction was carried out in a die, and a uniform compressive load of 22tons was applied. After compaction, the dimension of the specimens was calculated and was found to be 24.9-25.1 in diameter and 25mm in length (L/D=1).
3) *Sintering:* The sintering of compacted specimens was carried out in a muffle furnace. The temperature of the furnace was set according to the melting point of Aluminium. As the melting point of aluminum is 660^{0}C. Thus the furnace was heated to 500^{0}C which is 75% of the melting point. This sintering process was carried out in a Nitrogen environment to prevent any oxide or scale formation over the specimens. Duration of sintering was 60minutes.
4) *Hot Extrusion:* The extrusion process was carried out in the extrusion die, and an impact load was applied using a 200T friction screw press. The specimens before extrusion were preheated to a temperature of 400^{0}C.This temperature was selected from the literary works.

B. ECAP Process

This process was carried die out in a with channel angle of 110^0.Corner angle was set at 35^0. Route A(0^0 rotation) was adopted for this experiment. This route was selected due to the availability of homogenous and reduced residual stresses of the specimens after the extrusion process. A uniform strain rate of 0.1s-1s was applied for the process. Surface irregularities were removed due to the availability of uniform strain rate. This ECAP process was carried out at SASTRA Precision Forging (SPF).

Fig. 1. Specimens after ECAP process

Fig.2.Die used to do ECAP of specimens

C. Autogenous TIG Welding process

Autogenous TIG welding was performed on all the Aluminium specimens. ADOR CHAMPTIG 300AD welding machine was used for this purpose. The 1st specimen is subjected to Pulsed current AC TIG welding, 2nd to pulsed current DC TIG welding, 3rd to Mixed mode TIG welding, 4th to constant AC TIG welding and 5th specimen to constant DC TIG welding. The optimized TIG welding parameters were in accordance with Sivachidambaram et al. who performed an experiment on optimization of Pulsed current TIG welding parameters. This optimization was carried out using Taguchi array analysis[14].Before welding, all the specimens were polished with abrasive paper and pneumatic rotary brush to remove the surface impurities.

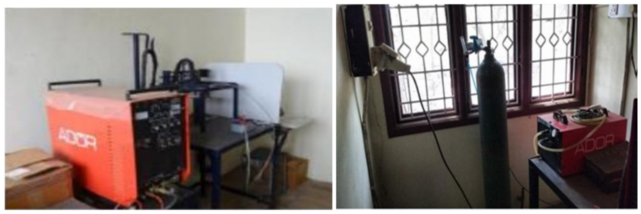

Fig. 3. ADOR CHAMPTIG 300AD machine used for the welding process

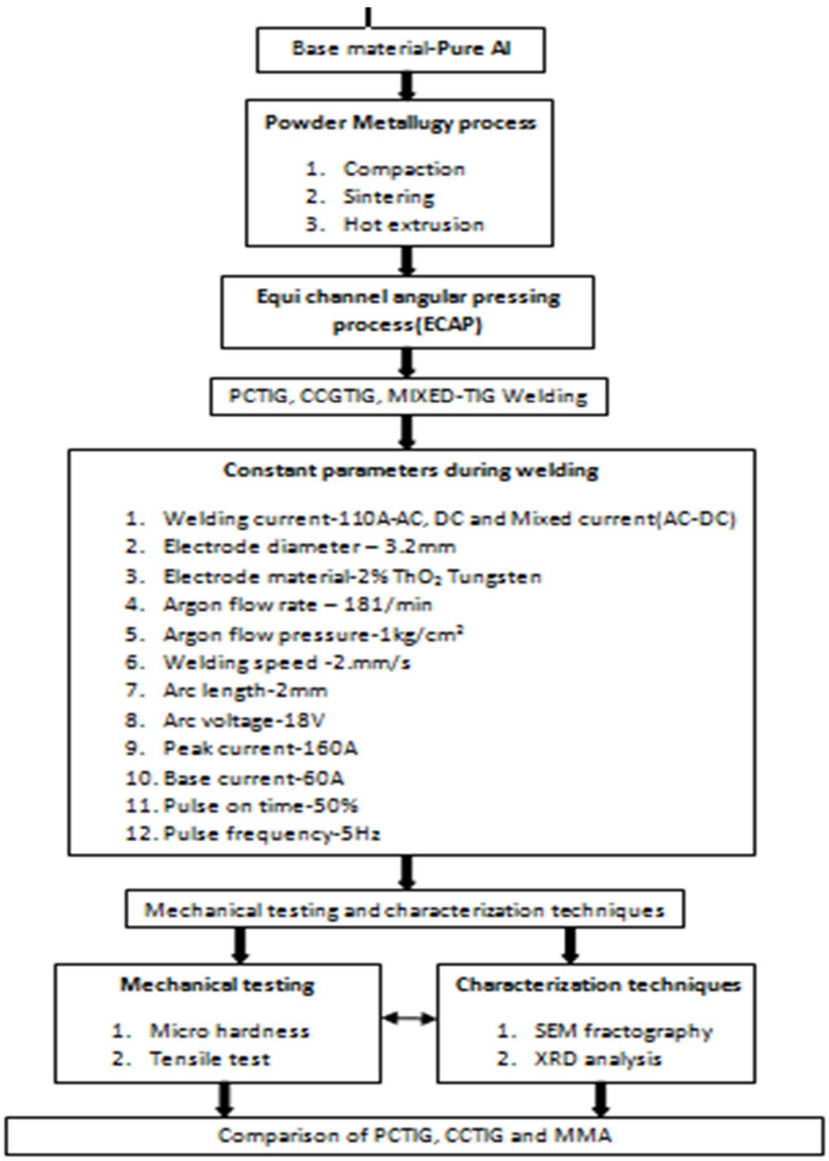

Fig. 4.Constant parameters used for PCTIG, CCTIG and MMA TIG welding and the experimentation process involved

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III. RESULTS AND OBSERVATIONS

A. Microhardness Test

After the welding process, microhardness test was taken on the specimens. Vickers microhardness method was chosen for the study since the Al material being soft will cause huge

Fig. 5. Vickers Microhardness Tester

Discrepancies when done with other methods. Microhardness of a different region of the weld zone, heat affect zone, and base material are measured using Shimadzu micro Vickers hardness tester as shown in figure 5 according to the standard of ASTM E 384.The readings were taken at 6 different distances each 1mm in the gap from the weld center. This is done in order to ensure the uniformity check. The uniform load applied throughout the experiment is 1.981N and a dwell time of 10s was provided for the loading.

Table1 shows the microhardness values obtained for PCTIG,MMA and CCTIG welded specimens. It can be observed from the table that the average microhardness value of PCTIG welded specimens(AC-63.2HV and DC-61.03HV) is greater than MMA(58.6HV) welded specimen which is greater than CCTIG welded specimens(AC-59.1HV and DC-56.06HV).Also, it is seen that AC current welded specimen(PCTIG and CCTIG) shows greater value when compared to DC current welded specimens(PCTIG and CCTIG).

Table.1.Microhardness Test results for the TIG welded specimens.

	Distance(mm)						
Samples	1	2	3	4	5	6	Average
Pulsed AC	68.1	67.3	66.6	61.9	59.6	57.1	63.20
Pulsed DC	65.1	64.1	62.3	60.2	58.1	56.4	61.03
AC	63.2	61.5	60.4	58.4	56.1	55.2	59.13
MMA	61.2	59.8	60.2	59.7	56.5	55.4	58.60
DC	58.6	57.8	56.9	55.8	54.2	53.1	56.06

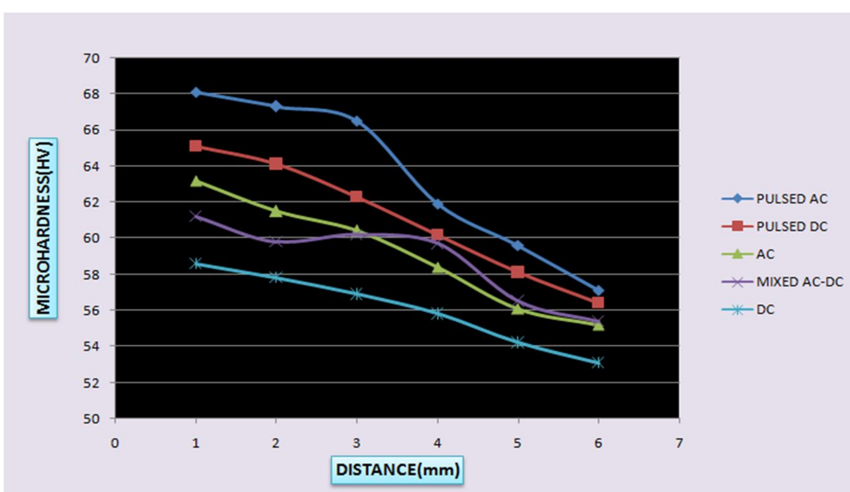

Fig.6.Graph showing the variation of microhardness value with respect to the distance for different welded specimens.

B. Tensile Test

Tensile test of both the specimens was taken according to ASTM E8 standard at room temperature to get properties such as yield strength, ultimate tensile strength, and %elongation of the specimens.

From the tensile report obtained (Table 2),it can be observed that the mechanical properties are of the order PCTIG(AC and DC)>MMA>CCTIG(AC and DC). Further, during the tensile test, fracture of the specimens obtained was observed using SEM analysis.

Table. 2.Tensile Test results for pulsed and non-pulsed current TIG welded specimens

Samples	Tensile strength(Mpa)	Yield strength(Mpa)	% Elongation
Pulsed AC	147	182	26
AC	100	147	18
MMA	101	163	22
Pulsed DC	103	176	24
DC	94	124	16

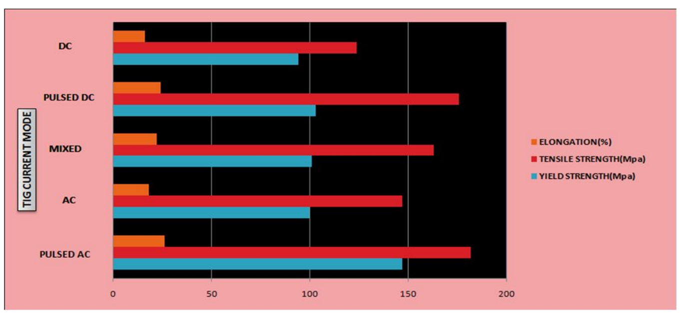

Fig.7.Showing the tensile property variation for PCTIG, CCTIG and MMA welded specimens.

C. Factrography Studies

After the fracture during the tensile test, it was observed that ductile fracture(cup and cone) was obtained for PCTIG welded specimens whereas ductile-brittle fracture(cleavage) was obtained for CCTIG welded specimens. Mixed welded specimen showed cup and cone fracture, but SEM analysis was not taken. The welded specimen is cut into a small piece to observe the fracture. Study the fracture surface; the factrographyis observed using Scanning Electron Microscope(SEM).SEM analysis was taken for 2 samples: pulsed AC welded specimen and constant AC welded specimen. SEM fractography is observed using scanning electron microscope of Vega3 Tescan; Japan makes for tensile tested samples with different magnification.

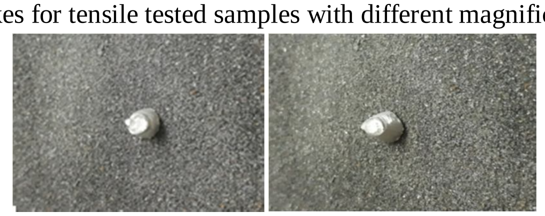

Fig.8. a)Pulsed AC fracture specimen and b) Pulsed DC fracture specimen(cup-cone)

Fig.9. a)Constant AC fracture specimen and b) Constant DC fracture specimen(flat-fracture)

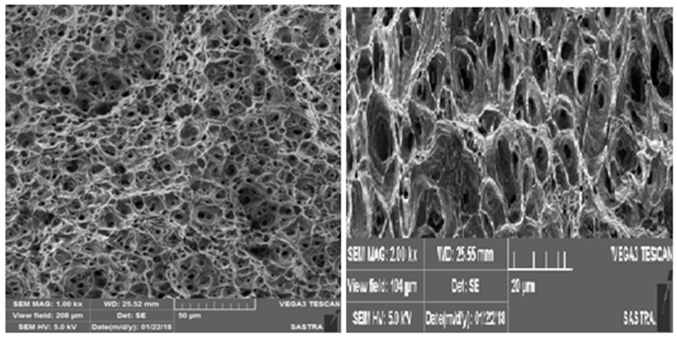

Fig.10.SEM image of pulsed current AC TIG welded specimen

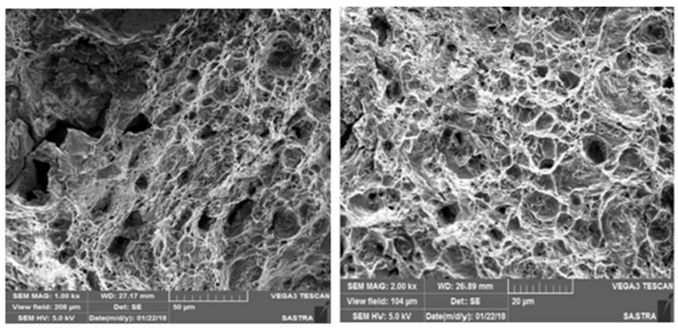

Fig. 11.SEM image of Constant current AC TIG welded specimen

It can be observed from the figure 9 that the fracture surface in pulsed current AC TIG welded specimen is ductile which has small and uniform dimples, cup and cone type failure. But from figure 10 it is observed that the fracture surface in constant current AC TIG welded specimen shows a combined ductile and brittle fracture. The features are many ductile dimples, voids indicating the ductile failure, and cleavage planes(flat planes with small atomic steps) indicating brittle failure. The size of the voids depends on the toughness of the sample.

D. X-Ray Diffraction studies

XRD analysis is carried out using Rigaku (Miniflux-300) X-ray diffractometer employing Cu-Kα source and NI filter to restrict Cu-Kβ rays. Diffraction patterns are recorded between 2θ values 10° to 120° at ascan speed of 10° per min with 0.010 step sizes.

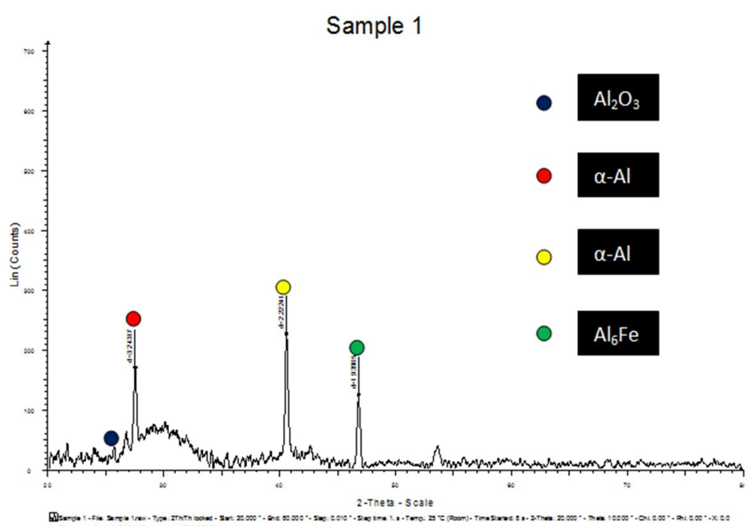

Fig. 12. image of Pulsed current AC TIG welded specimen

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Table. 3.XRD test result for Pulsed AC TIG welded specimen

Angle	d value	Intensity	Intensity %
2-Theta °	Angstrom	Count	%
25.035	4.87218	31	14.7
27.480	3.24317	165	74.4
40.560	2.22241	221	100.0
46.793	1.93985	119	53.9

Figure 12 and Table 3 shows the XRD result obtained for pulsed AC TIG welded specimen. From the results, it can be observed that Al_20_3 phase and Al_6Fe phases are present at angles 25.035^0 and 46.793^0 along with α-Al at angles 20.480^0 and 40.560^0.
Figure 13 and Table 4 shows the XRD result obtained for constant AC TIG welded specimen. From the results, it can be observed that Al_20_3 phase and Al_3Fe phases are present at angles 25.024^0 and 53.781^0 along with α-Al at angles 27.459^0 and 40.317^0.

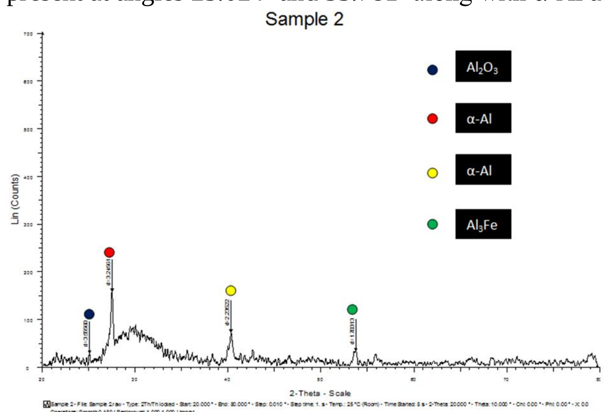

Fig. 13. XRD image of constant current AC TIG welded specimen

Table. 4.XRD test result for constant AC TIG welded specimen

Angle	d value	Intensity	Intensity %
2-Theta °	Angstrom	Count	%
25.024	3.55560	27.5	17.5
27.459	3.24561	158	100.0
40.317	2.23522	71.8	45.6
53.781	1.70313	32.6	20.7

IV. DISCUSSION

The dependence of stress of plastic flow in a material depends upon the impurities present in the material. Pure aluminum contains a smallnumber of impurities which affects its properties. The ductility, microhardness, tensile strength and other parameters get affected because of their presence, and these are found with the help of XRD(X-Ray diffraction)analysis. In the sample where the non-pulsed/constant current is performed the material showed peaks that ensured the presence of iron and a peak of aluminum oxide. The iron and oxide exist in the form of secondary phases with aluminum as monoclinic-Al_3Fe and Al_20_3.These occur due to the formation of excess phases in the solidification region. Even small amounts of iron contribute to the formation of Al_3Fe. The higher heat input in the constant current weld rises the temperature and when the cooling occurs the iron and silica being less soluble in aluminum at lower temperatures result in their appearance as precipitates. They exist in their metastable phases. Further this current induces higher thermal stresses as the thermal heat transfer is restricted due to insufficient time available during the process and due to this the iron and silica contain certain cracks with them. When the tensile load is applied gradually, the material fails in a ductile manner as conventional aluminum which has undergone severe plastic deformation does but afterward, the other oxide, ferrite, and silica phases become more prominent and these brittle phases make the material to fail in a brittle manner.

This can be explained as these impurities already contain cracks with them as mentioned above and when further stress gets formed they tend to carry the cracks with them as there is no continuous eutectic like formations which hinders plastic deformation and iron exists in needle shape structure which makes it prone to stress concentration and transfer the cracks. The sizes tend to increase because of these phases and as result of which the slip level is reduced, and lesser dislocation occurs and reduces the strain resistance and leads to the failure in a brittle manner. The failure occurs in an intra-crystalline way. Thus in the non-pulsedcurrent, the material fails first in a ductile manner and then in a brittle way due to high heat input and lower cooling rate in the weld zone.

In the pulsed current, monoclinic-Al_3Fetransforms to an orthorhombic-Al_6Fe phase which contains less Fe concentration compared Al_3Fe. Al_20_3 phase is also present similar to constant welded specimen but in lesser concentration. This is due to lower heat input, and the higher cooling rate in the weld zone and therefore the small particle precipitates formed during the further these do not contain any previously developed cracks in them as better distribution of heat takes place and thinner heat affected zone is formed due to larger solidification time available in the process. The thermal stresses are also reduced because of the reasons mentioned above. The weld strength is improved, and grain boundaries are more prominent, and therefore the slip level and dislocations are increased and the material therefore fails in a ductile manner throughout as more strength is induced in the material due to the pulsed current, though there are certain brittle phases present as shown by the peaks but these are lower, and their contribution is very less in comparison to the overall volume, and therefore the material fails in a ductile manner through the pulsed current.

V. CONCLUSION AND SCOPE OF RESEARCH

The pulsed current TIG welded specimen showed better mechanical properties in comparison with constant TIG welded specimen. Ductile type fracture was observed in the pulsed specimen. This is due to higher cooling rate in the weld zone, and less heat input which leads to the formation of orthorhombic-Al_6Fe phase and Al_20_3 phase whereas ductile-brittle fracture is observed in the constant welded specimen. This is the due lower cooling rate in the weld zone and high heat input which leads to the formation of monoclinic-Al_3Fe brittle phase which contains more Fe concentration than Al_6Fe phase along with the formation Al_20_3 phase. Pure Aluminium find applications for products ranging from structural materials to thin packaging foils. So Aluminium materials are subjected to high temperatures. So pulsed current TIG welded specimen can show better advantages like increased mechanical properties and longevity under these conditions when compared to constant welding of the materials. The overall performance of pulsed current GTAW is superior to constant current GTAW. The ECAP and hot extrusion processed were carried out for grain refinement and hence increase in its strength. Mixed Mode TIG welding showed greater mechanical properties compared to CCTIG welded specimens. Research works are to be carried out on the type of fracture obtained for mixed mode TIG welding and its ease of availability for industrial applications. Also, the Si impurity can be increased when compared to Fe in pure Aluminium to find its influence on the mechanical properties.

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