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EFFECT OF WELDING PROCESS ON MECHANICAL AND METALLURGICAL PROPERTIES OF AA6061 ALUMINIUM ALLOY LAP JOINT

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ABSTRACT

This paper investigates the mechanical and metallurgical properties of AA6061 ALUMINIUM ALLOY lap joint by making welding process such as GTAW, GMAW and FSW. The frequently used welding process is GTAW and GMAW which is better economy and easier**.** During weld metal hardening because of thermal properties the rough columnar grains appears on alloy of weld fusion zones. This frequently source inferior weld mechanical and metallurgical properties and . Friction stir welding (FSW) is a new innovative welding process developed principally for welding alloys and metal that before now had been arduous to weld using more orthodox fusion techniques. Here 6.35 mm thickness of rolled plates are used for this process. For preparing lap welded joints Rolled plates of have been used. The filler metal used for joining the plate is AA4043 (Al.SSi (wt %) grade aluminium alloy. The tensile properties, micro hardness, microstructure of the GMAW, GTAW and FSW joints are compared and evaluated.From this work, it is to be observed that GMAW joints of AA6061 aluminium alloy have superior mechanical properties when compared to GTAW and FSW joints.

INTRODUCTION

1.1INTRODUCTION:

Aluminium alloys find wide applications in aerospace, automobile industries, railway vehicles, bridges, offshore structure topsides and high speed ships due to its light weight and higher strength to weight ratio. In all cases, welding is the primary joining method which has always represented a great challenge for designers and technologists. As a matter of fact, lots of difficulties are associated with this kind of joint process, mainly related to the presence of a tenacious oxide layer, high thermal conductivity, high coefficient of thermal expansion, solidification shrinkage and, above, all, high solubility of hydrogen, and other gases, in the molten state Further problems occur when attention is focused on heat-treatable alloys, since heat, provided by the welding process, is responsible for the decay of mechanical properties, due to phase transformations and softening. AA6061 aluminium alloy (Al-Mg-Si alloys) is the most widely used medium strength aluminium alloy, and has gathered wide acceptance in the fabrication of light weight structures. The preferred welding processes for these alloys are frequently gas tungsten arc welding (GTAW) and gas metal are welding (GMAW) due to their comparatively easier applicability and better economy. Welding of these alloys, however, still remains a challenge. Apart from softening in the weld fusion zone and heat affected zone, hot cracking in the weld can be a serious problem. Friction stir welding (FSW) is an innovative solid phase welding process in which the metal to be welded is not melted during welding, thus the cracking and porosity often associated with fusion welding process are eliminated. Therefore, the FSW process can also be used to weld heat-treatable aluminium alloys in order to obtain high quality joints.

1.2 WELDING OF ALUMINUM ALLOYS

Aluminum and its alloys can be joined by more methods than any other metal, but aluminum has several chemical and physical properties that need to be understood when using the various joining processes. The specific properties that affect welding are its oxide characteristics, its thermal, electrical, and nonmagnetic characteristics, lack of colour change when heated, and wide range of mechanical properties and melting temperatures that result from alloying with other metals like Oxide, Hydrogen Solubility, Electrical Conductivity, Thermal Characteristics, Forms of Aluminum, Filler Alloy Selection Criteria. Ease of welding is the first consideration for most welding applications. In general, the non-heat-treatable aluminum alloys can be welded with a filler alloy of the same basic composition as the base alloy. The heat-treatable aluminum alloys are somewhat more metallurgically complex and more sensitive to "hot short" cracking, which results from heat - affected zone (HAZ) liquidation during the welding operation. Generally, dissimilar alloy filler having higher levels of solute (for example, copper or silicon) is used in this case.

1.3 WELDING PROCESSES

The GTAW (gas-metal arc welding) process has been used to weld thicknesses from 0,25 to 150 mm and can be used in all welding positions. Because it is relatively slow, it is highly manoeuvrable for welding tubing, piping and variable shapes. It permits excellent penetration control and can produce welds of excellent soundness. Weld termination craters can be filled easily as the current is tapered down by a foot pedal or electronic control. **The ac - GTAW** process provides an arc cleaning action to remove the surface oxide during the positive electrode half of the cycle and a penetrating arc when the electrode is operated at negative polarity.

The dc - GTAW Process. Negative electrode polarity direct current can be used to weld aluminum by manual and mechanized means.

Other arc welding processes include shielded metal arc welding (SMAW), as well as electro slag and electro gas welding (ESW, EGW). SMAW with flux-coated rods has been replaced to a very substantial degree by the GMAW process.
The oxyfuel gas welding (OFW) process uses a flux and either an oxyacetylene or oxyhydrogen gas flame. When the oxyacetylene flame is used, a slightly reduced flame is required, which causes a carbonaceous deposit that obscures the weld and slows the travel speed.
Electron - beam welding (EBW) in a vacuum chamber produces a very deep, narrow penetration at high welding speeds. The low overall heat input produces the highest as-welded strengths in the heat treatable alloys. The high thermal gradient from the weld into the base metal creates very limited metallurgical modifications and is least likely to cause intergranular cracking in butt joints when no filler is added.
Laser-beam welding (LBW) is now considered to be a viable fusion joining process for aluminum with the advent of commercially available, stable, high-power laser systems.

Because of aluminum is high reflectivity, effective coupling of the laser beam and aluminum requires a relatively high power density.

1.4 PROBLEM DURING WELDILNG OF ALUMINIUM ALLOYS:

1.4.1 Porosity:

Porosity is a result of hydrogen gas becoming entrapped within the solidifying aluminum weld puddle and leaving voids in the completed weld. Hydrogen is highly soluble in molten aluminum, and for this reason, the potential for excessive amounts of porosity during arc welding of aluminum is considerably high. During the welding operation, it is easy to introduce Hydrogen unintentionally through contaminants within the welding area. It is important to understand thoroughly the many sources of these contaminants in order to detect the cause and take the necessary action to resolve porosity problems.

1.4.2. Crack consideration:

The majority of aluminum base alloys can be successfully arc welded without cracking related problems, however, using the most appropriate filler alloy and conducting the welding operation with an appropriately developed and tested welding procedure is significant to success. In order to appreciate the potential for problems associated with cracking, it is necessary to understand the many different aluminum alloys and their various characteristics.

2.0 BASE METAL:

In this investigation, AA 6061 Aluminium Alloy sheets of 6.35 mm thickness has been welded by there different process, suchas, Friction Stir Welding (FSW), Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) welding process. AA 6061 alloy provide extremely high thermal conductivity when properly heat treated. These alloys do not produce good corrosion resistance and are, therefore, often clad with pure aluminium or special alloy aluminium. Table 2.1 show the chemical composition of base metals.

Element	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Al
AA6061-T6	0.04	0.15	0.35	0.8	0.15	0.4	0.15	0.25	Bal.

Table 2.1 Chemical Composition Of Base Metal (wt%)

MATERIAL	**Yield strength (Mpa)**	**Ultimate tensile strength (Mpa)**	**Shear Strength (Mpa)**	**Elomgation (%) at 50mm gauge length**	**Vickers hardness at 0.05kg (Hv)**
AA 6061 T6	240	294	201	22	104

Table 2.2 Mechanical Properties Of Base Metal:

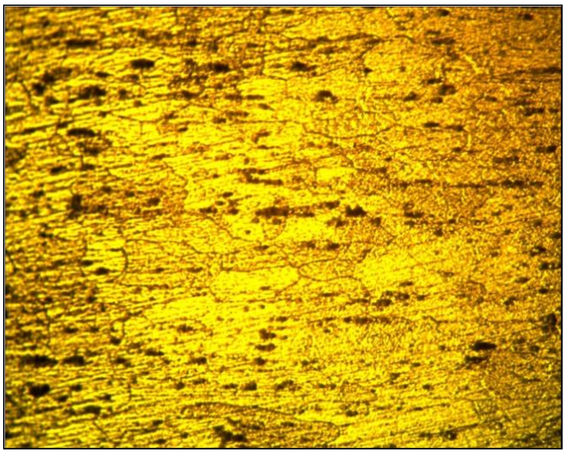


Fig 2.0 Base Metal Micro-Structure AA 6061 T6

2.1 FILLER MATERIALS

The welding metallurgy of NHT (Non-Heat Treatable) alloys is fairly simple since there is no precipitation reactions involved and are not prone to hot cracking or solidification cracking. Welding can be carried out with matching fillers (similar in composition to the base material).

Though certain alloying elements may get lost during welding, which can, however is compensated by using filler materials containing amounts of alloying elements. The 4xxx series alloys have Si added to reduce the melting point and to increase the fluidity in molten state. These are the least crack sensitive of all Al alloys and therefore, widely employed ea welding and brazing filler materials. The 5xxx series alloy have Mg added to increase their strength and ability to work-harden. They are very corrosion resistance and have highest strength of any of the NHT alloys. They are readily weldable, in most cases, with or without filler metal.

Filler Metal	**Si**	**Mg**	**Cu**	**Fe**	**Mn**	**Zn**	**Ti**	**Cr**	**Al**
AA 4043	5.0	0.05	0.30	0.80	0.05	0.10	0.2	-	Bal.

Table 2.3 Chemical Composition Of Filler Metals (Wt%)

Filler Metal	**UTS (Mpa)**	**YS (Mpa)**	**Hardness(BHN)**
AA 4043	382	305	115

Table 2.4 Mechanical Properties Of Filler Metals:

3.0 WELDING PROCESS:

3.1 GAS METAL ARC WELDING PROCESS:

Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding, is a semi-automatic or automatic arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used.

The basic technique for GMAW is quite simple, since the electrode is fed automatically through the torch. By contrast, in gas tungsten arc welding, the welder must handle a welding torch in one hand and a separate filler wire in the other, and in shielded metal arc welding, the operator must frequently chip off slag and change welding electrodes. GMAW requires only that the operator guide the welding gun with proper position and orientation along the area being welded. Keeping a consistent contact tip-to-work distance (the *stick out* distance) is important, because a long stickout distance can cause the electrode to overheat and will also waste shielding gas.

Stickout distance varies for different GMAW weld processes and applications. For short-circuit transfer, the stickout is generally 1/4 inch to 1/2 inch, for spray transfer the stickout is generally 1/2 inch. The positions of the end of the contact tip to the gas nozzle are related to the stickout distance and also varies with transfer type and application. The orientation of the gun is also important—it should be held so as to bisect the angle between the work pieces, that is, at 45 degrees for a fillet weld and 90 degrees for welding a flat surface. The travel angle, or lead angle, is the angle of the torch with respect to the direction of travel, and it should generally remain approximately vertical. However, the desirable angle changes somewhat depending on the type of shielding gas used—with pure inert gases, the bottom of the torch is often slightly in front of the upper section, while the opposite is true when the welding atmosphere is carbon dioxide

3.2 GAS TUNGSTEN ARC WELDING PROCESS:

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a nonconsumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by a shielding gas (usually an inert gas such as argon), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces energy which is conducted across the arc through a column of highly ionized gas and metal vapors known as plasma.

3.3 FRICTION STIR WELDING:

In FSW, a cylindrical-shouldered tool, with a profiled threaded/unthreaded probe (nib or pin) is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together. The parts have to be clamped rigidly onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. The length of the nib is slightly less than the weld depth required and the tool shoulder should be in intimate contact with the work surface. The nib is then moved against the work, or vice

3.4 FSW TOOL:

This technique uses a non-consumable welding tool to generate friction heating at the point of welding and to induce gross plastic deformation of work piece material is in a solid phase, resulting in complex mixing across the joint. In our experiment we have used high speed steel (HSS) tool. The advantages of HSS tool are

- Excellent red hardness
- Good wear resistance
- Good shock resistance
- Good machinability
- Good non-deforming property

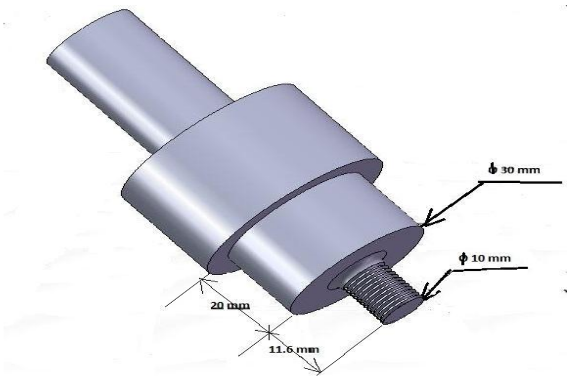


Fig 3.1 Dimensions of FSW Tool

4.0 EXPERIMENTAL PROCEDURE

The plates of AA6061 aluminium alloy were machined to the required dimensions (300 mm×150mm×6.35mm). Lap joint configuration, as shown in Fig. 4.11, was prepared to fabricate GTA and GMA welded joints. The initial joint configuration was obtained by securing the plates in position using tack welding for GTA and GMA welds. All necessary care was taken to avoid joint distortion, and the joints were made with suitable clamps. Single pass welding was used to fabricate the joints. AA4043 (Al-5%Si) grade filler rod and wire were used for GTA and GMA welding processes, respectively. High purity (99.99%) argon gas was the shielding gas. Lap joint configuration as shown in Fig. 1a was prepared to fabricate FSW joints.

A non-consumable, rotating tool made of high speed steel was used to fabricate FSW joints. The friction stir welding process is dominated by the effects associated with material flow and large mechanical deformation, which in turn is affected by process parameters such as rotational speed, welding speed and axial force. Compared to fusion welding processes, there is no porosity or other defects related to fusion. However, the hardening precipitates responsible for the good mechanical properties of heat treatable aluminium alloy are shown to be very affected by this process, partly because of their low stability.

The process parameters must be optimized to get defect free joints. work done in our laboratory, the optimum friction stir welding process parameter for joining AA6061 aluminium alloy are 200 rpm, 10 mm/min and 9.6 kN. Trial experiments and micro structural analysis (to identify any visible defects) were carried out for each mentioned process to find out the optimum process parameters.

4.1 SPECIMEN PREPARATION:

4.1.1 Specimen for Tensile Testing:

Tensile testing was carried out using a 100 kN, electro-mechanical controlled Universal Testing Machine (Make: FIE-Bluestar, India; Model: UNITEK-94100). The 0.2% offset yield strength was derived from the load-displacement diagram. Tensile specimens were prepared from the weld metal region (longitudinal direction) alone as per the ASTM E8M-04 standard to evaluate all weld metal tensile properties. The welded joints were sliced using a power hacksaw and then machined to therequired dimensions as shown in Fig. 4.12. American Society for Testing of Materials (ASTM E8M-04) guidelines were followed for preparing the test specimens. The tensile specimens were prepared to evaluate yield strength, tensile strength, elongation and reduction in cross sectional area.

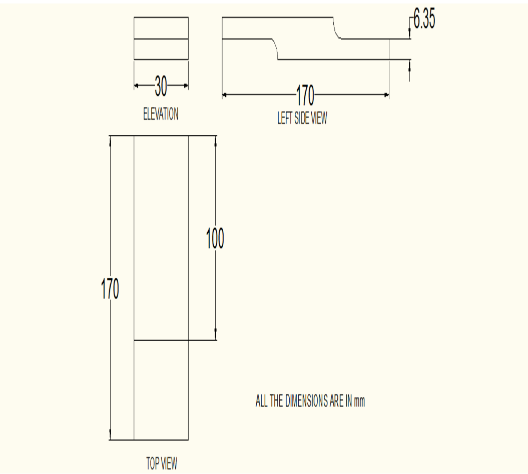


Fig 4.1.1 dimension of tensile specimen

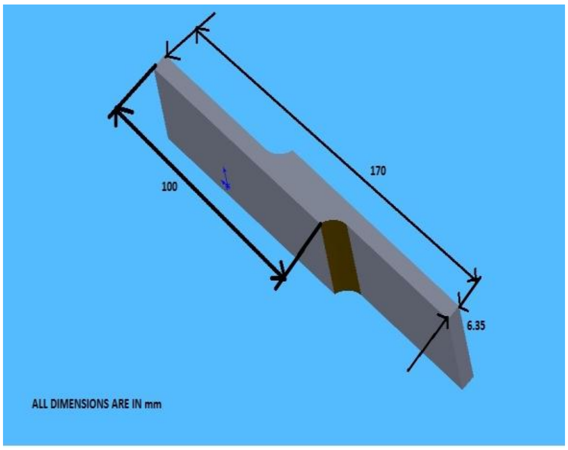
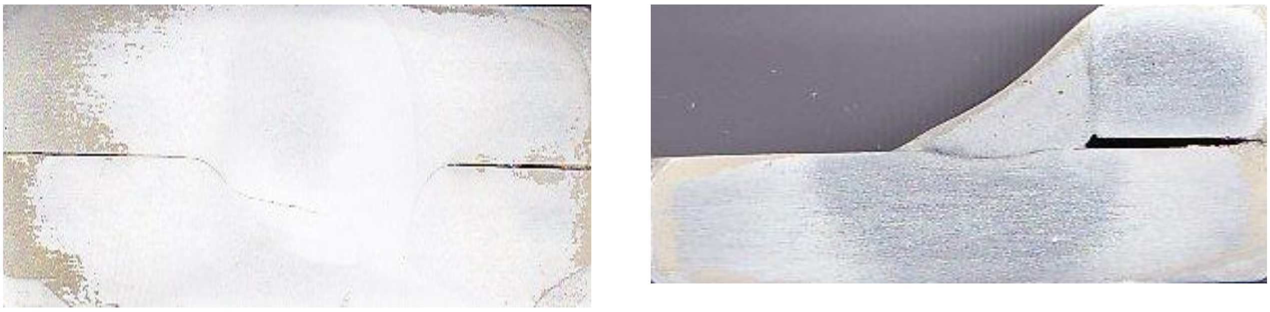


Fig 4.1.2 Tensile specimen

4.1.2 Specimen for microstructure analysis:

The specimen is prepared as per minimum required dimension (40X20 mm) by using power hacksaw. After the specimen surface is polished by emery paper (1/0 to 3/0). Vicker's micro-hardness tester (Make: Shimadzu, Japan and Model: HMV-2T) was used for measuring the hardness of the weld metal with a 0.05 kg load. Micro-structural examination was carried out using a light optical microscope (Make: MEJI, Japan; Model: MIL-7100) incorporated with an image analyzing software (Metal Vision). The specimens for metallographic examination were sectioned to the required sizes from the joint comprising weld metal, HAZ and base metal regions and polished using different grades of emery papers. Final polishing was done using the diamond compound (1 μm particle size) in the disc polishing machine. Specimens were etched with Keller's reagent to reveal the micro and macrostructure.

AS WELD



POST HEAT TREATMENT

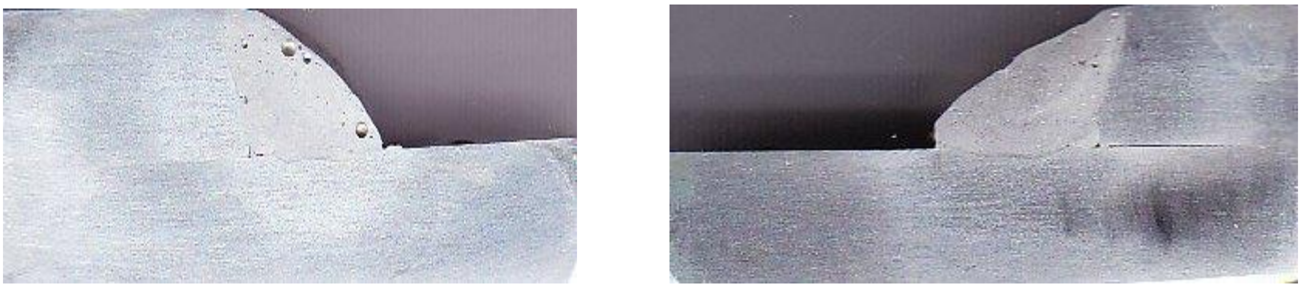


Fig 4.1.1 Specimen for microstructure

TENSILE TEST

Fig 4.1.2 Tensile Specimen

Properties:

The tensile tests are carried out in the 100 kN capacity electromechanical Universal testing machine at a displacement rate of 0.05 mm/min. The weld metal specimens are tested in the 100 kN capacity electromechanical testing machine in the same displacement rate as shown in fig. Load versus displacement was recorded in x-y axis. The 0.2 percent offset yield strength was calculated from load-stress diagram. The percentage elongation of the joint and the weld metal specimens are also estimated. Fig 4.1.1 shows the before testing and after testing specimens respectively.

Micro hardness survey:

Micro-hardness refers to hardness test made with loads not exceeding 1kg. Such hardness test has been made with a load as light as 1 gram, although the majority of micro-hardness tests are made with loads of 100 gram to 500 gram. In general, the term micro-hardness is related to size of the indentation rather than the load applied.

The degree of accuracy that can be attained by the surface smoothness of the specimen tested. If test load is decreases, surface finish requirements become more stringent. When the load is 100 grams or less a metallographic, finish is recommended. But for this investigation applied load is 5oo gram. The load is applied smoothly without impact and held in place for 20 sec. The indenter is made of diamond and is in form of a square base pyramid having an angle of 136 deg between faces. Micro-hardness is measured from the weld center to base metal. Fig 4.18c shows the micro-hardness testing machine.

Optical Metallography:

Microstructure examinations have been carried out using optical microscope to quantify various micro constituents present in the weld metals. Samples from the weld metals have been cut to the required sizes and the cross section of the weldment comprising the base metal, weld metals and HAZ regions is polished using different grades of emery papers (grade 1/0 to 4/0). Final polishing is done using the diamond compound (1µm particle size) in the disc-polishing machine. Samples are etched with keller’s reagent. Microstructure analysis has been carried using VERSAMET-3 light optical microscope with clemex-vision image analyzing system and the optical micrographs of weld zone are recorded. Fig 4.18b shows the microscope with clemex image vision system.

5.0 RESULTS AND DISCUSSIONS

5.1 TENSILE PROPERTIES:

The tensile properties such as Ultimate Tensile Strength (UTS), yield strength (YS) and (%) elongation are presented in the table.5.1 & 5.2

Specimen	Peak load in (KN)	Ult.stress in (KN/sq.mm)	Elongation in (%)	Breaking load in (KN)
GTAW 1	21.582	0.024	28.133	21.231
GTAW 2	27.959	0.031	40.667	27.374
GMAW 1	27.770	0.031	44.100	27.770
GMAW 2	29.921	0.033	41.033	21.056
FSW 1	4.640	0.005	40.033	4.640
FSW 2	11.520	0.013	70.567	3.470

Table5.1 BEFORE HEAT TRETMENT

Specimen	Peak load in (KN)	Ult.stress in (KN/sq.mm)	Elongation in (%)	Breaking load in (KN)
GTAW 3	24.971	0.028	18.300	24.971
GTAW 4	28.854	0.032	17.783	26.190
GMAW 3	31.788	0.035	19.883	27.270
GMAW 4	30.978	0.034	17.917	30.978
FSW 3	7.659	0.009	16.600	1.521
FSW 4	6.057	0.007	18.700	1.098

Table 5.2 AFTER HEAT TREATMENT

5.1.1 BEFORE HEAT TREATMENT

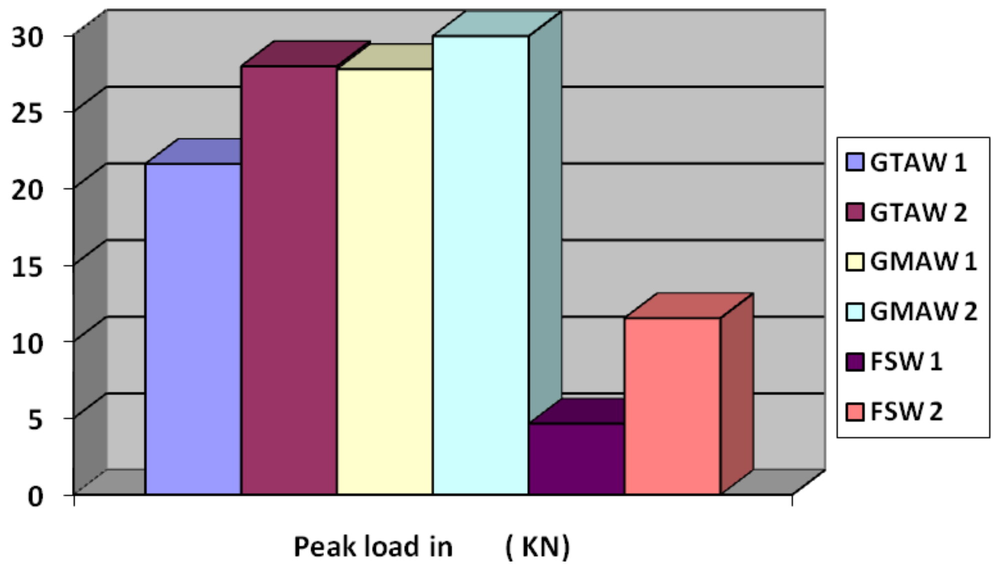


Fig 5.1.1a Tensile Shear Fracture Load

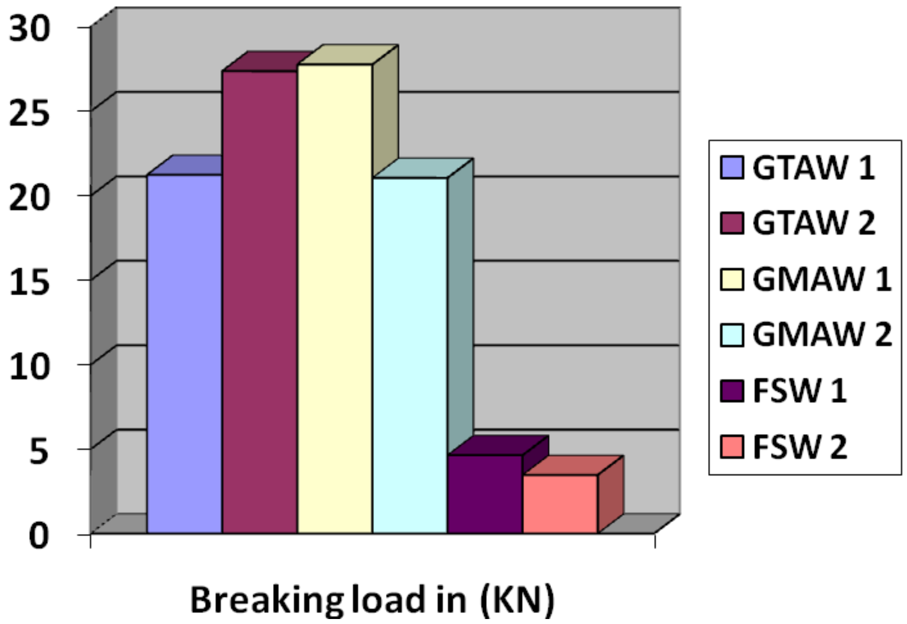


Fig5.1.1b Breaking Load

5.1.2 AFTER HEAT TREATMENT

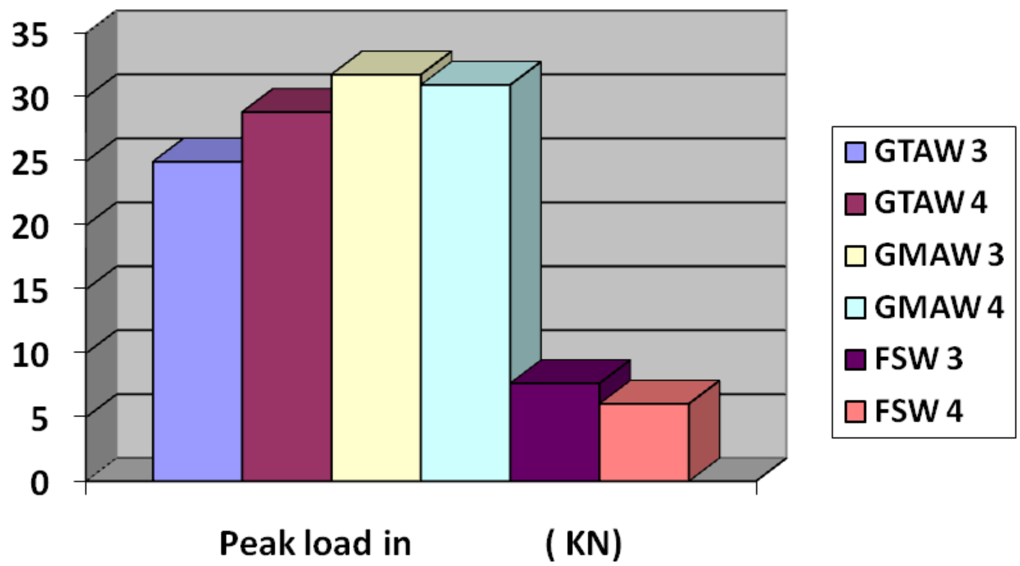


Fig 5.1.2a Tensile Shear Fracture Load

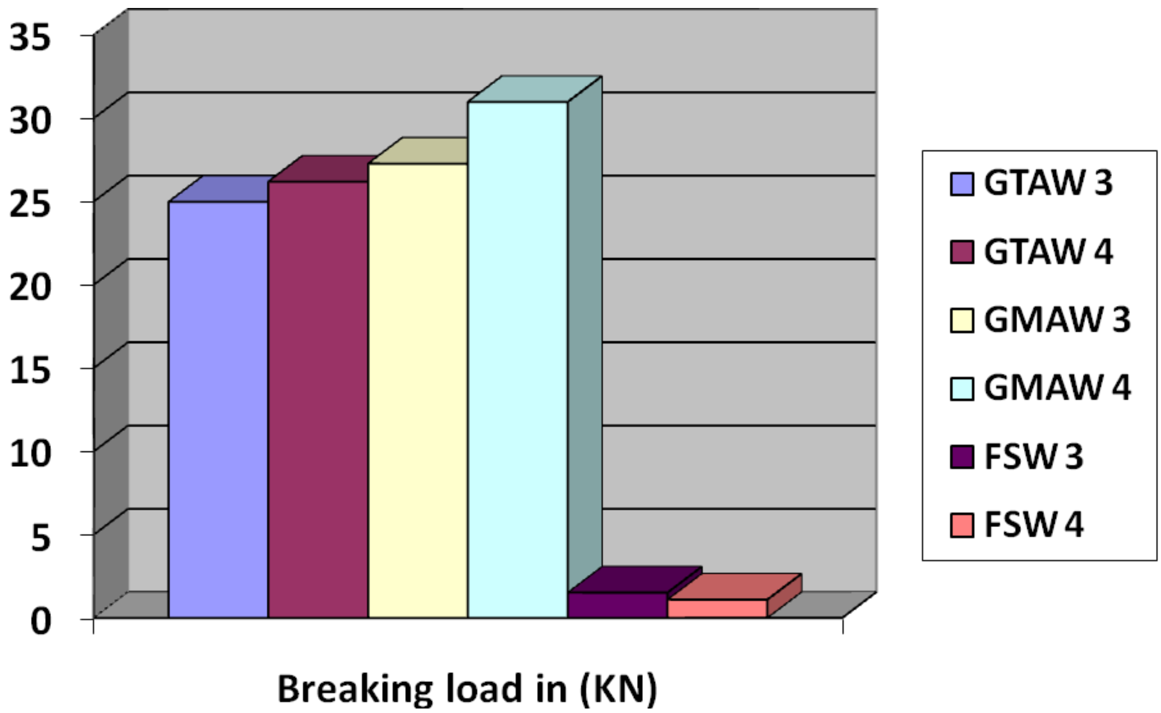


Fig 5.1.2 b Breaking Load

5.1.3 HARDNESS PROPERTIES:

Using vicker's micro-hardness, the hardness variation across the weld metal, to base metal regions are surveyed and the average values are shown in table 5.1.3.

Specimen	Micro-hardness	
	Before heat treatment (HV)	**After heat treatment (HV)**
GTAW	64.8	135
GMAW	85.56	119
FSW	53.97	87.4

Table 5.1.3 Microhardness

5.1.4 OPTICAL METALLOGRAPHY:

Microstructural examinations have been carried out using an optical microscope. Clemex vision image analyzing system has been used to take the microstructures as shown in table 5.4 &5.5.

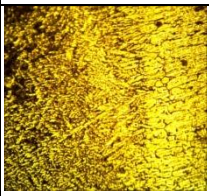
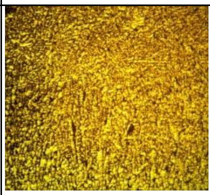
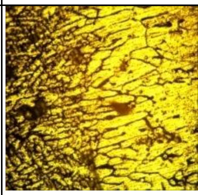
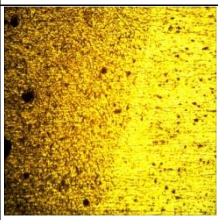
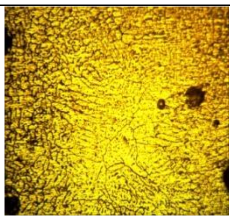
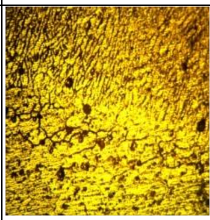
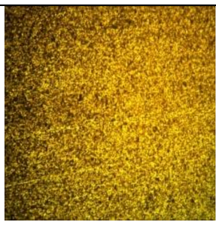
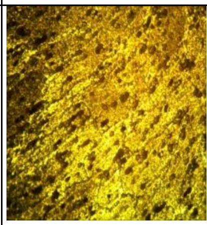
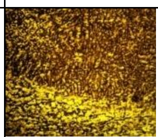
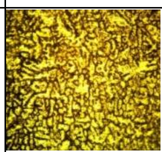
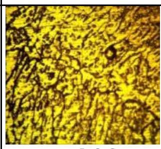
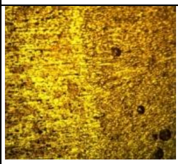
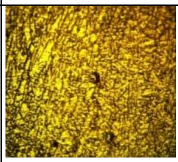
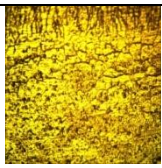
Specimen	Interface	Weld Region	HAZ	TMAZ
GMAW	 100X	 100X	 200X	-
GMAW	 100X	 200X	 200X	-
FSW	 100X	 100X	-	 200X

Table 5.1.4a Berofe Heat Treatment

Specimen	Interface	Weld Region	HAZ	TMAZ
GMAW	 **100X**	 **200X**	 **200X**	-
GMAW	 **100X**	 **200X**	 **200X**	-

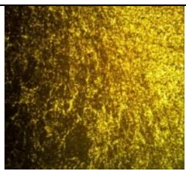
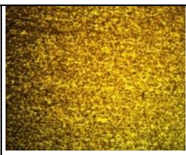
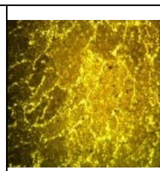
FSW	 **100X**	 **100X**	-	**200X** 

Table 5.1.4b After Heat Treatment

5.2 DISCUSSIONS

5.2.1 TENSILE TEST:

FSW process tensile failures occur in the welding region. Failure took as a 45º shear fracture and accompanied with some necking failure occurred as the advancing side of weld. Compared to the BM specimens tested transverse to the weld exhibit reduced strength and ductility.

GTAW process the weld zone would affected by the tensile fracture. Due to the heat input the welding zone and HAZ is affected by the tensile properties. GMAW process the fracture occurred in the HAZ. The tensile properties would not affect the weld zone due to the high welding strength.

5.2.2 MICROHARDNESS:

In friction stir weldments, there is considerable softening through out weld zone, compared to base material. The outside region retains the base material hardness. Since the hardness in the base material is scattered between 50 to 53 HV.

And the GMAW process the HAZ having maximum hardness and away from weld zone the hardness is gradually reducing. GTAW process welding center zone hardness varies from 69.8 to 59.9 gradually decreasing to base material hardness.

5.2.3 MICROSTRUCTURE:

Microstructure evolution in the base material is normally elongated grains due to rolling process. Optical microscope shows the BM-WC interfaces in GTAW. There is a coarsened dendritic grain structure in the WC zone. Grain size is quit variable in these areas, and is much longer than the original BM grains. The lamellar grains are the welding regions, BM region quite lamellar to coarsened grains are forms.

The grain size is fine at welding region in FSW. The FSW welding region grains are compared to BM it is more or less similar. The fine grain size would effect increasing mechanical properties.

5.2.4 MICROSTRUCTURE ANALYSIS:

Microstructure analysis has been carried out with the help of VERSAMET-3 light microscope with clemex-vision image analyzing system. The standard metallographic procedures have been followed to prepare the specimens. Optical micrographs have been taken at different locations but the micrographs of weld center regions are displayed in the fig.

5.3 CONCLUSIONS

FSW process produces fine equi-axed grains in the Dynamically Recrystalized Region (DRX).In GTAW welding cast structure with equi-axed grain are formed and the precipitates are coarsened with dentritic nature in grain boundaries. Grain refinement with fine distribution of precipitates shows better strength and ductility in GMAW.FSW joints show comparatively poor mechanical properties when compared to GMAW and GTAW joints. To join (AA6061-T6) Al alloy GMAW welding technique exhibit good mechanical properties.

6.0 REFERENCES

1. Matrukanitz RP (1990) Selection and weldability of heat-treatable aluminum alloys. ASM Handbook-Welding, Brazing and Soldering 6:528–536
2. Senthil Kumar T, Balasubramanian V, Sanavullah MY (2007) Influences of pulsed current tungsten inert gas welding parameters on tensile properties of AA6061 aluminium alloy. Mater Des 28(7):2080–2092
3. Balasubramanian V, Ravisankar V, Madhusudhan Reddy G (2007) Effect of pulsed current welding on mechanical properties of high strength aluminium alloy. Int J Adv Manuf Technol (in press)
4. Madhusudhan Reddy G, Gokhale AA, Prasad Rao K (1998) Optimization of pulse frequency in pulsed current gas tungsten arc welding of aluminium – lithium. J Mater Sci Technol 14:61–66
5. Mohandoss T, Madhusudhan Reddy G (1996) Effect of frequency of pulsing in gas tungsten are welding on the microstructure and mechanical properties of titanium alloy welds. J Mater Sci Lett 15:626–628 CrossRef
6. Knipstrom KE, Pekkari B (1997) Friction stir welding process goes commercial. Weld J 76:55–57
7. Mahoney MW, Rhodes CG, Flintoff JG, Spurling RA, Bingel WH (1998) Properties of friction stir welded 7075-T651 aluminum. Metallurgical Mater Trans A 29:1955–1964 CrossRef
8. Campbell G, Stotler T (1999) Friction stir welding of armor grade aluminum plate. Weld J 78:45–47
9. Liu HJ, Fujii H, Maeda M, Nogi (2003) Tensile properties and fracture locations of friction stir welded joints of 2024-T351 aluminium alloy. J Mater Process Technol 36:402–408 CrossRef
10. Maggiolino S, Schmid C (2007) Corrosion resistance in FSW and in MIG welding techniques of AA6XXX. J Mater Process Technol (in press)
11. Moreira PMGP, de Figueiredo MAV, de Castro PMST (2007) Fatigue behaviour of FSW and MIG weldments for two aluminium alloys. Theor Appl Fract Mech 48:169–177 CrossRef
12. Squillace A, De Fenzo A, Giorleo G, Bellucci F (2004) A comparison between FSW and TIG welding techniques: modifications of microstructure and pitting corrosion resistance in AA 2024-T3 butt joints. J Mater Process Technol 152:97–105 CrossRef

13. Munoz C, Ruckert G, Huneau B, Sauvage X, Marya S (2004) Comparison of TIG welded and friction stir welded Al-4.5 Mg-0.26 Sc alloy. J Mater Process Technol 152:97–105 CrossRef
14. Elangovan K, Balasubramanian V, Valliappan M (2007) Influences of tool pin profile and axial force on the formation of friction stir processing zone in AA6061 aluminium alloy. Int J Adv Manuf Technol (in press). DOI 10.1007/s00170-007-1100-2
15. Elangovan K, Balasubramanian V (2008) Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy. Mater Des 29(2):362–373
16. Mondolfo LF (1997) Aluminium alloys - structure and properties. Butterworths, London
17. Shinoda T, Ueno Y, Masumoto I (1990) Effect of pulsed welding current on solidification cracking in austenitic stainless steel welds. Trans Jpn Weld Soc 21:18–23
18. Madhusudhan Reddy G, Gokhale AA, Prasad Rao K (1997) Weld microstructural refinement in a 1441 grade Al-Li alloy. J Mater Sci 32:4117–4126 CrossRef
19. Kwon YJ, Shigematsu I, Saito N (2003) Mechanical properties of fine-grained aluminium alloy produced stir process. Scr Mater 9:785–789CrossRef
20. Fonda RW, Lambrakos SG (2002) Analysis of friction stir welds using an inverse problem approach. Sci Technol Join 7(3):177–181 CrossRef
21. Potluri NB, Ghosh PK, Gupta PC, Reddy YS (1996) Studies on weld metal characteristics and their influences on tensile and fatigue properties of fatigue properties of pulsed current GMA welded Al-Zn-Mg alloy. Weld J 75:62s–70s
22. Norman AF, Drazhner V, Prangnell PB (1999) Effect of welding parameters on the solidification microstructure of autogenous TIG welds in an Al-Cu-Mg-Mn alloy. Mater Sci Eng, A 259:53–60 CrossRef
23. Madhusudhan Reddy G, Mohandoss T, Prasad Rao K (2005) Sci Technol Weld Joining 10:121–128 CrossRef
24. Jata KV, Seminatin SL (2000) Continuous dynamic recrystallization during friction stir welding of high strength aluminium alloy. Scr Mater 43:743–749 CrossRef
25. Zhang Z, Zhang HW (2007) Material behaviors and mechanical features in friction stir welding process. Int J Adv Manuf Technol 35:86–100CrossRef
26. Colegrove PA, Shercliff HR (2005) 3-Dimensional CFD modelling of flow round a threaded friction stir welding tool profile. J Mater Process Technol 169:320–327 CrossRef
27. Zhang Z, Zhang HW (2007) Numerical studies on effect of axial pressure in friction stir welding. Sci Technol Weld Joining 12(3):226–248 CrossRef
28. Su JQ, Nelson TW, Mishra R, Mahoney M (2003) Microstructural investigation of friction stir welded 7050-T651 aluminium. Acta Mater 51:713–729 CrossRef
29. Ma ZY, Mishra RS (2003) Cavitation in super plastic 7075 aluminium alloys and prepared via friction stir processing. Acta Mater 51:3551–3569CrossRef
30. AWS Welding Hand book (1996) 3:232–235