Aluminum Alloys Welding: A Review

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Abstract- In recent year's aluminum and aluminum alloys are widely used in industries. These are light weight having good malleability and formability, high corrosion resistance and high electrical and thermal conductivity. High mach inability and workability of aluminum alloys are prone to porosity due to gases dissolved during melting processes. Aluminum alloys since the technique was invented in 1991 is reviewed on this paper. The basic principles of FSW are described, including the applications of aluminum alloys and material thickness used in different process.

Keywords- *Friction stirs processing, Aluminum alloys and applications, Material Thickness*

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I-INTRODUCTION

Aluminum and aluminum alloy are gaining huge industrial significance because of their outstanding combination of mechanical, physical and tri biological properties over the base alloys. These properties include high specific strength, high wear and seizure resistance, high stiffness, better high temperature strength, controlled thermal expansion coefficient and improved damping capacity [1]. The various Aluminum Welding techniques involves - Flux Cored Welding,Friction Welding, Laser Beam Welding, MIG- GMAW, Oxy-fuel Welding, oxy-fuel troubleshooting, Plasma Welding, SMAW- Arc Welding, SMAW- Arc Weld Troubleshooting, TIG- GTAW, Robotic Welding, SAW- Submerged Arc Welding, Spray Welding, thermit Welding, Underwater Welding, Friction Stir Welding [71].

In this paper the applications of aluminum alloys and their different processes are reviewed.The various thicknesses of parent materials during operations are also discussed. The effective process for aluminum alloys considered as friction stir processing between all welding processes.A method of solid phase welding, which permits a wide range of parts and geometries to be welded are called Friction Stir Welding (FSW), was invented by W.Thomas and his colleagues at The Welding Institute (TWI), UK, in 1991. Friction stir welding has a wide application potential in ship building, aerospace, automobile and other manufacturing.

Thus fundamental studies on the weld mechanism, the relation between microstructure, mechanical properties and process parameters have recently been started. Friction stir welding is a relatively simple process as shown in Fig.1. Friction stir welding (FSW) is a fairly recent technique that utilizes a non-consumable rotating welding tool to generate frictional heat and plastic deformation at the welding location, thereby affecting the formation of a joint while the material is in the solid state. Fig.1 shows the schematic drawing of friction stir welding representing all the relevant parameters of the process [2]. A rotating tool is pressed against the surface of two abutting or overlapping plates. The side of the weld for which the rotating tool moves in the same direction as the traversing direction, is commonly known as the 'advancing side'; the other side, where tool rotation opposes the traversing direction, is known as the 'retreating side'.

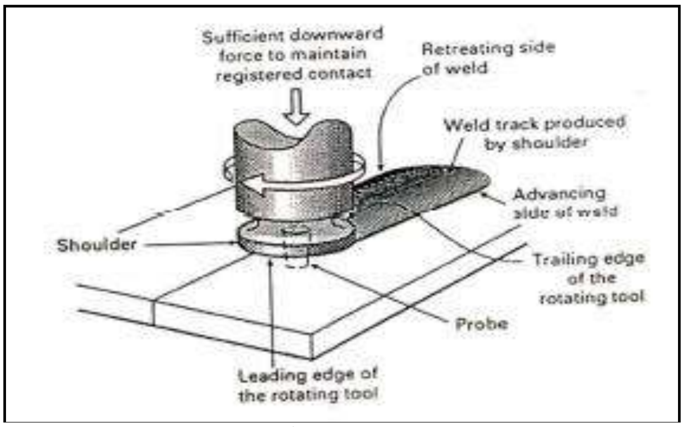

Figure.1: Schematic illustration of Friction Stir Welding [2]

II- MAJOR ALLOYING ELEMENTS IN ALUMINIUM

The major alloying elements in Aluminum and aluminium alloys typically include Silicon (Si), copper (Cu) and magnesium (Mg).

A. Silicon - Silicon is the most important single alloying element used in majority of aluminum casting alloys. It is primarily responsible for so –called good cast ability, high fluidity, lowshrinkage, low density which may be advantage in reducing total weight of cast component and has very low solubility.

B. Copper- Copper affects the strength and hardness of aluminum casting alloys, both heat treated and not heat treated and at both ambient and elevated service temperature. It also improve the mach inability of alloys by increasing matrix hardness, on the down side.

C. Magnesium- It Provides substantial strengthening and improvement of the work-hardening characteristics of aluminum. It can impart good corrosion resistance and weld ability or extremely high Strength Silicon combine with magnesium to form the hardening phase.

III- APPLICATIONS

TABLE I APPLICATION AREASOF ALUMINIUM ALLOYS [6]

S.No.	Part-I Aluminum and their application areas
1	Aircraft
2	Production of Hydrogen
3	Automotives
4	Aerospace
5	Automobile
6	Marine
7	Rail
8	Buildings
9	Packaging
10	Industry
11	Engineering
12	Energy distribution
13	Sports and leisure
14	Architectural
15	Constructions

TABLE II APPLICATION OF ALUMINIUM ALLOYS AND TEMPERS

Part-II Applications of Common Aluminum Alloys	
Al Alloy & Temper	**Typical Properties and Applications**
1100-O 1100-H14	Commercially pure aluminum resistant to chemical attack & weathering, low cost, ductile for deep drawing & easy to weld, used in chemical equipment.
2014-O 2014-T4, T451	Truck Frames, aircraft structures, automotive parts, cylinders &pistons, machine parts, structural applications
2017-T4	Fasteners, fittings
2024-O 2024-T3, T4 2024 -T351 Al clad	High strength structural applications, excellent mach inability in T-temper, fair workability &corrosion resistance, al clad combines high strength and corrosion resistance, used in truck wheels, aircraft structures, automotive parts, fasteners, recreation equipment.
3003-O 3003-H12 3003-H14 3003-H16	Most popular general-purpose alloy, stronger than 1100 with same good formability & weld ability, used in cooking utensils, chemical equipment, pressure vessels, sheet metal work, builder's hardware, storage tanks.
3004-O 3004-H38	Sheet metal work, storage tanks, agricultural applications, building products, containers, electrical applications, furniture, trucks.
3105-O 3150-H14 3150-H18	Siding, sheet metal work, automotive parts, building products, electronics, furniture, trucks & trailers
5005-H34	Appliances, utensils, architectural, electrical conductors, general sheet metal, hardware, marine applications.
5052-O 5052-H112 5052-H32 5052-H34	Stronger than 3003, readily formable, good weld ability & resistance to corrosion, used in sheet metal work, hydraulic tube, appliances, pressure vessels, hardware signs, marine applications, trucks.
6061-O 6061-T4 6061-T6, T651	Good formability, weld ability, corrosion resistance, & strength in the T-tempers, good general-purpose alloy used for a broad range of structural applications & welded assemblies, pipeline, marine applications, furniture, agricultural applications, aircraft's, architectural, building products.
6063-T5 6063-T6	Pipe railing, furniture, architectural extrusions, marine applications, truck & trailer, recreation equipment, building products, electrical and electronic parts.

IV- USE OF ALUMINIUM ALLOYS IN VARIOUS PROCESSES IN INDIA

The three tungsten based tools materials used, W99 (W–1% La2O3) tool exhibited better micro structural stability without undergoing physical changes in tool configuration, It was found that the tool made of 99% W and 1% La2O3 withstood high strain rate, temperature and flow stresses generated during FSW of HSLA steel. It is understood that tool deformation and wear manifestation during FSW of harder alloys could be overcome successfully by proper selection of tool material tool design and process parameters. [1]. Samples with one through three passes with 100% overlap were created using friction stir processing (FSP) in order to locally modify the microstructure and mechanical properties of a cold-rolled Al-5083 alloy. A constant traverse speed and two different rotational speeds were used for processing. The results indicated that single-pass FSP caused dynamic re crystallization in the stir zone, leading to equaled grains with high angle grain boundaries [2]. Al-7B04 alloy of 2 mm thickness sheets under T6, T4 and O tempers were subjected to friction stir processing (FSP). The microstructure, Vickers hardness and tensile properties of the stir zone were characterized. The results show that the initial base metal temper has a significant impact on the microstructure and the mechanical properties of the stir zone. FSP led to the formation of full re-crystallized microstructure, the average grain size in the stir zone ranged from 2.1to2.2 μm when the base metal tempers wereT6 and T4 [3].Friction stir processing (FSP) was successfully applied to modify the microstructure and texture of an Mg- 8Gd-5Y-1.1Nd-0.45Zr (wt.%) alloy. Two kinds of original alloys, i.e., solid solution (SS) alloy and aging (AG) alloy were used for a comparative study. The results show that the grains in SZ were greatly refined to 3-4 mm after FSP in both SS and AG alloys [4.].

Friction stir welding of AA7075 alloy with the addition of boron carbide powder resulted in the improved hardness and refinement of microstructure in nugget zone. Microstructure of nugget zone was found to be responsive to the post weld heat treatments of peak-aging (T6), retrogression and RRA. Maximum value of hardness at the rate of 67.25 Hv was observed at weld pitch of 0.050 mm/rev. with 20 mm tool shoulder diameter [5].The best quality weld was acquired using hexagon tool profile. A mathematical model was developed to predict the corrosion resistances of friction stir welded AA2219 aluminum alloy joints with 95% of confidence level. The model was developed by incorporating the welding parameters and tool profiles using statistical tools, such as design of experiments and regression analysis [6].An Al–Zn–Mg–Cu, Al 7075, alloy was subjected to friction stir processing (FSP) using several processing conditions, two different backing anvils and three initial precipitation states in order to reach the maximum feasible processing severity to produce ultrafine grain sizes. Microstructures formed by fine, equaled and highly mis oriented grains were obtained [7].

The micro hardness of the Al/B4C surface nano composites is higher in comparison with B4C micro particles. The presence of nano size B4C particles contributes to produce ultrafine grain size. [8].The FSP of cast Al-17% Si has been successfully performed with designed tool dimensions such as shank diameter 25 mm, shoulder diameter 18mm, pin diameter 8mm, pin length 3.5. The significant refinement of eutectic and coarse primary Si particles and improved distribution of Si particles in the Al matrix takes place as a result of FSP in cast Al-17% Si alloy. [9].

The values of the concentration of the reinforcing phase are not the same in all of the tested areas and are subject to large fluctuations from about 8% in the nugget zone to about 18% on the retreating side. The value of the anisotropy coefficient was not directly dependent on the concentration of the reinforcing phase. The lowest values of the coefficient j were recorded for the nugget and the highest for TMAZ on the retreating side [10].Submerge friction stir process is capable of producing fine AA5083/Al2O3 nano-composite. In lower number of passes, some agglomerations were seen in the microstructure of the underwater friction stir processed sample; increasing the number of passes was successful in re ducing the sea agglomerations to a more satisfactory level. In air FSP,the difference between yield strength of the powder-less sample and the one with reinforcement phase is more than that for the corresponding samples processed under water [11].

During multi-pass FSP, accumulated plastic strain continuously decreased the size and aspect ratio of Si particles, while repeated thermal cycles introduced the nanoscale and ultrafine Si particles within the grain interior. Multiple strengthening mechanisms including load transferring, grain refinement, Orowan strengthening and quench strengthening were considered in the FSPedcomposites [12].After SFSP, coarse grain sand second phases in a s-castMg–Y– Nd alloy are significantly refined to _1.3 μm and _280 nm, respectively Particles in Mg–Y–Nd alloy are not the dominated factor for the stress concentration during super plastic deformation; cavities are easily formed at the grain boundaries instead of the interface between particles and matrix. GBS a accommodated by lattice diffusion is the dominated de- formation mechanism during super plastic deformation [13].A successful welding is carried out between AISI 304 SS and pure Cu without any filler metal by CO2 laser having acceptable weld Strength of above 190 MPa. Hence, there is still scope for obtaining a smoother transition in microhardness values by controlling heat transfer rate and mode of welding [14].

A significantly high tensile strength of 187.8 N/mm2, which is 91 % of that of the base material, was achieved at high weld pitch of 0.05 mm/rev with tool shoulder diameter of 20 mm due to sufficient heat generation, proper grain refinement and ductility. Grain size decreased with increase in weld pitch. Thus average grain diameter of 9.2 μm was observed at weld pitch of 0.050 mm/rev. with tool shoulder diameter of 20 mm [15].Friction stir surfacing of as cast A356 Aluminium alloy is able to refine the microstructure and form hard surface composite by reinforcing boron carbide particles in the aluminium matrix. Friction stir surfacing is an effective strategy to enhance the wear resistance of as cast A356 aluminum-silicon alloy to be used for high performance engineering Applications like torpedoes in defense.[16].The three welded joints, the joint fabricated by FSW process exhibited higher strength values, and the enhancement in strength value is approximately 13% due to grain refinement in SZ, unique weld metal composition and strain-induced deformation during FSW. The three joints, the joint fabricated using GMAW exhibited 28% and 10% higher impact toughness, respectively, compared to the joints fabricated by FSWand SMAW processes. The presence of martensite-austenite (M-A) constituents and the ferrite laths in biotitic matrix in the weld zone microstructure are the key reasons for enhancement of toughness properties [17].

While the micro- structure of the aluminum alloy composed of a coarse-grained structure (_50 mm) with elongated complex(Fe,Mn,Cr)3SiAl12 precipitate sand round Mg 2 Si particles , FSP refined the grain structure toabout10 mm through a dynamic recrystalization process androd-like precipitates of Al–Fe–Mn–Si besideoftheCr2 and Mg2Si particles with respectively cuboidal and spherical shapes were formed [18].Compared with NFSP, SFSP has remarkable grain refinement effect. The average grain size of the NFSP and SFSP specimen is 8.4 • } 1.3 and 2.8 • } 0.8 _m, respectively. Furthermore, the microstructures in the TMAZ and HAZ for the SFSP are much finer than those for the NFSP. After FSP, the coarse network β-$Mg_{17}Al_{12}$ phases in the as-cast condition are changed into particles pinned on the grain boundaries. [19].The unprocessed and processed welds had lower hardness as well as lower yield and tensile strengths than the base material. The grain refinement of the microstructure and the removal of MIG weld defects, achieved by the friction stir processing; have the major contribution to the improvement of fatigue resistance [20].The slow welding speed results in better fatigue performance. This is because the slow speed produces a highly refined, homogeneous and defect free microstructure [21].The trend of age hardening response in FSPed alloy is exactly similar than that of cast alloy As compared to T6 treated cast alloy, the FSPed alloy after peak ageing showed a significant increase in YS, UTS and ductility. The enhancement of mechanical properties may be due to combined effect of precipitation hardening, or wan strengthening and grain boundary strengthen-ing [22].

The tool pin profile and tool rotational speed are having influence on tensile properties of the FSW joints. Out of two pin profile used to fabricate the joints, straight cylindrical pin profile exhibited superior tensile properties compared to other joints [23]. The shoulder diameter of FSW and heat input during the welding process determines the width of the hardness. Higher performance in production rate and quality, as well as decreasing production costs, can be obtained by FSW welding. The required pre-operations before the welding process are very limited in FSW. This feature of the FSW process saves consumable material time cost and improves the quality of welds [24].The transverse shrinkage generated in GTAW weld joint is comparatively lower than that in GMAW weld joint. From the EDS analysis, it is concluded that the use of GTAW process reduces the severity of weld thermal cycle in weld deposit and HAZ region. X-ray Diffraction patterns revealed that Al is the major phases, and small amount of Al_2Cu was observed [25].

Post weld heat treatment of AA7075 alloy friction stir weld to Retrogression and reaging (RRA) treatment had shown a good combination of high tensile strength and corrosion resistance over as-welded and PWHT-T6 samples. The finer grains and continuous precipitates along the grain boundaries in T6 samples lead to high pitting corrosion [26].The use of low hydrogen ferritic steel consumables is found to be beneficial to enhance the fatigue crack growth resistance of armour grade Q&T steel joints than the joints fabricated by conventional ASS consumables [27].Friction stir processing promotes fatigue resistance improvement, mainly due to microstructure grain refinement and the removal of previous welding defects, such as porosity and lack of wetting. The stress concentration reduction, due to toe radius increase also contributes to fatigue life enhancement [28].

Friction stir processing improves fatigue life of reinforced and non- reinforced MIG welds. This improvement was caused by geometric modification, grain refinement and the removal of previous defects, such as porosity and lack of wetting [29].Tools with convex shoulder geometry allow the placement of the nugget on the MIG weld toe but cause weld defects such as cavities or reduction in plate thickness. Friction stir processing causes significant grain refinement in the nugget in both alloys studied and removes defects [30].

The Tailor welded blank of AA2024 and AA7075, having a thickness ratio of 1.3 have been successfully buttwelded using FS welding technique. The transformation of the plasticized material from the advancing side to the retreating side is uniform in all the elements .The weld strength is lower as compared to the base metals, which is due to the thickness ratio of the dissimilar welds being greater than unity [31].For a given FSW tool shoulder diameter and parameters, the taper angle of the taper cylindrical (TC) tool pin and volume of tool pin penetration in to steel have significant influence onthe thickness and composition of the inter metallic compound (IMC) layer formed and hence the joint performance. The FSW tool with TC pin profile having10° taper angle has produced the best joint with a joint tensile strength of 188MPa at a tool axis offset of 2 mm towards Al alloy [32].Ferrite content in the weld metal of the AISI 304L joints when welded using heat input in the range of 8.7 to 14.7 kJ/cm length of the weld, does not change significantly, but its morphology changes from lathy to vermicular as heat input is increased. This variable degree of HAZ grain coarsening exerts a significant influence on the degree of carbide precipitation that occurs inter granularly, when subjected to post-weld thermal aging treatments [33].

The highest joint strength of about 91% of the UTS of the base Al alloy is obtained at a tool traverse speed of 45 mm/ min and both at higher and lower tool traverse speeds, the joint strengths are low. SEM and EDS quantitative analyses suggest that the inter metallic compound (IMC) layer formed at the joint interface are $FeAl_2$ and $FeAl_3$ and the tensile strength of the joint greatly depends on the thickness of IMC layer formed at the joint interface [34].The fracture toughness of the welded joint for a transition of crack from the copper side to the steel side is greater than the case in reverse. For the transition of the crack from the weaker copper to the stronger steel, the interface is positive and increased as long as the crack tip positions are held before and near the interface between copper and nickel-weld. This is due to the shielding effect caused by the elastic–plastic mismatch coupled with the compressive residual stresses [35].In the FSW welding processes, the decisive influence on the quality of the joint is exerted by the process parameters such as the rotational speed, and the rate of feed, the angle of inclination, and the profile and dimension of the stirring tool. A relatively wide range of process parameters was found to produce qualitatively satisfactory joints within the sets of the investigated material combinations. The main reason for the presence of discontinuities in the region of the root of weld is the insufficient depth of penetration of the mandrel into the welded material [36].

The allowable tolerance for the deterioration of the transverse yield strength would vary depending on the application of the welded joint and the operating environment therein. Fatigue testing was beyond the scope of this study but it is likely the determination of the tolerances levels to tool centre line deviation would be influenced by fatigue [37].The strength values decreased from weld metal to base metal. The A-GTAW joint weld metal exhibited higher yield strength followed by SAW, FCAW and SMAW respectively. The HAZ of SMAW joint showed higher YS followed by A-GTAW, FCAW and SAW respectively. The volume fraction of polygonal ferrite was observed to be inversely proportional to the strength of weld metal in the arc welded joints [38].

Sound FSW weld joints were developed with and without in-process cooling. Following conclusion can be made based on this investigation. The in-process cooling during FSW of AA7039 extracts the excess process heat which in turn minimizes the extent of static grain growth inWNZ and coarsening in HAZ. Therefore, size of a aluminum grains in WNZ, TMAZ and HAZ was significantly lower than normal joints [39].Post weld heat treatments adversely affected yield strength (3.3–66.5%) more than the tensile strength (5.1–38.7%) of friction stir weld joints.

The post weld heat treatment changed the fracture location from HAZ in as welded condition to TMAZ–HAZ interface for naturally and artificially aged joints, or WNZ for step aged and solution treated joints with and without artificial aging. Solution treated joint with and without artificial aging showed ductile–brittle mode of fracture [40].In the stirred zone, fine equi-axed grains of size ranging are transformed from the parent metal grain structure; The tensile strength of welded joints can be increased using the FSW process compared MIG; Hardness change in the welded material is affected by the amount of the heat input during the welding process; The heat-affected zone of FSW process is narrower than that of the MIG process. Higher heat intensity in the MIG process negatively affects of the mechanical properties of the welded material [41].

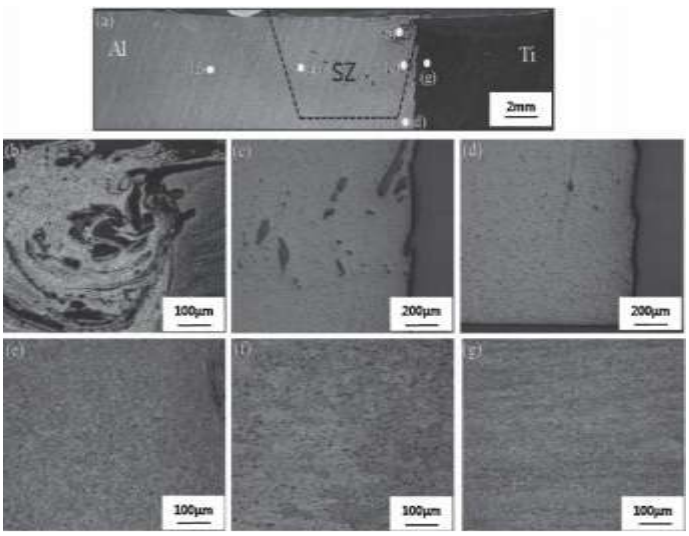

Figure 2 (a) Macro image of weld zone, (b) probe root area of interface, (c) middle area of interface, (d) probe tip area of interface, (e) SZ of AA6061-T6, (f) BM of AA6061-T6, (g) BM of Ti-6Al-4V [36]

V- MATERIALS AND ITS THICKNESSES

TABLE III- THICKNESS OF VARIOUS MATERIALS USED IN DIFFERENT PROCESSES [1-40]

S.No	Parent Materials	Thickness
1	HSLA Steel	5 mm.
2	Al-5083	3.5 mm
3	Al-7 B04	2 mm
4	Mg- 7.88Gd-4.28Y-1.1Nd-0.45Zr	6 mm.
5	AA7075	8 mm.
6	AA2219	7 mm.
7	Al 7075	3 mm.
8	Al5083	8 mm
9	Al17%SI	6 mm
10	Ignot	4 mm.
11	Copper +Al+Polymer	6 mm.
12	A356	6 mm.
13	Cast Mg–4.27Y–2.94Nd–0.51Zr	6 mm.
14	AISI 304	3 mm.
15	AZIB-Omg	5 mm.
16	A356	50 mm.
17	HSLA Steel	5 mm.
18	AA5052	5 mm.
19	AZ91	6 mm.
20	6082-T651	6 mm.
21	DH36 Steel	6 mm.
22	Cast Ingot	8 mm.
23	AA6061	6 mm.
24	AA6061	9.5 mm.
25	AA2219	25 mm.
26	AA7075	8 mm
27	AISI 4340	14 mm.
28	5083-H111	6 mm.
29	AA6082-T6	6 mm.
30	5083-H111 & 6082-T651	6 mm.
31	AA2024 T3	5 mm.
32	AA 5052	3 mm.
33	AISI 304L	6 mm.
34	AA5052	3 mm.
35	En31	10 mm.
36	Al1000,Al5000,Copper M1E	4 mm.
37	DH36	6 mm.
38	HSLA Steel	10 mm.
39	AA7039	5 mm.
40	AA7039 T6	5 mm.

VI- CONCLUSION

Alloying elements are selected based on their effect and Suitability. The present review has demonstrated the extensive research effort that continues to progress the understanding of FSW of aluminum alloys and its influence on their microstructure and properties. It identifies a number of areas that are worthwhile for further study. From an engineering perspective, there is a need to investigate the occurrence and significance of flaws in friction stir welds. In particular, the influence of tool design on flaw occurrence and the development of nondestructive testing techniques to identify flaws in both lap and butt welds would be beneficial. Metal flow modeling may have a role to play here; though capturing this aspect of the thermo mechanical behavior remains a significant challenge.There are vast areas as applications of aluminum alloys in India with worldwide. The different processes of engineering and welding technology with friction stir processing are valuable, effective and accurate.

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