Friction Stir Welding (FSW) of Aluminum Alloys: A Review

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Abstract:- **The main goal of this research work is to consider and provide a complete analysis of friction stir welding on aluminum alloys undertaken by the majority of researchers. The impact of process factors on weld reactions, material flow, and microstructure is the focus of the research. FSW factors such as tool rotational speed, welding speed, shoulder diameter, tool pin diameter, and tool pin profile have a substantial impact on the micro hardness, tensile strength, yield strength, and strain rate of FSWed aluminum alloys, according to the study.**

Keyword: Friction stir welding, strain rate, ultimate tensile strength, micro-hardness.

I. INTRODUCTION

Friction-stir welding (FSW) is a solid-state method, which implies that the base metals are bonded without melting during the process, preserving the parent material's original features as much as possible after welding [1-2]. FSW is done with the assistance of a specially designed tool that consists of a shoulder of cylindrical shape and a pin of different profiles that spins and plunges into the parting line of the two-base plate. When the tool pin and the workpiece make contact, friction is created, which provides heat for welding, softening the workpiece without melting it and allowing the tool to move along the weld line under force. Intermixing of work-piece material occurs as a result of tool rotation, and work-piece plates are connected together[3].The demand for lightweight materials, particularly aluminium and its alloys in structural components, is increasing in practically all industries, including cars, aircraft, marine, and defence [4]. The permanent bonding of different aluminium alloys would improve structural design flexibility and increase its uses [5]. As a result, a number of fusion and solid-state welding methods have been used to examine the welding of incompatible aluminium alloys [6]. Due to the increased potential for solidification cracking, greater residual stress, intermetallics, and vaporisation of alloying elements caused by high heat input, the use of fusion welding methods in welding dissimilar aluminium alloys is limited[5].Because of its high weld quality, cheap cost, and low energy consumption, friction-stir welding (FSW) is often used to weld lighter materials including aluminium and magnesium alloys.

II. LITERATURE REVIEW

The influence of different friction stir welding/ processing process parameters on different metals has been reviewed after a thorough study of numerous research data. This review is offered in tabular form and consists of published works on dissimilar metals. The Table A below summarizes the parameters that were considered by previous writers.

Table 1 Literature review of aluminum alloys: -

Sr. No.	Year	Author	Work-Piece	Tool & type of joint	Input parameters	Output parameters	Finding
1	2003	Prado et al.	AA6061+20% Al_2O_3	butt joint	traverse speed and tool pin profile	Tool wear and wear rate	1) When weld or traverse speeds are increased, tool wear and the wear rate are found to decrease. [7, 8]
2	2005	Fratini,L. and, Buffa,G.	AA 6082-T6	butt joint		strain, strain rate and temperature	1) An inverse-identification technique based on a linear regression methodology was employed to provide the required material characterization. [9].
3	2006	Kulekci, et al.	AA5754	Lap joint	tool pin dia., and tool rotation speed	fatigue strength and microstructure	1) The fatigue strength of joints is reduced when tool rotation is increased for a fixed tool pin diameter. The fatigue strength of joints is reduced when tool pin diameter is increased for a fixed tool rotation [10].
4	2012	Liu et al..	AA 2219-T6		non-rotational shoulder dia. And welding speed	micro structure, hardness and tensile strength	1) Microstructures and Vickers hardness distributions revealed that this novel welding method improves asymmetry and in homogeneity, particularly non the weld nugget zone. Up to 69 percent of the basic material's tensile strength was achieved [11].
5	2007	Scialpi et al.	AA6082		shoulder geometries	transverse tensile strength, microstructure	1) According to the findings, the best joint for thin sheets was welded by a shoulder having cavity and fillet [12-15].
6	2006	Cavalier et al.	AA2024-7075			tensile, fatigue strength,	T1) he two sheets were successfully welded one after the other, and the welded sheets were tested under strain at room temperature to

						hardness and microstructure	determine their mechanical reaction in comparison to the parent materials [16].
7	2012	Deplus et al.	AA 2024-T3, AA5754-H111 and AA 6082-T6	thin copper, brass and tungsten of dia. 0.05 to 0.3 mm	Machining Gap, Thermal Energy, Dilectric Pressure, Current	MRR and Surface Finish	1) The static deflection of the wire and vibrational behaviour have been reported to produce inaccuracies [17]. intelligent systems or Expert knowledge have been stated to lessen the inaccuracy due to the static deflection of the wire and vibrational behaviour.
8	2007	Zhang et al.	AA 6061 -T6		rotation speed, axial forceand welding speed	material flow	1) There appears to be a quasi-linear relationship between the variation of the equivalent plastic strain and the variation of the applied loads on the shoulder. On increasing in the pin's translational and angular velocity, the material flow may be accelerated [18].
9	2008	Raghu Babu, et al.	AA6082-T6	butt joint & HSS tool	rotation speed, axial force and welding speed	tensile strength, hardness and microstructure	1) The joint's tensile strength is less than that of the parent metal. And it's proportional to the speed of travel / welding [19-22].
10	2005	Heurtier, et al.	AA2024-T351	butt joint		micro-hardness, estimations of the temperatures strains and strain rates.	1) The semi-analytical model may be employed to calculate stresses, micro-hardness, strain rates, and temperature estimates in different weld zones [23].
11	2011	Aval et al.	AA5086		Tool rotational speed, welding speed	temperature distribution, yield & tensile effect.	1) The final microstructures and mechanical characteristics of welded alloys can be greatly influenced by work-hardened and annealed conditions [24].
12	2016	Mehtaa et al.	AA6061-T651	tool steel of M2 grade	cylindrical, triangular, square and hexagonal Pin profile	defects	1) Welds constructed using triangular pin shapes produced the most uneven and massive copper particles. Furthermore, holes, tunnels, fractures, and fragmental flaws were generated by polygonal pin profiles, regardless of their static and dynamic constant areas. 2) Additionally, as the number of polygonal edges increased, faults reduced. The cylindrical tool pin profile has been reported to have a defect-free macro joint [25].
13	2016	Zhang et al..	AA2219-T6		welding speeds,water-coolingand air-cooling conditions & artificial ageing	tensile strength andhardness	1) The ideal method to increasing the mechanical characteristics of FSW2219Al-T6 joints has been demonstrated to be a combination of post-welding artificial ageing and high welding speed, with a highest joint efficiency of 91 percent attained [26].
14	2016	Guillo. et al.	AA5754-H22	FSWtool ofH13toolsteel	Rotationalspeed, travelingspeed, tiltangle		1) A robot with an inbuilt real-time algorithm for compensating lateral tool deviation may recreate the same FSW edquality as a gantry-type CNC system, according to this article [27].
15	2016	Nam et al.	6061 aluminum alloy	SKD11toolconsist of a narrower probe and a columnar shape.	welding speed	Potentiodynamic and EIS studies	1) According to the findings, a high-quality thin coating on the surface with improved properties resulted in a high-corrosion-resistant alloy. This might be owing to the FSW's homogenous impurity distribution in the alloy, on which a homogeneous passive coating was generated to improve corrosion resistance [28].
16	2009	Babu. et al.	AA2219 aluminium alloy	High carbon steel tool	rotational speed, tool pin profiles, welding speed and axial (downward) force.	Tensile strength	1) With a 95% confidence level, a mathematical model was built to estimate the tensile strength of FSWed AA2219 joints [29].
17	2015	Dongxiao. et al.	7075-T651 aluminumallo y	Butt joint	Tool rotational speed (rpm), Welding speed (mm/min)	Microstructural characteristics, welding process,Hardness and tensile strength	1) Both the existence of precipitates and the displacement of component particles may be blamed for the reduced crack initiation energy in the heat affected zone (HAZ). The presence of precipitates in the HAZ was the primary cause of the SSFSW joint's lower tensile strength [30].
18	2015	Bahemmat. et al.	AA7075-O and AA2024-T4	Threaded with four flute and threaded taper tool	Tool rotation speed,welding speed	Ultimate Tensile strength, Elongation,Hardness,yield strength,	1) The purpose of the microstructure analysis is to see how the pin profile and rotating speed affect grain size. Furthermore, one of the most important aims in the current study is to get high-quality welds with the least amount of money [31].
19	2008	Chionopoul et al.	5083-H111 aluminum alloy	butt joint, thermal treated steel a) Compact conical	Rotational speed, (N) and Welding speed, (S)	Microhardness, Microstructure	1)It was shown that under particular welding conditions, only the conical pin shape resulted in defect-free welds. In terms of the in the case

				pin tool, b) Screw type pin head.			of screw type pins, these first studies resulted in defective welds, most likely owing to the screw's unique design or the welding settings used, which were not ideal. 2)Micro-hardness measurements were made on specimen cross sections and associated with the establishment of FSP zones. The ideal parameters matched to welding zones that were free of flaws and other interruptions. In any event, the welding instrument suffered no damage as a result of the procedure [32].
20	1999	Mishra et al.	AA 7075-T6	Single pass FSPed zone of 0.3 m length	traverse speed of 15 cm/min.	Strain rate, Tensile tests	1) The current findings show that friction stir processing may be used to create a microstructure in a commercial aluminum alloy that is susceptible to high strain rate superplasticity [33].
21	2011	García-Bernal et al.	AA 5083 produced by continuous strip casting with different Mn	FSP tool of MP159 alloy.Mn and Cr dispersoid formers	rotation rate -400 rpm and 0.42 mm/s traverse speed	Strain rate	1) Increased Mn concentration increases ultimate and yield strength. The two alloys with the lowest Mn concentration had the highest elongation values (almost 800 percent) [34].
22		DANAF et al.	AA5083, 3 mm thickness	H13 tool steel tool was used	rotational speeds - 430 and 850 rpm and traverse speed -90 mm/min	Tensile tests andstrain rates	I) The attributes of the DRX refined microstructure achieved in the 439–90 FSP condition were far better to those of the 850–90 FSP condition. 2) Demonstrated that reducing grain size increased ductility and reduced forming loads considerably. 3) The presence of a rather high strain rate sensitivity shows that superplastic deformation is operating under these experimental conditions [35].
23	2012	Kandasamy.J, and Rajesham. S.,	6mm thick AA7075 and AA6061	High speed steel toolwith 10% cobalt 1) Shoulder dia. (16mm) 2) threaded Pin dia (6mm) 3) length (5.8mm)	1) Tool rotational speed (1400rpm) 2) traverse speed (16mm/min) 3) Axial force (6kN)	Yield strength Tensile strengt %Elongation Hardness Shear strength Distribution Vickers micro hardness across the weld line	1)The goal of the experiment is to reduce the temperature difference between bottom surfaces and the top of the plates as much as possible.. 2) The creation of Al_2Cu and Al4Cu9 IMCs increases bond strength, according to analysis of the generated intermetallic compound (IMC)[36].
24	2010	Suresha. et al.	AA7075-T6 of 5mm thickness	square butt joints. Nonconsumable tools made of hot die steel 1) Square tool 2) conical tool	1) Tool rotational speed (900,1120,1400RPM) 2) Welding speed (40,50 and 63mm/min) 3) Plunge depth (4.93,4.96 and 4.99 mm)	Tensile strength, joint efficiency	1) The welded joints of the conical tool are more efficient than those of the square tool. 2) ANOVA was used to determine the percentage contribution of these FSW process parameters, and it was observed that tool rotating speed, when compared to weld traverse speed and plunge depth, has a substantial contribution in both conical and square tools [37].
25	2015	Amini.S., and Amiri.M.,	friction stir welding on aluminum 5083with dimensions of 120 mm×60 mm×4 mm.	Four tools of AISIH13 with 1)shoulder dia.-18 mm, 2) pin dia.- 5.5 mm, 3) angle - 9° 4) pin height - 3.85 mm Different shapes of tool pin were used	1) Rotational speed - (560,900,1120,1400rpm) 2) Translational speed- (63,100 mm/min) 3) Tool tilt angle - (1.5°)	vertical force and welding force	1) The impact of an offset pin on vertical force and welding force reduction (between 50 and 70 percent) is larger than the impact of a concentric pin with the tool shoulder axis on these forces. 2) Tools with a half pin and an arching pin exert greater force than tools with an offset pin, but less force than tools with a concentric pin [38].
26	2006	Scialpi. et al.	AA 6082 T6	The tool made of 56NiCrMoV7-KU. The tool with pin 1.7 mm dia. and 1.2 mm height.	1) Tool rotation speed - 1810 rpm 2) traverse speed - 460 mm/min) tilt angle 2 & 0.1 mm plunge Shoulders with three different features1. scroll (TFS)2. cavity (TFC)3. fillet (TF)	Mechanicaland Microstructural properties	1) A study of three shoulder geometries was conducted in this study. The tool analysis was performed on 1.5 mm thick AA 6082 T6 sheets. The tool was rotated at 1810 rpm with a federate of 460 mm/min during the welding operation. 2) The analysis revealed that the optimum junction for thin sheets was welded by a shoulder with fillet and cavity [39].

27		Mastanaiah. et al	AA2219-T6 Al-Cu alloy and AA5083.	Squar- butt joint	1) Rotation speed (400,800,1200,1600,2000 rpm) 2) Tool traverse speed (30 210 390 570 750 mm/min) 3) Tool offset from joint line (-2, -1, 0, 1 ,2mm)	1) % El. 2) Joint efficiency on UTS 3) Failure location	1) Using diverse methods such as macrostructural analysis and electron probe micro analysis, the impacts of process parameters and tool-offset on the degree of material intermixing and to reduce percent area of volumetric defects were investigated in detail. 2) It is well established that the tool offset and welding settings have the greatest impact on the nugget zone mixing pattern and subsequent joint strength [40].
28	2007	Johannes et al	AA5083.	High strength cobalt alloy (MP159) tool. shoulder - 25 mm Tool pin length - 6.4 mm.	1) Rotational rate - 600 rpm 2) traverse speed - 25.4 mm/min	Microstructure examination Tensile testing	1) By modifying the size and distribution of component particles before to cold rolling, FSP assists in the reduction of post-recrystallization grain size. It was discovered that adding the FSP stage refined the recrystallized grain size, decreased flow stresses and enhanced elongations [41].
29	2012	Magdy. M. E. and Ehab A. E.,	AA- 6082-T651 plates , 6mm thick	Tool material Mo–W tool steel	1) Tool rotational speed - 850 rpm 2) Transverse speed- 90,140,224 mm /min	1) Microstructural characteristics 2) Second phase particles 3) Mechanical characteristics	1) The results of the hardness and tensile tests showed that increasing the number of passes resulted in softening and a decrease in UTS, but increasing traverse speed enhanced strength and hardness. 2). Multiple passes resulted in increased grain size, precipitate dissolution, and fragmentation of second phase particles due to the accumulated heat.[42].
30	2014	Deepati,et al.	AA5083 and AA1100(T- 6-mm)	Tool made of H-13 tool steel 2) Straight &tapered cylindrical pin tool	1) Tool-rotation speed - 1000,1400 RPM 2) welding speed - 56,80 mm/min	1) Hardness 2) Tensile Test	1) Tool geometries have a substantial impact on dissimilar material FSW weld quality. In the case of taper cylindrical tools with the same process parameter, both hardness and tensile strength were greater. 2) In dissimilar friction stir weldments, lower traverse rates combined with greater rotating speeds produce the highest tensile characteristics [43].
31	2012	Klobcar.D., et al.	AA 5083 (T- 4-mm)	Tool made of EN 42CrMo4 steel. FSW tool geometry was used with a threaded pin	1) tool-rotation speed -200 r/min to 1250 r/min 2) welding speed - 71 mm/min to 450 mm/min	1) Microstructure 2) Hardness 3) Tensile properties	1) The microstructure was prepared for examination under a polarized light source using a light microscope. At an FPR of 0.35 mm/r, a set of ideal welding conditions was identified, allowing excellent welds to be formed with a small improvement in hardness and a 15% reduction in tensile strength [44].
32	2012	Jerome.S. et al	AA5083 /TiC particles	Tool made of EN 31 steelShoulder Dia.- 18 mm, Pin Dia. and length 6 mm and 2 mm, respectively	1) Tool Rotation Speed- 710,900,1120,1400 Rpm2) Traverse Speed - 16mm/min	1) Microstructural Observations.2) Microhardness Details	1) The microhardness profiles of the treated samples were assessed along the top surface and across the cross section. When compared to the base metal (88Hv), the average hardness along the top surface increased by 27.27 percent [45].
33	2014	Krishna et al	AA6351 and AA5083	High speed steel (HSS)	Feed rate - 20 mm/min 1) Rotational speed - 1000, 1100,1200,1300,1400,1500 RPM	Yield strength, Tensile strength and % elongation	1) Describes the effect of an FSW process including butt joining of identical AA6351 and AA6351 combinations and dissimilar AA6351 and AA5083 combinations on tensile, hardness, and impact behaviour. 2) When compared to different alloy combinations, the tensile, hardness, and impact characteristics of Aluminum alloys of comparable alloy combinations show better results [46-49].

III. CONCLUSION

The results of this investigation showed the process factors employed during the welding of several aluminum alloys, as well as the impact of those parameters on the weld reactions. Process factors such as rotating speed, weld speed, tool pin shape, tool tilt angle, tool offset, and others were shown to have a substantial impact on the weld quality of friction stir welded aluminum alloys. The following findings may be taken from the preceding research.

1) In compared to different aluminum alloy combinations, comparable aluminum alloy combinations have higher tensile strength, hardness, and impact strength.

2) The final microstructures and mechanical characteristics of welded AA5083 alloy can be greatly influenced by work-hardened and annealed conditions.

3) The creation of Al_2Cu and Al4Cu9 IMCs by the interaction of AA6061 and AA7075 with copper in coating form increases bond strength, according to analysis of the generated intermetallic compound (IMC).

4) ANOVA was used to evaluate the % contribution of these FSW process factors, and it was discovered that in the case of both square and conical tools during welding AA7075, tool rotating speed has a significant contribution compared to weld plunge depth and traverse speed.

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