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Mechanical Characterization of Magnesium Alloy AZ31B Processed by Friction Stir Welding and Gas Tungsten Arc Welding

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Abstract- Magnesium alloy AZ31B plates are welded utilizing two different welding techniques. One is friction stir welding, a strong solid state procedure, and other tungsten inert gas welding with alternating current, a famous fusion welding technique. Imperfection free, complete infiltration welds are acquired after several attempts utilizing different procedure parameters such as tool rotational speed, tool transverse speed, peak current, gas flow rate etc. Then impact of two welding methods are compared on mechanical properties of AZ31B joints that were assessed utilizing tensile test, fatigue test, Microhardness measurement, metallography, stereography and fractography. Welds obtained from friction stir welding technique showed better tensile and fatigue properties as compared with tungsten inert gas process. FSW gives tensile strength of 164.5 MPa and GTAW joint 121.5 MPa. Increment in the hardness is observed in the gas tungsten arc welded joint, and decrease in friction stir joints. Welds by friction stir technique demonstrated fine grains in the heat affected zone (HAZ), and also in the stir zone (SZ). It is revealed that both procedures are appropriate to get the good joints of the magnesium alloy AZ31B, but welds by friction stir process showed the stronger welds.

Keywords- FSW, GTAW, Tensile test, Fatigue test, Microhardness, Metallography, Stereography, Fractography, HAZ, SZ

I. Introduction

Magnesium found on the earth's crust is the 6th most abundant nonferrous element. Magnesium has a great importance in the vehicle and aerospace industry due to its excellent strength to weight ratio. Magnesium and it alloys are very light weight basic structural material which are approximately 39% lighter than aluminum and similarly about 80% lighter than steel. Welding processes plays an important role in the performance of the magnesium alloy. Friction stir welding founds the fusion and solidification problems related with magnesium alloys when welded by other fusion welding techniques. Initially FSW was used to weld the aluminum alloys. Now a day this welding technique is very good for the weldments of different aluminum, magnesium and steel alloys. FSW can create no porosity joints, since porosity is the reason for metal hardening and are disposed of. Moreover it is a nature friendly joining method, since no protecting gas and no consumable filler material is need and no vapors are created during the preparing. This welding method does not produce any welding defects, like porosity and hot spits [1, 2]. Gas tungsten filler arc welding (GTFAW) is a welding technique, where electric arc is produced between the work piece and a tungsten electrode having non-consumable properties. Due to electric arc a spark is generated which is responsible for the fusion of work piece, and furthermore the filler wire may also be used. The joints of this welding technique have better results than other fusion welding techniques due to the neatness of the method, unwavering quality and weld's strength. Moreover, with GTA welding technique, high purity protecting gases like helium or argon is important to avoid the weld contamination. Oxidation may occur in the weld region due to the high temperature and greater chemical reactivity of the alloy. Till now there is found a very little research on the welding of magnesium alloys. In this research work great efforts are made to acquire good quality joints utilizing friction stir technique a strong solid state procedure and gas tungsten arc filler welding a fusion welding technique. The work incorporates assessment of tensile properties, fatigue properties of welds and investigations of welds using metallography and fractography.

II. Literature Review

Because of amazingly light metal, magnesium and it alloys have astounding strength to weight ratio [3], brilliant sound damping capacities [4, 5], great cast capacity [6], and magnificent machinability [7] and can also be reused. These characteristics of magnesium alloys make them appealing and gaining great significance in defense, automobile and in aviation sector [8-10], where weight reduction is a great concern. Welding processes plays an important role in the performance of the magnesium alloy.

In this paper magnesium alloy AZ31B, a medium quality Mg-Al amalgam having vast scope of engineering problems has been used. AZ31B has extraordinary mechanical properties, there is no need of heat treatment and besides has a normal work solidifying rate among other magnesium alloys. There is not a difficult task to weld the magnesium alloys but it needs prudent steps, because the value of thermal expansion is very high of magnesium alloy, they have greater thermal conductivity, having greater solidification shrinkage. Temperature range for solidification is very vast and having brittle nature intermetallic phases in many of the cases[11, 12].

Az31 alloy is welded by the laser and gas tungsten welding and results reported that the strength of laser joints is higher than the joints by tungsten inert gas welding[13]. Finer or litter grains were observed in the stir zone [14], when AZ31B are welded using friction stir method, decrease in hardness was also observed in the welded joints. A researcher studied the impact of heat distribution on mechanical and microstructure properties of AZ61 butt joints processed by the tungsten arc welding method [15]. Hardness of the stir zone is lower than the base metal of AZ31 when welded by friction stir welding [16]. Resistance to fatigue crack growth rate for AZ31B is better in case of laser welding when compared with FSW & GTAW [17]. Anyway comprehensive comparative study on FSW and GTAW filler joints of AZ31B has not been yet accounted for. The inspiration behind this work is to weld the magnesium AZ31B in such a way to achieve the maximum capacity of this particular material. The aim of this research is to compare the results of welds in the form of microstructure and mechanical properties when processed by the FSW and GTAFW, because this material is known for its superb weight and strength and broadly used in the aviation and automobile sector.

III. Materials and Methods

In this paper magnesium alloy AZ31B plates of thickness 4mm are used which contains 0.2% Mn, 2.5% Al and 0.5% Zn. Squared butt joint assembly has been utilized and plates are precisely cleaned with the help of wire brush and then using acetone to get the neat surface. Complete penetration, single pass welds are made utilizing GTAW filler and Friction stir welding methods, schematic diagrams for both the methods are shown in Figure 1. In both cases many attempts were made to get the defects free welds as shown in Figure 2. For friction stir welding a conical tip tool of H13 tool steel is used having smaller to larger diameter ratio of 2:4. Length of the tool tip is 3.8 mm and shoulder diameter is 16 mm, tool is shown in Figure 3. For GTAW a filler wire of square cross section of 2×2 is used cut from the same base metal. Argon is used as a shielding gas. The welding parameters used for both welding techniques are presented in Table 1.

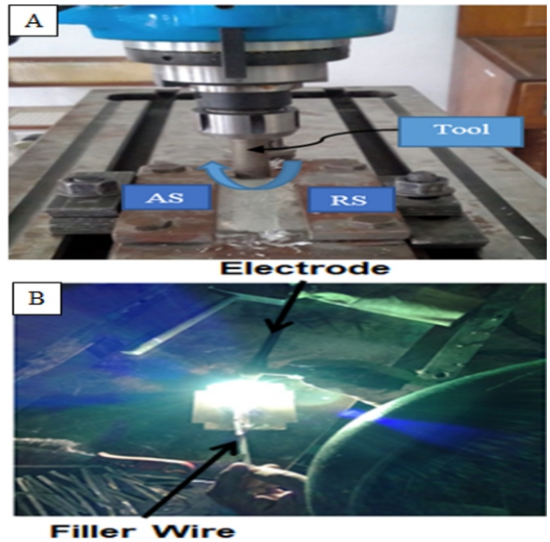

Figure 1: Welding processes (A) Friction stir welding (B) Gas tungsten arc welding

Table 1 Welding parameters

Friction Stir Welding	Gas Tungsten Arc Welding
Machine – Vertical Milling Machine (Figure 4)	Machine – WSE-400 USA
Welding Speed - 40 [mm/min]	Welding Speed-30 [mm/min]
Tool Revolving Speed – 1200 [RPM]	Welding Current - 190 [A]
Tool Tilt- 1.5 [degrees]	Gas Flow rate- 15 [L/min]
Axial force – 2kN	Axial force – zero
Filler wire – No	Square filler wire of 2×2 cut from base metal
Tool pin Profile- Conical	Shielding gas- high purity Argon
Tool Pin dia - 2:4 [mm]	Polarity – AC
Tool Shoulder dia - 16 [mm]	Trailing and backing gas shield

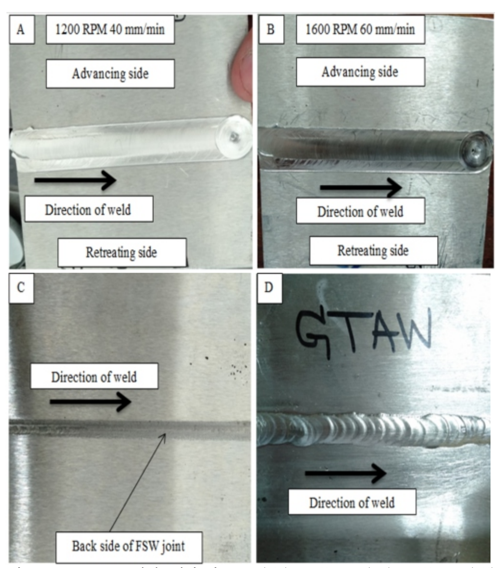

Figure 2: Welded joints (A) FSW (B) FSW (C) Backside of FSW (D) GTAW

Figure 3: Friction stir welding conical tool H13 tool steel

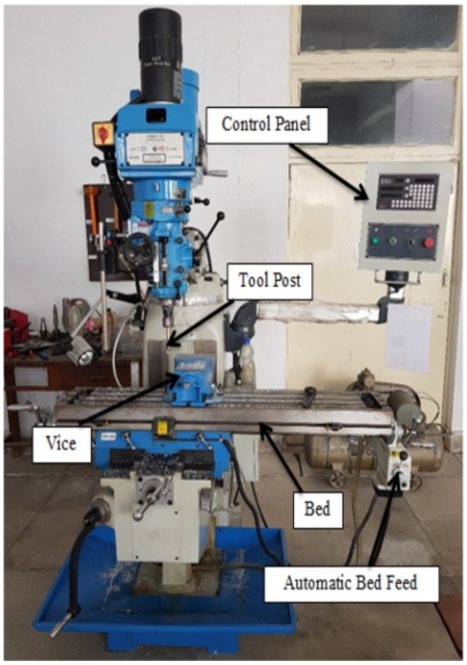

Figure 4: Vertical milling machine used for FSW

Welded plates are then cut and machined to get the desired specimens for different tests like hardness, fatigue, tensile and microstructure. ASTM standard E8M04 is used to get the specimens for tensile test; moreover substandard size of 100 mm length is used as shown in Figure 5. Vicker's Microhardness machine was used to check the hardness at different regions of the weldments utilizing a load of 100 grams applied for 10s. Mirror polishing was performed to get the specimens for metallography and fractography. Best suitable etchant Acetic-Picral is used containing (12ml distilled water, 4.2 gram picric acid, 75ml ethanol, 12ml acetic). Fatigue tests were performed on the both weldments and specimens are prepared as per ASTM E 466-96 standards shown in Figure 6. For comparison with the base metal tensile and fatigue tests were also performed on the base metal.

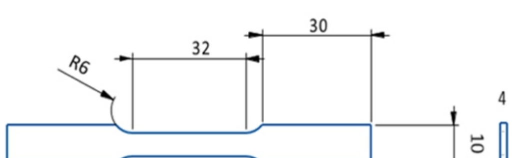

Figure 5: ASTM E08 standard dog-bone sample for tensile testing

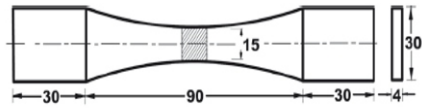

Figure 6: Standard E 466-96 for un-notched fatigue specimen

IV. Results and Discussion

Tensile Properties: Yield stress (σ_y), ultimate tensile stress (σ_{uts}), percentage elongation and welds efficiency of the base metal, FSW joint and GTAW joints of magnesium alloy AZ31B are shown in Table 2. Strain rate of 1 mm/min is used for all the test specimens. The strength of the both welded joints is observed lower as compared to the base metal. It can be seen from the table 2 that yield strength and ultimate strength for both joints is lower than that of base metal. Strength of the FSW joints is observed higher when compared to the gas tungsten arc welds as can be seen from the Table 2.

Table 2 Tensile test results

	σ_{uts} [MPa]	σ_y [MPa]	Percentage Elongation (%)	Weld Joint Efficiency (σ_y)
Base Metal	245	195	15 %	-
FSW	164.5	139	11.2 %	67 %
GTAW	121.5	99	5.9 %	50%

Figure 7 shows the tensile test specimens before and after fracture. Stress-Strain curves of base metal, friction stir welded joint and gas tungsten arc welded joint are shown in figure 8A, 8B and 8C respectively.

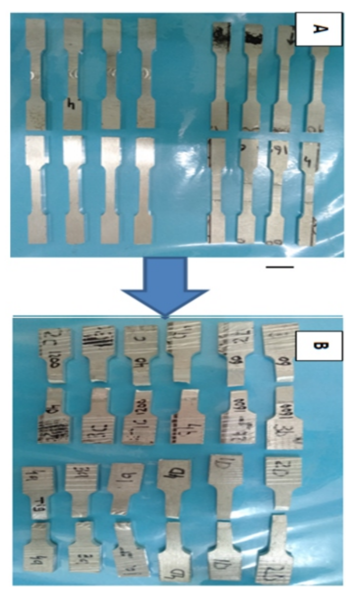

Figure 7: Tensile test specimens (A) Before failure (B) After failure

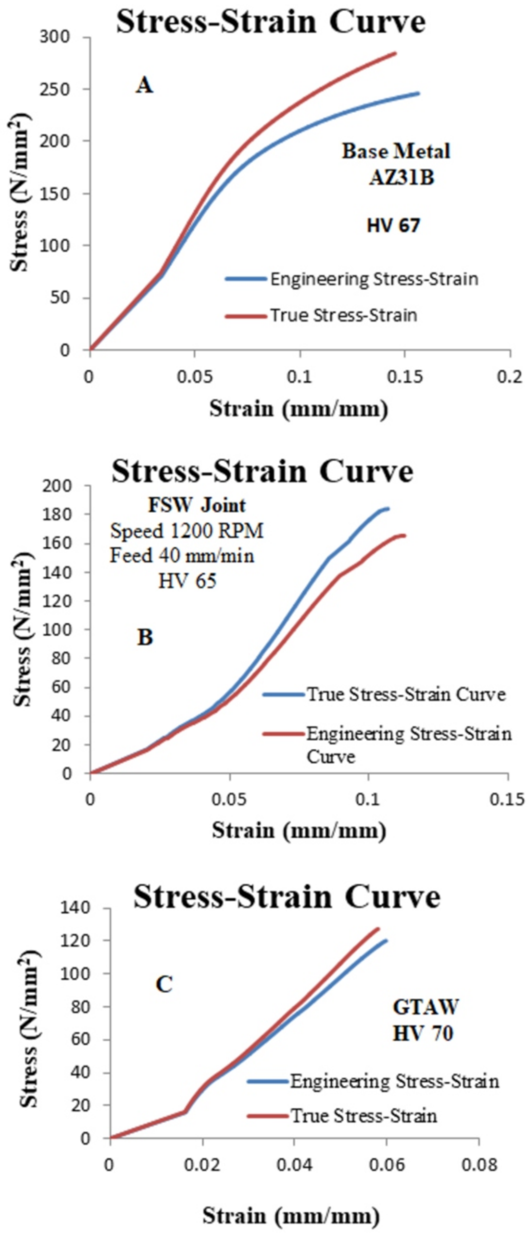

Figure 8: Stress-Strain curves for tensile test (A) Base metal (B) FSW joint (C) GTAW joint

Fatigue Properties: Fatigue test information are normally communicated in the form of S-N curves, plotted between cyclic stress 'S' and the number of cycles 'N' required to fracture the specimen. The welded joints were cut utilizing the specimen cutter and after that machined on the vertical milling machine to get the desired size Unnotched fatigue test specimens following ASTM standard E466-96 as shown in Figure 6. A hydraulic controlled (Zwick/Roell, Model: Z100), testing machine is used having fatigue capacity of 120 kN. To investigate the fatigue strength of base metal and welded joints a frequency of 10 Hz is set up with a constant stress load of ($\sigma_{min}/\sigma_{max}$ = 0.1). Fatigue tests were performed at four distinct stress levels (20, 40, 60 and 80) on smooth un-notched specimens. Average fatigue strength for 2×10^6 cycles is recorded and follows as; for base metal 70MPa, for FSW joint 42MPa and for GTAW joint 34 MPa. Fatigue data for the four samples is recorded in the Table 3. S-N curve from the given data is shown in Figure 9 in the form of log-log plot. Figure 10 shows the fatigue test specimens before and after fracture.

Table 3 Fatigue test data

Base Metal		FSW		GTAW	
Levels	No. of cycles	Levels	No. of cycles	Levels	No. of cycles
80	2.31E+05	80	7684	80	1840
60	6.86E+06	60	1.05E+05	60	1.15E+04
40	3.83E+07	40	8.11E+05	40	4.69E+04
20	8.05E+07	20	3.27E+06	20	9.01E+04

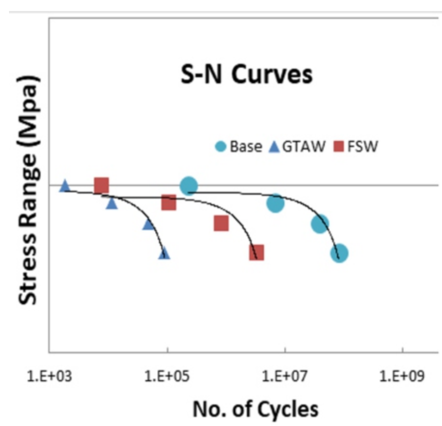

Figure 9: S-N curves for base metal, FSW and GTAW joint

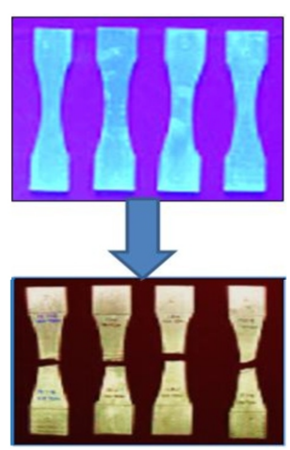

Figure 10: Fatigue test specimen before and after failure

Microhardness: Vickers Microhardness test was performed along the both sides of the weld joint at an interval of 2 mm for both FSW and GTAW joints. Gas tungsten arc welded joints showed the maximum hardness due to the fusion of metal and then sudden cooling. As the thermal conductivity of tungsten inert gas welded joints is higher as compared to FSW joints so the heat generated due to GTAW is more than FSW. Microhardness measurements in different parts of the welds are taken utilizing a Vickers Microhardness machine by applying a load of 100 g for the time of 10 s. Microhardness of the base metal was recorded 67 HV. Maximum Microhardness values for the gas tungsten and friction stir welded joints were 70 HV and 65 HV respectively. Microhardness profile for the different welding joints is presented in Figure 11.

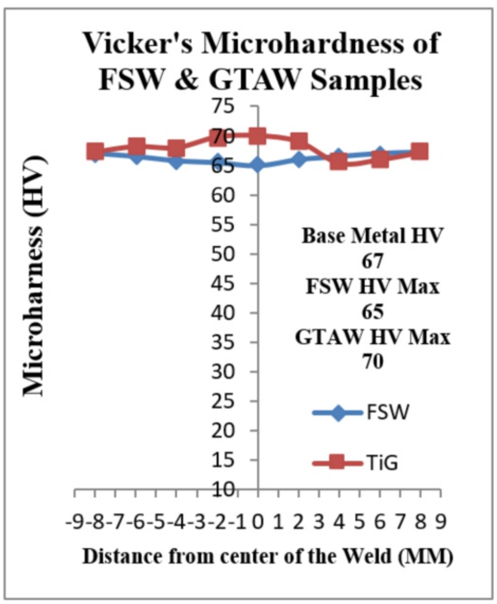

Figure 11: Vicker's Microhardness profile of FSW and GTAW samples

Microstructure: Microstructure of the base metal shows somehow fine grains that are presented in the Figure 12 (A). Finer recrystallized grain are observed in the weld stir zone of the friction stir welded joint that can be seen in the Figure 12 (B,C) and also fine grains are observed in the TMAZ adjacent to the nugget zone. In case of GTA filler welding coarse grains are observed similar to the base metal in size Figure 12 (D) shows the microstructure of GTA welding joint. It can easily be seen from the Figure 12 (B, C) and Figure 12 (D) that there is a huge difference between the microstructure in the stir zone of FSW joint and in the GTA welded joint. Dynamic recrystallization is the main factor behind the fine grain size in the stir zone. In the GTA welding the coarse grains are presented in the fusion zone due to the quick cooling of metal. Same information was also found about the microstructure of magnesium alloy AZ31B[18].

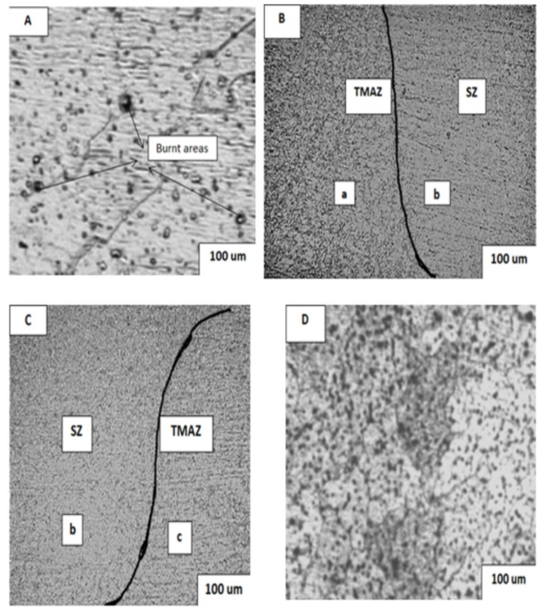

Figure 12: Microstructure (A) Base metal (B, C) FSW SZ and TMAZ (D) GTAW

Stereography: Stereographic images taken with the help of high resolution camera are presented in Figure 13. In case of friction stir welding smooth striations are formed in the flow direction as seen in Figure 13 (A), and similar flow pattern can be seen from the Figure 13 (B) for gas tungsten arc welding. Due to improper penetration of friction stir welding tool in the abutting area of the plates, few cracks are also observed as shown in Figure 13 (D).

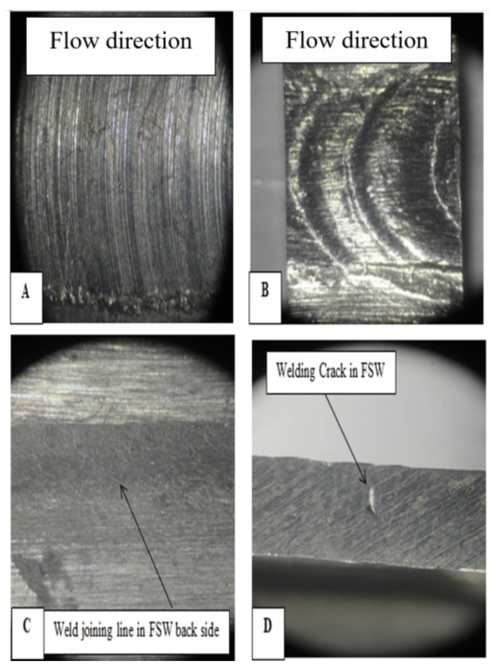

Figure 13: Stereographic images of welded joints (A) FSW Joint (B) GTAW Joint (C) Back side of FSW Joint (D) Welding crack in weld line of FSW joint

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Fractography: Figure 14 shows the fractography images of tensile specimens after fracture. Porosity was observed in all joints and can be seen easily. Figure 14 (A) shows the fractured surface of the base metal, cup and cone behavior is observed. Figure 14 (B) and (C) shows the fractured surface of FSW joint, small gaps are observed due to improper tool penetration, porosity is also detected in the few areas of the joint. Fracture of base metal and friction stir welding joint shows ductile behavior. Figure 14 (D) shows the fractured surface of gas tungsten arc welded joint, due to fusion of the metal some area of the plate melts and burn. Due to fusion of the metal in GTAW joint a brittle failure is observed. Large size pores are also presented in the welded area of the GTAW joint, due to which strength of these joint decreases.

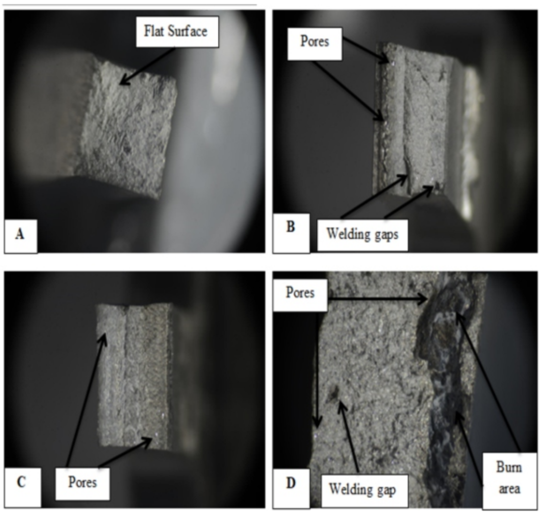

Figure 14: Tensile test fractography of welded joints (A) Base metal (B) FSW joint cone side (C) FSW joint cup side (D) GTAW joint

V. Conclusion

This work demonstrates the joining of simple Mg AZ31B of 4 mm thick plates by using friction stir and gas tungsten filler arc welding with zero offset. A proper clamping is used to get the cracks free and defects free joints. Following conclusions are drawn from this work.

- Best FSW butt joint welds are obtained using tool rotational speed of 1200 rpm and transverse speed of 40 mm per min and poor weld was attained at very high speed (above 2000 rpm) and at very low speed because at very high speed material melts and flows and at very low speed there was no desirable heat generation due to friction and so proper plastic deformation is not possible.
- Best GTAW butt joint weld was obtained at alternating current by setting welding current at 190 Amperes and welding speed 30 mm/min and gas flow rate of 15 l/min.
- In FSW at 1200 rpm and 40 mm/min maximum Microhardness was achieved, and same in the GTAW at 190 Amperes and at 30 mm/min. An increment in the hardness is observed in the GTA welded joints and decrease in hardness in found in the FSW joint.
- Tensile strength of FSW joint has a better strength than GTAW joint i.e. 164.5 vs 121.5 MPa. Gas tungsten arc welding joint shows the brittle fracture while friction stir welding joint shows somehow ductile behavior.
- FSW joints showed the higher fatigue strength than that of GTAW joint. At 2×10^6 cycles fatigue strength of FSW joint is measured 42 MPa and for GTAW joint it was 34 Mpa.
- There is a reduction in percentage elongation when using GTAW as compared to FSW.
- Metallography images show the fine grain structure in the nugget/stir zone in FSW due to strong stirring of tool and dynamic recrystallization as compared to GTAW.
- Fractography analysis of welds with FSW and GTAW shows the porosity in the weld areas.

VI. Recommendation

Future work can be done on the using of threaded tool used in FSW and pulsating current may be used in GTAW, its effect was discussed on the mechanical properties on the same magnesium alloys and its effect on the different zone of the weld i.e. heat affected zone and thermo mechanical affected zone. There may be using of single and multi-pass of welding technique to analyze the mechanical and microstructure changes in the welded region for the sophisticated applications. This may also be performed by using different alloys which are not weldable in fusion welding techniques. In future the fixing technique can also be discussed because it plays an important role in FSW. Another aspect of research could be in future with respect to the temperature distribution by using different types of ceramics particles and investigating its effect on the weld properties. Mathematical modeling and numerical simulation of this work can also be done for checking the better response. Same work can also be done on the other non-ferrous alloys like aluminium, copper.

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