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REVIEW ARTICLE

A review of dissimilar aluminum alloys welding via Friction stir welding

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Abstract

In the present study, a review was carried out on the friction stir welding of dissimilar aluminum alloys. Friction stir welded joints hold promise due to its low welding heat input and capacity to reduce the degree of intermetallic compound (IMC) production in dissimilar metals. The goal of the current paper was to evaluate the effect of various processing parameters like tool rotating speed, welding/transverse speed, tool pin profile, tool tilt angle and shoulder diameter etc. on the weld quality of dissimilar aluminum alloys. From the present study it can be concluded the processing parameters significantly affects the mechanical characteristics of the weld quality of dissimilar aluminium alloys. This study will serve as a foundation for researchers to take FSW into account for a variety of diverse aluminum alloys.

1. Introduction

Friction stir welding (FSW) is a solid-state method, which means that the joining materials do not melt during welding. It is utilized when the original qualities of metal must be preserved to the greatest extent feasible. This is due to the mechanical intermixing of the two metal pieces, which allows them to be fused by softening them with mechanical pressure [1-4]. In FSW, a revolving tool of cylindrical shape is used, which moves along the parting line of two metal plates. Frictional heat is generated from friction between the work piece and the rotating tool, allowing the material to soften without melting under mechanical pressure. The weld is generated when the material is deformed at temperatures less than the melting point. The traverse and rotation speed of the FSW tool generates a specific imbalance between the neighbouring surfaces throughout the welding process. The advancing side (AS) is where the tool rotation aligns welding tool translation, whereas the retreating side is where the two motions, rotation and translation, oppose each other [5-8]. Various investigations have been carried out on the welding of different aluminum alloys using different combinations of processing parameters of FSW like tool rotating speed (TRS), welding speed (WS), tool shoulder diameter, tool tilt angle and tool pin profile etc., the effect of processing parameters on the mechanical characteristics of the weld joint was investigated. Sadeesh et al. investigated the impact of TRS, WS and five-pin profiles with a 2° constant tool pin angle on the tensile strength, hardness and microstructure of weld joint dissimilar AA2041/AA6061 [9]. Ratnam et al. examined the effect of twin pin profiled tools with different TRS and WS to weld dissimilar AA2041/AA6061 [10]. Ying Li et al. studied the solid-state flow during FSW of AA6061 and AA2024 [3]. Babu et al. revealed the effect of the advancing side of position in the case of dissimilar AA2041/AA6061 on ultimate tensile strength (UTS) [11, 12]. Anil Kumar et al. compared the result of similar welding of AA5083 and 6082 with dissimilar weld joints of both and investigated the effect of TRS, WS and tool

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tilt angle on the joint efficiency of AA5083 with AA6082 [13]. Dragatogiannis et al. They have added Tic micro and nano-particles to enhance the weld joint's mechanical properties. The effect of TRS, WS and tool tilt angle variation on the joint strength was also investigated [14]. Reinforcement particles were mixed with ethanol for easy filling and managing reinforcement, revealing TiC reinforcement's effect on corrosion resistance [15]. Jain et al. optimized the process parameters of FSW, which were TRS and WS. Shoulder diameter and pin profile using the Taguchi method for single response optimization and grey relation with weight method for multi-response optimization [16]. Tasman et al. studied the effect of the constant ratio of TRS to WS with triangular and pentagonal tool pins on mechanical properties [17]. Various researchers have researched joining aluminum alloy 5083 with aluminum alloy 6061 because both are most widely used in marine industries [18-21]. FSW of AA5083-O with 6061-T6 carried at four different tool rotation speeds of 450,560, 710 & 900 rpm and the joint strength was compared with the joint strength of welding carried by fusion welding, i.e., TIG and MIG welding with a filler rod of AA4043 [18]. Comparison of FSW of AA5083/AA5083, AA6061/AA6061 and AA5083/AA6061 done on rotational tool speed of 630, 1600 rpm and welding speed of 16, 25 and 40 mm/min. Dissimilar welding of AA6061/AA5083 was performed by taking AA 6061 on AS. 13 experiments were performed to make similar and dissimilar joints of AA6061 and AA5083 [19]. Davaiah et al. join AA5083-H321 with AA6061; both have a thickness of 5 mm at four different WS of 40, 63, 80, and 100 mm/min with constant TRS of 1120 rpm, 2.5-degree tool tilt angle and axial force keeping AA6061 on AS and AA5083 on RS in all experiments [20].

2. Tool used

Generally, tool made of H13 steel is used for joining aluminum similar and dissimilar alloys. The difference consisted of pin and shoulder profiles with different sizes per thickness and base material properties. A high-speed tool with nickel coating having a taper square cross-section was used by as shown in Fig. 1 [13]. H13 steel tools of five-pin shapes were used to check the effect on weld quality shown in Fig. 2 [9]. The effect of four pin profiles, i.e., cylindrical threaded, square, cylindrical, and trapezoidal, made up of high carbon steel, was revealed and considered as a process parameter in FSW shown in Fig. 3 [16]. Davaiah used H13 steel with cylindrical threaded taper pin and shoulder of concave scrolled contour having a diameter of 18mm and pin length and diameter of 4.7 mm and 6mm, respectively [20].

Figure 1: Square pin profiled tool [13]

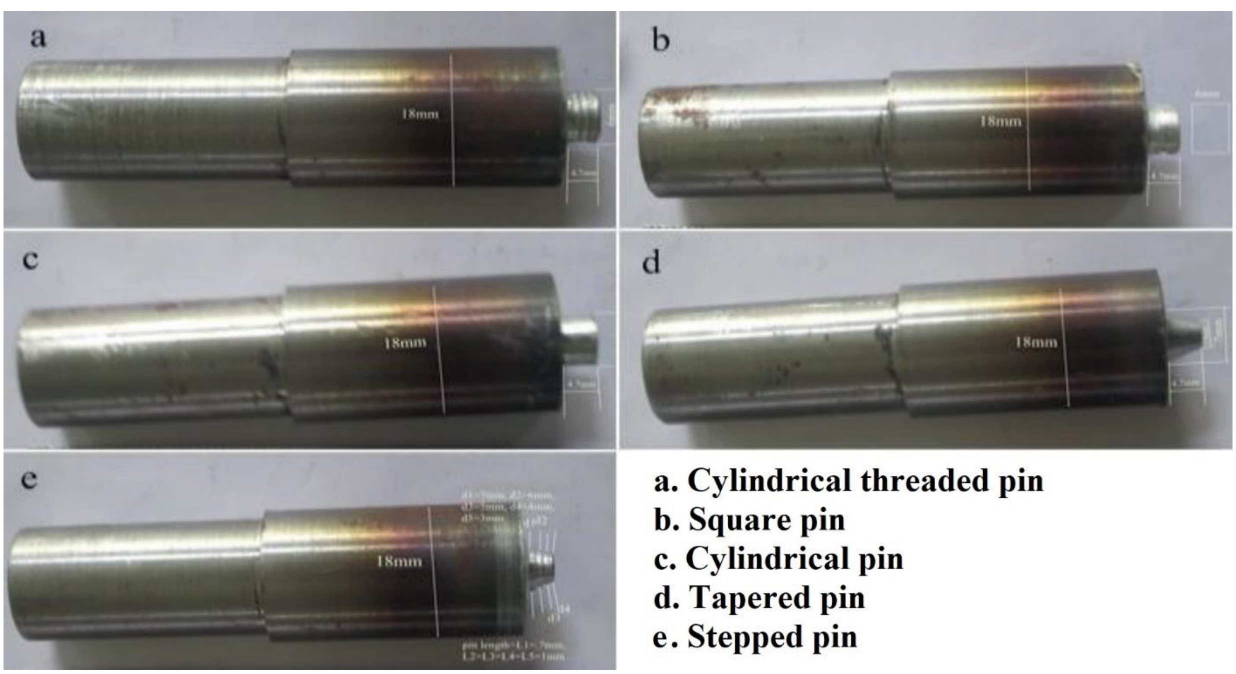

Figure 2: Pictorial view of different tool pins used [9]

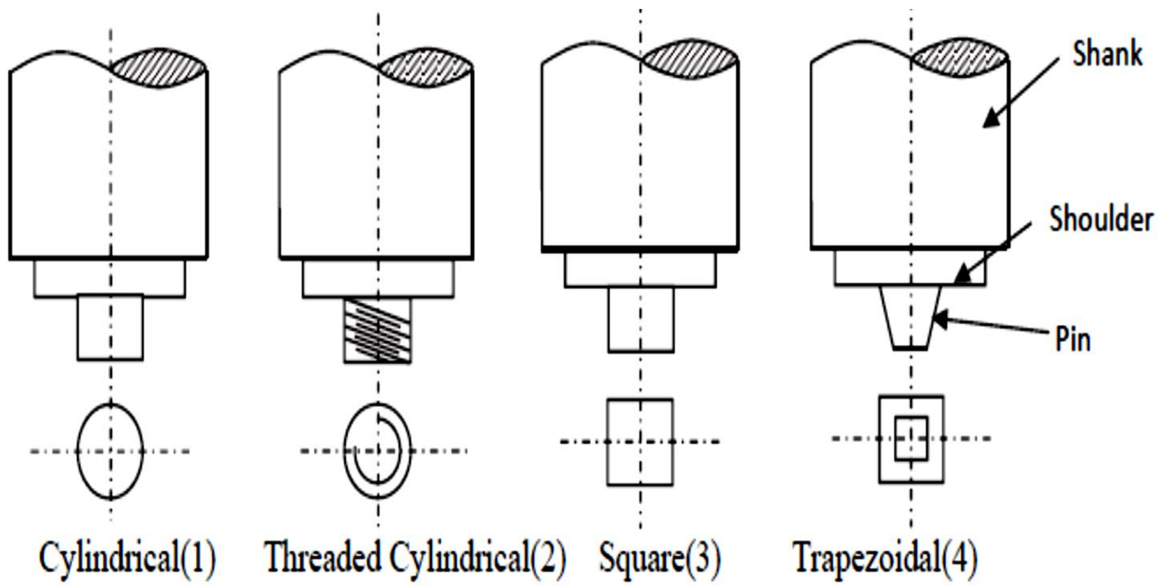

Figure 3. Different tool pin profiles used in FSW of AA6082/AA5083 [4]

Table 1: Literature review of FSW of aluminium alloys

S.No	Authors name	Output responses	Materials used	Conclusions
1	Krishna et al. (2014)	Yield strength, Tensile strength and % elongation	AA6351 and AA5083	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 behavior. When compared to different alloy combinations, the tensile, hardness, and impact characteristics of Aluminum alloys of comparable alloy combinations show better results [22-25].
2	Jerome.S. et al. (2012)	Microstructural Observations. Microhardness Details	AA5083 /TiC particles	The hardness profiles of the treated samples were assessed along the top surface and across the cross-section. Compared to the base metal (88Hv), the average hardness along the top surface increased by 27.27 % [26].
3	Klobcar.D. et al. (2012)	Microstructure, Hardness, Tensile properties	AA 5083 (T-4-mm)	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 slight improvement in hardness and a 15% reduction in tensile strength [27].
4	El-Danaf,et al. (2014)	Hardness, Tensile Test	AA5083 and AA1100(T- 6- mm)	Tool geometries substantially impact dissimilar material FSW weld quality. In the case of taper cylindrical tools with the same process parameter, both hardness and tensile strength were greater. In dissimilar friction stir weldments, lower TS combined with more incredible RTS produce the highest tensile characteristics [28].
6	Johannes et al. (2007)	Microstructure examination Tensile testing	AA5083.	By modifying the size and distribution of component particles before 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 [29].
7	Scialpi. et al. (2006)	Mechanical and Microstructural properties	AA 6082 T6	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. The analysis revealed that a shoulder welded the optimum joint for thin sheets with fillet and cavity [30].
8	Amini.S., (2015)	Vertical force and welding force	FSW on AA5083 with dimensions of 120 mm×60	The impact of an offset pin on vertical force and welding force reduction (between 50 to 70 %) is larger than the impact of a concentric pin with the tool shoulder axis on these forces. Tools

			mm×4 mm.	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 [31].
9	Suresha. et al. (2010)	Tensile strength, joint efficiency	AA7075-T6 of 5mm thickness	The welded joints of the conical tool are more efficient than the square tool's. 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 [32].
10	Kandasam y.J, (2012)	Yield strength, Tensile strength % Elongation, Hardness, Distribution	6mm thick AA7075 and AA6061	The experiment's goal is to reduce the temperature difference between the bottom surfaces and the top of the plates as much as possible. The creation of Al2Cu and Al4Cu9 IMCs increases bond strength, according to the analysis of the generated intermetallic compound (IMC) [33].
12	Mishra et al. (1999)	Strain rate, Tensile tests	AA 7075-T6	The current findings show that friction stir processing may create a microstructure in a commercial aluminum alloy that is susceptible to high strain rate superplasticity [34].
14	Bahemma t. et al. (2015)	Ultimate Tensile strength, Elongation, Hardness,	AA7075-O and AA2024- T4	The microstructure analysis aims to see how the pin profile and rotating speed affect grain size. Furthermore, one of the essential aims of the current study is to get high-quality welds with the least amount of money [35].
15	Dongxiao. et al. (2015)	Microstructural characteristics, welding process, Hardness tensile strength	7075-T651 aluminumallo y	Both the existence of precipitates and the displacement of component particles may be blamed for the reduced crack initiation energy in the HAZ. The presence of precipitates in the HAZ was the primary cause of the SSFSW joint's lower tensile strength [36].
16	Babu. et al. (2009)	Tensile strength	AA2219 aluminium alloy	With a 95% confidence level, a mathematical model was built to estimate the tensile strength of FSWed AA2219 joints [37].
17	Nam et al. (2016)	Potential dynamic and EIS studies	6061 aluminum alloy	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 [38].
18	Guillo. et al. (2016)	Inbuilt real-time algorithm	AA5754-H22	According to this article, a robot with an inbuilt real-time algorithm for compensating lateral tool deviation may recreate the same FSW equality as a gantry-type CNC system [39].
19	Zhang et al.. (2016)	tensile strength and hardness	AA2219-T6	The ideal method to increase the mechanical characteristics of FSW2219Al-T6 joints has been demonstrated to be a combination of post-welding artificial aging, and high welding speed, with the highest joint efficiency of 91 percent attained [40].
20	Mehtaa et al. (2016)	defects	AA6061-T651	Welds formed the most erratic and substantial copper particles with triangular pin geometries. In addition, polygonal pin profiles produced holes, tunnels, fractures, and fragmentary faults independent of their static and dynamic constant regions. Also, defects decreased as the number of polygonal edges grew. The macro joint on a cylindrical tool pin profile has been claimed to be devoid of flaws [41-43].
21	Aval et al. (2011)	Temperature distribution, yield & tensile effect.	AA5086	The final microstructures and mechanical characteristics of welded alloys can be significantly influenced by work-hardened and annealed conditions [44].
22	Heurtier, et al. (2005)	Microhardness, estimations of the temperatures strains and strain rates.	AA2024-T351	The semi-analytical model may be employed to calculate stresses, micro-hardness, strain rates, and temperature estimates in different weld zones [45].
23	Raghu Babu, et al. (2008)	tensile strength, hardness and microstructure	AA6082-T6	The joint's tensile strength is less than that of the parent metal. And it's proportional to the speed of travel / welding [46].
24	Zhang et al. (2007)	Material flow	AA 6061 -T6	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 [47].
25	Deplus et al. (2012)	MRR and Surface Finish	AA 2024-T3, AA5754- H111 and AA6082-T6	The static deflection of the wire and vibrational behaviour have been reported to produce inaccuracies [46]. intelligent systems or Expert knowledge have been stated to lessen the inaccuracy due to the static deflection of the wire and vibrational behaviour.
26	Cavalier et al. (2006)	Tensile, fatigue strength, hardness and microstructure	AA2024-7075	The two sheets were successfully welded one after the other, and the welded sheets were tested under strain at room temperature to determine their mechanical reaction in comparison to the parent materials [49].
27	Scialpi et al. (2007)	Tensile strength, microstructure	AA6082	According to the findings, the best joint for thin sheets was welded by a shoulder having cavity and fillet [50-52].
29	Kulekci, et al. (2006)	fatigue strength and microstructure	AA5754	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 [53].
30	Prado et al. (2003)	Tool wear and wear rate	AA6061+20% Al2O3	When weld or traverse speeds are increased, tool wear and the wear rate are found to decrease [54].
31	Fratini,L. (2005)	strain, strain rate and temperature	AA 6082-T6	An inverse-identification technique based on a linear regression methodology was employed to provide the required material characterization. [55].

3. Results and discussion

3.1 Tensile strength

The joint efficiency of dissimilar weld joints of AA2024/AA6061 was found to be 80% with cylindrical threaded tool pins and 81% with square tool pins [9]. Higher welding speed with a twin pin tool induces the maximum UTS. AA2024 on AS gives the maximum UTS compared to AA6061 on AS [10]. UTS of the weld joint of AA5083 with 6061 by FSW was higher than the joint strength by fusion welding. The maximum UTS by FSW obtained was 200 MPa which was higher than the 160 MPa and 192 MPa obtained by TIG and MIG welding, respectively [13]. On performing the tensile test, the joints failed at the Thermo-mechanical heat affected zone and nugget zone, The UTS of the weld joint of AA5083/AA5083 found 57.1% of the UTS of base material and the best result obtained of the joint of AA6061/AA6061 with joint strength of 77.7% compared with base material of AA 6061-T4. The dissimilar sound joints of AA6061-T4 and AA5083-O was obtained at 1600 rpm with joint strength of 71.2% joint efficiency. The decreased heat input on increasing welding speed showed better sound weld quality. At higher welding speeds with a higher cooling rate lacking mixing occurs because the material on the advancing side travels much less into the retreating side and causes defects that decrease UTS [14]. The joint efficiency of dissimilar welding of AA6082/AA5083 with joint efficiency of 85% compared with the joint efficiency of AA5083/AA5083 and AA6082/AA6082 joint efficiency of 56% and 62%, respectively [14]. The UTS yield strength and elongation (El) can also be increased by adding TiC reinforcement in the stir zone (SZ) of FSWed AA6082/AA5083[15]. Process parameters optimization for UTS obtained by Taguchi were 1200 rpm of TRS, 35mm/min of welding and 14mm tool shoulder diameter. The multi-response optimization results were obtained by the GRA-based weight method and were calculated based on different weightage to different responses. The optimum parameters for 0.5 weightage of UTS and elongation were at 1200 rpm TRS, 35 mm/min WS, and 14 mm shoulder diameter with a trapezoidal pin profile. On giving 0.7 weightage to UTS and 0.3 to El optimum parameters obtained were 1200 rpm TRS, 35mm/min WS, and 16mm shoulder diameter with square tool pin; if 0.3 weightage given to UTS and 0.7 to El, then optimum parameters obtained were 1200 rpm TRS, 35mm/min WS and14mm shoulder diameter with trapezoidal pin profile [16]. The triangular pin gives better results on UTS compared with the pentagonal pin profile and increases on increasing TRS and WS [17].

3.2 Microhardness

The hardness of the nugget zone is higher than TMAZ and AA6061 but lower than AA2024 [12]. The hardness of similar weld joints of AA5083/AA5083 and AA6082/AA6082 was compared with the dissimilar FSWed joint of AA 5083/AA6082, and it was found that the hardness of Weld zone (WZ) in the case of FSWed AA5083/AA 6082 was higher than FSWed AA5083/AA5083 and AA6082/AA6082 shown in [13]. Fig. 4 shows the hardness distribution profile of the TIG and TIG+FSP weldments of AA5083 and AA8011 [56]. The microstructure of the welded area may be connected to the microhardness variation. The variances in hardness levels indicate that grain structures are not homogeneous. The dominant component in determining the hardness value may be the grain structure or size, although it is not the only one. The hardness of the welded zone is impacted by temperature distribution, strain rate, and particle density [17]—increased strain hardening results from a drop in temperature. As a result, TIG+FSP welded joints underwent strain hardening due to decreased grain size and low-temperature strain rates. Due to the combination of base metal and ER4043 in the TIG weldment, the HAZ area shows the most inadequate hardness in TIG welded connections. TIG + FSP welded joints had a hardness distribution pattern comparable to yet distinct from TIG welded joints. The insufficient material flow created by the FSP tool is the cause of the inhomogeneity of microhardness un SZ [17]. The fine-grain structure was shown to have increased hardness at room temperature by the Hall-Petch correlation. TIG weldments showed a substantial variation compared to TIG + FSP welded connections. This is due to intermetallic phases precipitating in TIG joints made of coarse Mg2Si and Al13Fe4. Stronger than the Mg2Si and Al13Fe4 phases, the -Al phase possesses a large volume fraction. If the indenter were positioned near the primary -Al phase rather than the Mg2Si phase in the opposite situation, the hardness value would be reduced; a high hardness value was found.

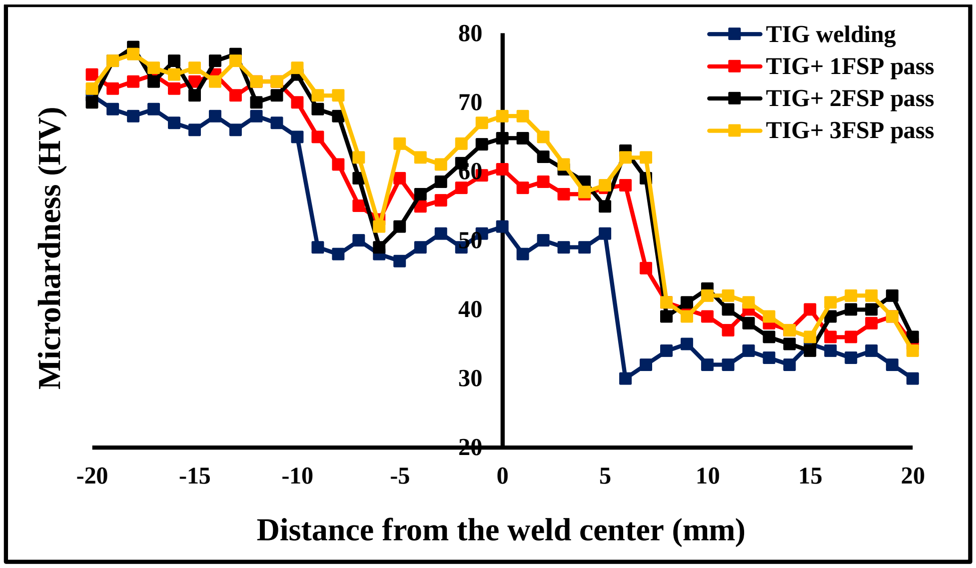

Figure 4: Hardness distribution profile of TIG and TIG+FSP welded joints of AA5083 and AA8011 [56]

3.3 Microstructure

The FSW reconstruction sectional view of the weld joint of AA2024 and AA6061 at 400 rpm is shown in Fig. 5 [11]. The microstructure of the TIG SV + FSP and TIG DV + FSP joints of AA8011 and AA6082 is shown in Fig. 6. Three elements come together to create FSPed joints. The first is a plastic material stirring, which gathers the plasticized multi-layered materials behind the FSP tool and is influenced by a complex interaction between traverse speeds, pin profiles, and RTS. The second occurs when the parent material in the SZ becomes softer because of a rise in temperature in the welded zone [57]. The third involves the FSP tool shoulder hot forging plasticized material. If any incorrect change of these parameters occurred, the flawed FSPed region would be discovered. The microstructure of AA6061 on RS exhibited elongated particles of Mg-Si and Al-Si in a matrix, and AA2024 on AS exhibited elongated particles of Al2Cu and Mg-Si in a matrix. Voids in a matrix were also noticed, as depicted in Figs. 7, 8 [12]. The hardness obtained by the FSW weld joint was lower in the heat-affected zone and higher in WZ [18]. Generally, the hardness decreases from top to bottom in the thickness of WZ, but there is an increase in the hardness from a distance of 1200 µm down from the top of the surface due to rapid cooling on the top surface as compared to the lower surface. And the harness decrease at a distance of about 1200 µm above the bottom surface. The micro-harness was lower on the advancing side because of higher heat input on the advancing side [19].

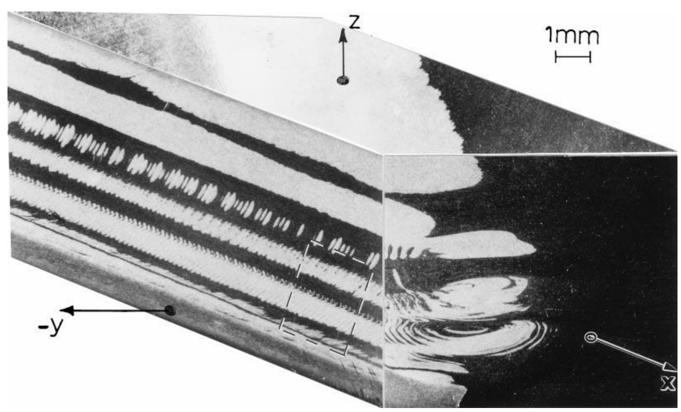

Figure. 5 Reconstruction view of weld joint of AA2024/AA6061 [11]

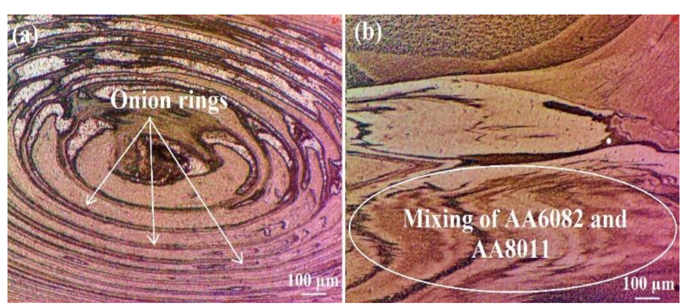

Figure 6: Microstructure of TIG+FSP welded joint, (a) TIG SV+FSP, (b) TIG DV+FSP [57]

The ductility and formability of aluminum alloys are unsatisfactory at room temperature, leading to early failure under challenging stress conditions. The hexagonal close-packed (HCP) crystal lattice's poor symmetry, high basal roughness, and restriction on the number of active slip systems all contribute to this [58-60]. Due to these factors, there is insufficient strength, severe fatigue, and little creep resistance.

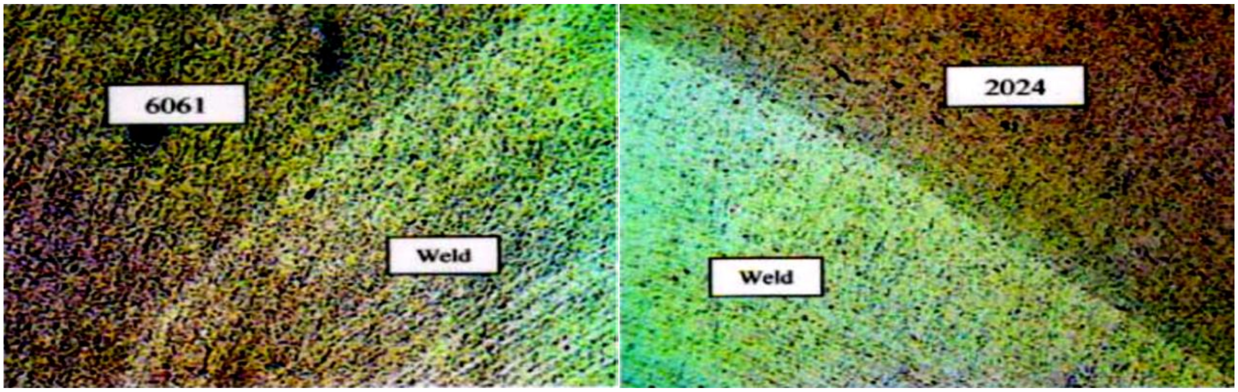

Figure. 7 Microstructure view of AA2024 on advancing side at WS of 35mm/min [12]

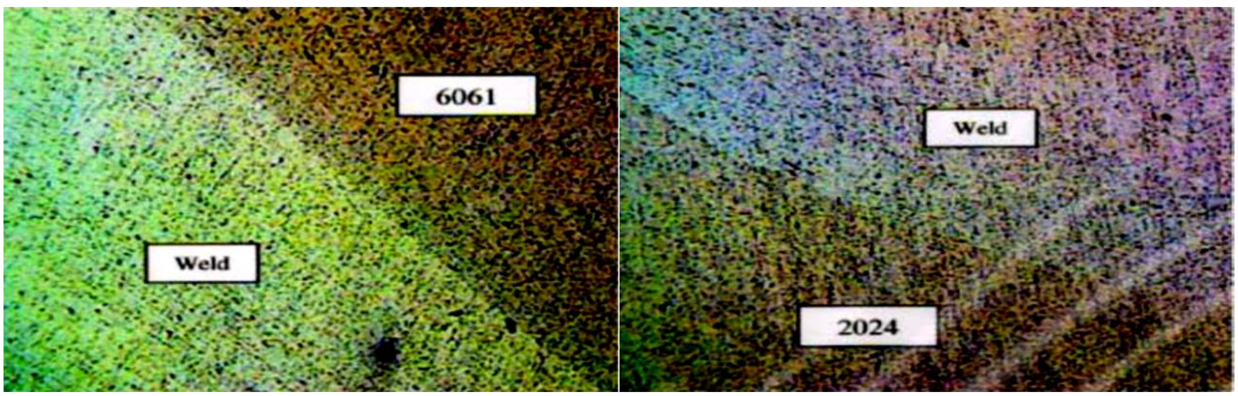

Figure 8: Microstructure view of AA6061 on advancing side at WS of 35 mm/min [12]

4. Conclusions

From the current study following conclusions can be drawn:

- The joint efficiency of dissimilar weld joint of AA2024/AA6061 found 80% with cylindrical threaded tool pin and 81% with square tool pin.
- The sound dissimilar joint of AA6061-T4 and AA5083-O obtained at 1600 rpm with joint strength of 71.2% joint efficiency.
- The triangular pin gives better result on UTS of AA5083/AA6082 on comparing with pentagonal pin profile and UTS increases on increasing TRS and WS.
- Positioning of materials (advancing/retreating side) is an important consideration in case of joining dissimilar aluminum alloys.
- The hardness of weld zone in case of FSWed AA5083/AA6082 was higher than FSWed AA5083/AA5083 and AA6082/AA6082.

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