Jurnal Kejuruteraan 35(1) 2023: 13-28
https://doi.org/10.17576/jkukm-2023-35(1)-02

Influence of Welding parameters on Mechanical property during Friction Stir Welded joint on Aluminium Alloys: A Review

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Received 12 February 2022, Received in revised form 24 June 2022
Accepted 28 July 2022, Available online 30 January 2023

ABSTRACT

The friction stir welding (FSW) is widely used in the fabrication of Aluminium alloy and other non-ferrous alloy. It has good potential to be used in major industries such as automobiles, aerospace, shipbuilding and can be used in the joining of high strength alloys. The FSW process low distortion and heat affected zone (HAZ) with fine recrystallized microstructure which leads to better mechanical properties at the weld zone and produces great stability. In this study, the different FSW parameters such as weld speed, tool rotation speed, tool tilt angle, feed per min has been discussed. The different types of tool pin profile and shoulder have also been discussed and their impacts on mechanical and microstructural properties at welded joints. Among various welding parameters the rotational speed is the most influencing parameter in FSW. Increasing the rotational speed exhibits the increase at tensile strength and is supposed to improve the mechanical properties. The most affected tool pin profile would be considered to be tapered threaded cylindrical pin profile which makes the adequate mixing of material with better flow ability and provide the fine grains at nugget zone. Comparing the FSW with other arc welding processes, it shows a wide range of environmental benefits which are noticeable such as saving in consumable materials, decrease in consumption of filler material and reduction in grinding wastes. Harmful emissions created from arc welding causes a health hazard to the welder. For achieving the high joint-strength for aerospace aluminium alloys and high temperature sustainable metallic alloys, friction stir welding will be preferred.

Keywords: Aluminium; tool design; rotational speed; welding tool speed; tool profile; mechanical properties

INTRODUCTION

Friction stir welding (FSW) is a solid-state welding process which has been recognized for its potential of joining for high strength aluminium alloys. It was first invented and patented by TWI in the year 1991. During the development phase, the friction welding only restricted to aluminium alloy and mainly used to reduce the weight of aircraft but with the span of time, its research area increased to a range of materials, which is possible due to development in tool profiles. The aluminium alloys have rapidly gathered attention for a wide range of structural application as well as for innovation in improvement of the welding technique. It is being extensively used for similar as well as dissimilar joining of Al, Mg, Cu, Ti and their alloys. Possibly it is difficult to join dissimilar material using solid-state joining methods without having the compatibility issues of physical properties of the materials as well as formation of intermetallic compounds. Hence, a suitable interlayer which prevents the formation of intermetallic compounds is often employed in such cases.

Friction stir welding (FSW) has emerged as one of the vital alternative technologies which has good potential to use in major industries like automobiles, aerospace, shipbuilding, railways and can be used in high strength alloys.

With the use of friction stir welding, the common problems of fusion welding such as solidification, liquation cracking and porosity have become vanished. As the composite materials have hardness, rigidity, fatigue strength, flexural strength, modulus of rigidity, etc. FSW is very suitable for the composite material. The heat is generated through the translation rotating of a non-consumable tool which increases the temperature of material and leads to a fine grain structure being produced in the weld area which raises the mechanical strength of the material. During FSW process at the faying surface the advancing side from where material starts melting and the other is the retreating side where material gets cooled. Material flow path also possess the responsibility for better mixing of material. However, attentive choices of welding parameters were required for enhancing the microstructural and mechanical properties. During the joining of soft materials like aluminium alloys, FSW becomes the first priority compared with any other fusion welding process as it has other environmental benefits. The illustration of FSW process is depicted in Figure 1. It was initially developed for only aluminium alloys but with the glimpse of time it becomes suitable for joining a large number of materials. In friction stir welding, a rotating cylindrical tool with respective pin geometry is plunged into the spindle and contacts it with the upper surface of the workpiece. With this process, heat is generated due to friction and visco-elastic dissipation of mechanical energy at high strain rates which softens the material and produces the weld. The tool is high wear resistant and when it becomes in contact with workpiece metal, it produces friction heat. Due to this, the workpiece reached a high temperature which softened the material and made solid phase connection between two parts. But initially the tool materials couldn't able to resist the high temperature such as steels and other high-strength materials and failure occurred. Advancement in technology made it a better strength of material which comes with tungsten, rehenium, ceramics and polycrystalline cubic boron nitride. The study of the major influencing parameters of welding and tool design has been carried out. Also, the impact of these parameters on mechanical and microstructure properties has been discussed. The comparison of friction stir welding and other arc welding processes has been attempted.

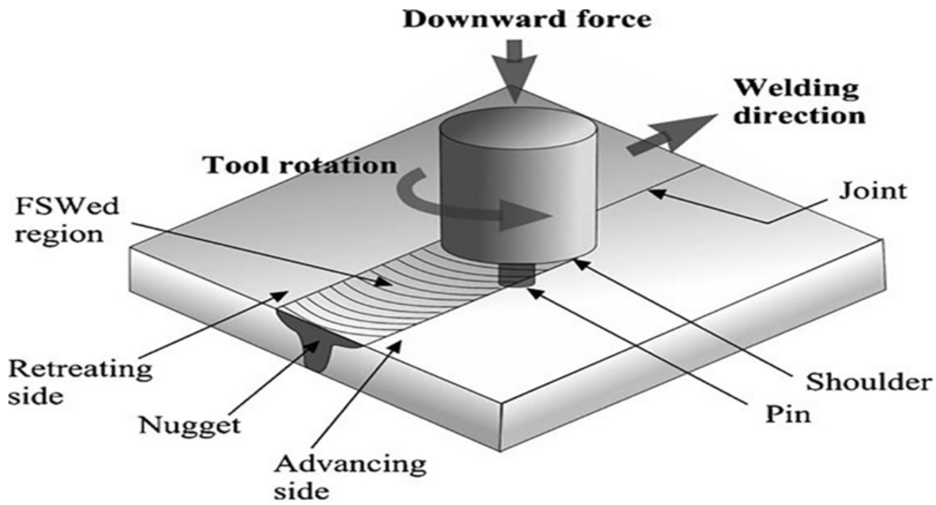

FIGURE 1. Illustration of Friction Stir Welding (adapted from Elatharasan et al. 2020)

LITERATURE REVIEW

Reported the flow of shear layer and deposition of them into the cavity at the end of pin. As from the welded sample, two small defects can be seen which were due to insufficient shoulder flow in the upper weld. The shear zone was made to start from the advancing side and end at the retreating side where the material is deposited to form the nugget zone. They conclude that the cavity made in the advancing side was stable and filled continuously when the pin is continuing to move forward in the front side (Chen et al. 2008). Studied the asymmetric mechanical and tensile properties of AA5083 during friction stir welding joints. The asymmetry of microstructure can be seen from the results as from stirred zone to thermo-mechanically affected zone, the ring was clearly seen at the advancing side but decreased when going towards weld center. They concluded that because of root flow, the FSW was fractured through the retreating side (Rao et al. 2013). Trying to show the influence of multi-pass friction stir welding on various properties of AA6082. With the increase in number of passes, the dynamic crystallization in the stirred zone which leads to equiaxed grains at FSP, also increased. While increase in the feed rate would not affect more but reduces the particle size and increases the mean hardness and tensile strength. They concluded that if the rotation speed were increased, the coarse grain in the stirred zone could be seen while change in hardness and other mechanical effects would inconsiderable (Rayer et al. 2012). Worked upon commercial 7075-T6 aluminium alloy and explored the grain refinement, thermal stability and thermal properties. When the material was annealed to the temperature 623K to 773K, the grain refinement was fine but going above 773K temperature range, it leads to an abnormal grain growth with large grain size. The superplastic behavior can also be seen where strain hardening takes place at the initial deformation where it increases due to decrease in temperature. They conclude that the same alloy while respected to friction stir processing reveals the maximum elongation due to variation in experimental conditions which can also influence the fine-grained microstructure (Goloborodko et al. 2004). Investigates the effect of different process parameters using dissimilar AA5085 and AA 6082 aluminium alloy. By using neutron and synchrotron X-ray diffraction, they found that the maximum longitudinal stress is two or three times the transverse direction stress. They reported that the change in residual stress towards weld line could be seen which was more influential than change in transverse speed, which shows that rotation speed would be more beneficial to optimize the residual stress as shown in their work (Steuwer et al. 2006). Reviewed and studied the several researchers and their work study. They study the different process parameters used by researchers and show through their work. On the basis of various researchers, they concluded that FSW still needs more research and scrutiny with influencing the rotational speed, thickness and other vital parameters which directly affects the welded material (Abdullah et al. 2017).

Scrutinize the material flow and microstructure of similar and dissimilar aluminium alloy during friction stir welding. They found vortex-like structure in similar weld of AA6061 and lamellae on dissimilar AA6061-AA2024 with the three distinct regions of nugget zone. Mechanically mixed region (MMR), Stirred-induced plastic region (SPFR) and Unmixed region (UMR), the weldment is able to sustain high degree of plastic deformation and goes to recrystallization, which enhances its hardness. They concluded that a fast rotational speed gives the more uniform mixture in dissimilar welds (Ouyang et al. 2002). Explore investigate the microstructural behavior of two dissimilar aluminium alloy while aligned them in perpendicular rolling direction during friction stir welding. Metallurgical analysis shows the fine equiaxed grains throughout the nugget zone. The HAZ shows the non-uniform grains with slightly layer size and the hardness was found to be low with respect to base metal. The joint of AA2024 and AA7075 dissimilar aluminium alloy shows better ductility with higher tensile strength. Through SEM analysis, the ductility behavior shows the typical fracture surface with very fine grain size (Cavaliere et al. 2006). Studied the microstructural properties and behavior of dissimilar AA6061-T6 and AISI 1018 steel with friction stir welding. The tensile results of both the welded joints showed the different values for low and high pressure and suggested that higher pressures were beneficial for better joint strength. They reported that FeAl is rare in solid-state processes but while going above 1200ºC, the intermetallic phase was formed of Fe-rich FeAl and Fe_3Al (Taban et al 2010). Investigates the different regions in the welded samples of AA7075 using microstructural characterization of friction stir processed weld. They found that the formation of new grain was developed due to continuous dynamic recrystallization (DRX) where in a big amount nuclei were created and formed grain boundaries. The dynamic recovery (DRV) creates the sub grains for enhancing the size and orientation of sub grains boundaries during continuous DRX. Through overall microstructure evolution, the author suggested that tool design process parameters and cooling rate directly puts the effect on final microstructure (Oing Su et al. 2005). Investigates that on what variation of machine parameters, the tensile strength does affect while joining dissimilar AA7075-AA6061 friction stir welds. They used response surface methodology (RSM) in which statistical analysis and central composite design were taken and successfully scrutinized the influence of machine variables on weldment. The stable joints with defect free weld was formed with proper clamping design but the joint strength was slightly lowered. They concluded that the tool design for tensile strength is the most affecting factor. Overall, from this study, it was recommended that tapered tool with threads or flat surface would have achieved better material mixing and high UTS value as compared to smooth cylindrical pin (Hassan et al. 2017). Predicted the residual stress in friction stir welding by finding the calculated data and experimental measured data and comparing it with the proposed methods. They obtained the good capability of the welded material and are equivalent to calculated ones (Buffa et al. 2011). Predicts the average grain size by using a neutral network during friction-stir welding. Using the experimental evidence and numerical prediction, the lap and T-joints were processed and made strongly joint resistance from process parameters to find grain size (Fratini et al. 2009). Scrutinize the dwell phase in friction stir welding and compare it with experimental data. The recording of applied torque with two rotational speeds indicates the lower friction rate at the interface of tool and workpiece (Gemme et al. 2010). Simulates the material flow using finite element technique which results in a quasi-linear strain during friction-stir welding. They concluded that the distribution of equivalent plastic strain exhibits more at the advancing side and the material flow at the retreating side is faster in front of the pin while slower at behind the pin (Zhang et al. 2007). Presents a thermomechanical model for friction stir welding which estimates temperature contours, sliding ratio and power dissipation in the welded coupon. They found that with the increase in tool rotational velocity, the sliding ratio increases which elaborates that if it is too high, the flash or local melting which creates instabilities during welding (Jacquin et al. 2011). Investigates the joining of dissimilar AA6063 and AA7075 and observe the several welding parameters like tool rotation, welding speed during friction stir welding. They concluded that the better weld finish and strong joint strength can be achieved by using square tool and also the tensile strength shows the better result at 800 rpm and 900 rpm (Arunprasath et al. 2007). Examine the different behaviors of friction stir welded butt joints and evaluate the microstructure of AA6061 and AA063. With the high joint efficiency, the hardness of AA6063 is higher but the tensile strength is poor than AA6061. They reported that the grains were slightly elongated at HAZ with fine cracks for AA6061 (Venkatesha et al. 2014). Trying to develop an empirical relationship for AA2219 to estimate the tensile strength during friction stir welding. They concluded that the square pin profile reveals the best tensile strength by focusing on welding parameters using ANOVA and design of experiments. They also shows the defects on aluminium alloys related to variation in rotational speed. The lower rotational speed of 1450rpm shows pinhole type defect at weld region. Due to having defects like tunnel, pinhole, micro-void and cracks in the weld region, the fractured points also dislocated from lowest hardness zone to defected area. Similarly at high rotational speed of experimental value 1850rpm, the size of defect becomes large due to high heat input and becomes tunnel defect (Elangovan et al. 2008). Trying to estimate the recent advances in friction-stir welding which includes the properties, structure and process parameters. They investigated that there were some uncertain parameters such as frictional and heat transfer coefficient, extent of slip which contributes to lack of reliability. They concluded that the researchers should contrast on cooling rates, geometry of stirred zones and other attributes so that it will become successful in the entire quantitative knowledge (Nandan et al. 2008). Trying to approaching the sustainability analysis of friction stir welding at 5xxx series aluminium alloy. They used life cycle assessment (LCA) methodology to calculate the effect of friction welding on environment. At the lowest parameters i.e. at low rotational speed and feed rate, the environmental impact index (EII) value found to be lowest. The mechanical properties of joints makes the conditions most favorable to EII as according to welding parameters (Bevilacqua et al. 2017).

IMPACT OF TOOL GEOMETRY AT FRICTION STIR WELDED JOINT

The design of the tool perceives the vital role in having a good welding property as it has the ability to improve quality of weld and welding speed. Figure 2 shows the basic geometry of a friction welded tool. The tool material should be high wear resistant, high temperature resistant and strong enough to have good oxidation. Also the pin design matters a lot. Many researchers have mentioned in their research that tapered cylindrical pins give the best mechanical and microstructural properties as compared to square, rectangle and triangle pin profiles. The improved tool design will help to make the joint precisely good and also provide improved quality. Figure 3 shows the different tool pin profile with shoulder and pin. The pin of the tool should be considered to be tapered or conical as due to low thermal conductivity, the material flow and mixing becomes proper at aluminium joints.

The tool design plays a very crucial role in terms of weld quality and achieve better mechanical and microstructural property. According to most of the researchers, the square pin profile shows highest hardness and tensile strength without any defect at 1600rpm out of five profiles, which proves that different pin profile provides great impact on both the welding properties. The straight cylindrical pin profile was the lowest performing profile and creates coarse granular appearance with uneven surface.

The tool geometry could have been optimized using several pin profiles and through mechanical testing, it would become clear that which is suitable for their respective work. The tool pin profile affects the heat generation, torque and traversing force during friction welding and also affects the material flow on Aluminium Alloys.

Using threaded tools, trying to understand the flow path of material during friction stir welding process. They found that the deposition of material with unthreaded pins were the same as of the classical threaded pins as in the upper part of the advancing side and lower part of the retreating side. Through their work, they reported that with the increase in plunge force and rotational speed, the size of the weld joint first increased and then decreased (Lorrain et al. 2010). Used two profiles of shoulder to investigate the effect of its geometry on flow of material during friction stir welding. The shoulder with cavity made the onion ring structure around the pin and throughout the plate thickness with some reduction (Leal et al. 2008). Represents the multiple optimization by varying the welding parameters like tool rotation speed, translational speed, etc. during friction stir welding of two dissimilar aluminium alloy. Due to the presence of kissing bond and uneven joining of dissimilar aluminium alloy, the joint fractures from the center line and shows the low UTS value, when keeping the AA5052-H32 at the advancing side. While using square and triangular pin geometry, a large amount of plastic deformation was held due to which formation of stress takes place in localized strain. This shows that the fracture is at TMAZ and possesses the configuration of higher strength value of the weld (Kesharwani et al. 2014). Using thermoplastic material, specifically high density polypropylene plate to optimize the process parameters on friction stir welding. With the several experimentation trials, the best parameters they found were 1000rpm of rotational speed and 10mm/min of feed rate with 1º of tilt angle and tapered cylindrical as tool pin profile (Jaiganesh et al. 2014).

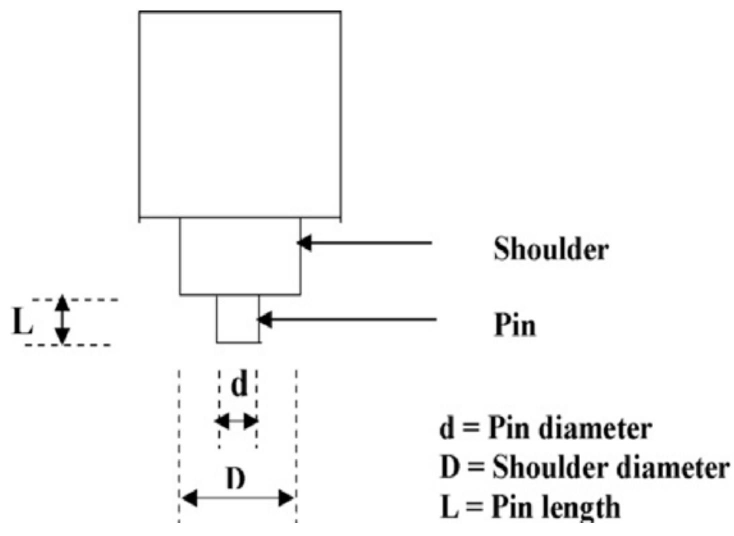

FIGURE 2. Illustration of FSW tool (adapted from Elangovan et al. 2008)

Investigated the impact of tool profile and axial force on AA6061 of friction stir processing zone. They reported that from the experimental values of five tool pin profiles, the square pin profile makes defect free weld at 78kN of axial force with better surface finish (Elangovan et al. 2008). Used an assisted heating tool for friction welding of thermoplastics to obtain a better weld surface finish. They concluded that the assisted tool design provides more heat and enhances the tensile strength for propylene welded coupons (Banjare et al. 2017). Trying to optimize the welding parameter for enhancing the tensile strength of AA6061 during friction-stir welding. They concluded that the values optimized from Hooke and Jeeves algorithm were closely same enough as experimental values with the developed mathematical model (Elangovan et al. 2008). Scrutinize the friction-stir butt welded joint by using the spindle motor electric current as a parameter. They found that the square and conical tool pin profile consumes less power and provides good tensile strength but as the thickness increases, the power consumption increases (Kumar et al. 2013). Find the impact on pin profile and rotational speed on AA2219 with friction stir processing zone. They concluded that the experiments performed with square pin profile, shows the best tensile strength and produce defect free FSP zone (Elangovan et al. 2008). Analyze and scrutinize the erosion of aluminium alloys as they are the most applicable materials used in sea applications. They used AA5083 and AA6061 to make dissimilar friction-stir welded joints for observing the variation in mechanical and microstructural properties. They found that the grains were equally axed and with the use of a cylindrical pin, the tensile strength was achieved to be maximum at 800rpm. As pH value decreases, the erosion becomes lower from the center of weld and shows that pH value prevails over another parameter. They also added that with the help of these outcomes, the essential things were enlightened as for the use of marine applications (Ramesh et al. 2020).

Conducted the experiments on different welding parameters and optimized it for friction welded AA6061 and AA6082 samples. Different types of tool pin profiles were used for observing the difference between the flow of material and mixing using the Taguchi array. They reported from their research that the octagonal pin type of tool possesses the maximum tensile strength as compared to others. The threaded and tapered cylindrical type of pin was inappropriate to make proper mixing which leads to less hardness and tensile strength. The tensile strength and hardness was observed between 264MPa to 273 MPa and 77 to 85 μ_{HD} respectively (Kumar et al. 2013).

TABLE 1. Various types of tool profile used in friction stir welding process

Sr. No.	Author	Experimental Material	Variable Tool Profile	Outcomes
1	Lorrain et al. 2010	AA7076-T6	Straight and tapered cylindrical pin	Tapered cylindrical pin shows less deformation but with unexpected change in thickness
2	Leal et al. 2008	AA518-H111 AA6016-T4	Conical shoulder, Scrolled shoulder	Reduction, onion ring structure at conical pin less reduction in thickness and provide good mechanical properties
3	Kesharwani et al. 2014	AA5052H32 AA5754-H22	Circular, square and triangular	Square pin shows the maximum mechanical strength
4	Jaiganesh et al. 2014	Polypropylene Composite	Cylindrical, tapered and grooved cylindrical	At particular parameter, tapered tool profile found to be optimum
5	Elangovan et al. 2008	AA6061	Straight, tapered and threaded cylindrical with square and triangular	Square produces highest pulsating action followed by triangular pin without any defect
6	Banjare et al. 2017	Polypropylene	Threaded cylindrical	With the preheat, threaded tool makes smooth surface, proper material mixing
7	Elangovan et al. 2008	AA6061	Square	Square pin profile shows optimum tensile strength with change in axial force and rotational speed
8	Kumar et al. 2013	AA6063-T6	Square, triangular, circular, conical	Square profile improves flow of material and produces highest pulses per second at 1000rpm, conical profile also shows good tensile strength
9	Elangovan et al. 2007	AA2219	Straight, Tapered and Threaded cylindrical, triangular, Square	The defect free welded joint was made by square pin profile due to adequate working of plasticized metal and pulsating action of pin profile.
10	Ramesh et al. 2020	AA5083	Taper tool pin, threaded and cylindrical pin	Taper produces maximum hardness while cylindrical pin provides maximum tensile strength
11	Kumar et al. 2013	AA6061 AA6082	Octagonal, threaded and tapered cylindrical	Maximum deformation due to eight edges of pin, Octagonal help to provide good surface finish as due to more edges

Impact of various types of tools at friction welded joints is shown at Table 1.

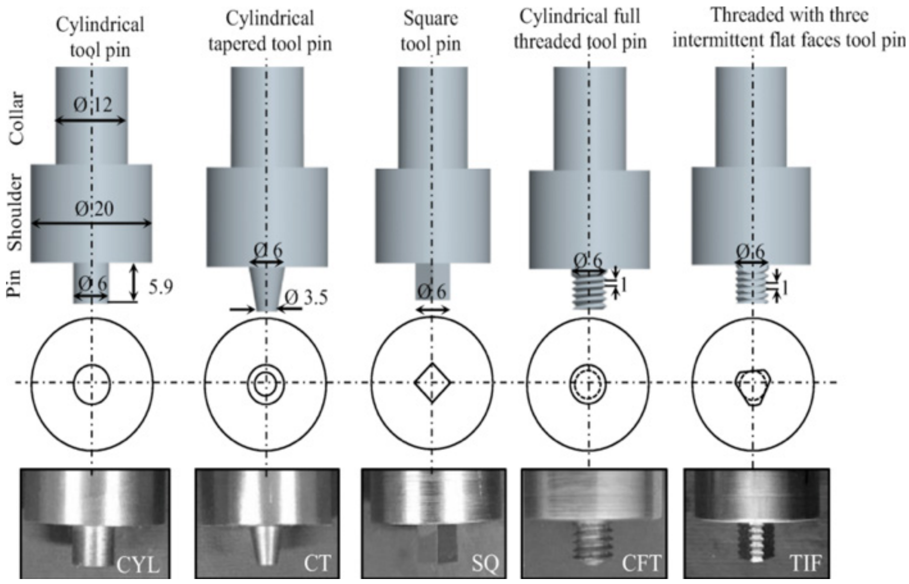

FIGURE 3. Different tool profile with shoulder and pin diameter (adapted from Garg et al. 2019)

INFLUENCE OF WELDING PARAMETERS ON FRICTION STIR WELDED JOINT

The tool rotation and traverse speed have their own preferences in the field of their outcomes. It proposed how fast the tool rotates and how quickly it traverses along the interface. For having efficient and successful welding cycles, these factors could persist. The tool rotation shows the variation in tensile strength as if it increases, the weld temperature becomes high and could variate microstructure. The flow of heat should be adequate so that it forms a good weld. So to enhance it, a dwell time and traverse speed is needed whose variation becomes a good generation in heat input. Sometimes it is possible that the area ahead of the tool is so cold that flow of stress becomes high and results in tool fracture. So it is the responsibility to make a hot zone which is due to high traverse speed and resulting in good welding. The plunging depth is a crucial factor which has its vitality because it is the depth under the surface of the workpiece at the lowest point of the shoulder of the tool. It defines the weld quality and creates pressure on the material. The tool tilt angle shows the enhancement in mechanical properties as increase in tool tilt angle increases the welding temperature. The slight tilt is given at the back of the material so that the welding defect should minimize. The input parameters in friction stir welding are influential in the output of fabrication. The shape, size, tool geometry, plunging depth, rotational speed, dwell time all persist an importance in having the best outcomes.

Proper Rotational Speed will be required for achieving the better mechanical properties. Likewise, it shouldn't be less than 800rpm which causes inadequate heat generation while rotational speed more than 1700rpm will cause turbulence and made pinhole type defect. But overall, high tensile strength would found at every high rotational speed as per the experimental values. Similarly lower the welding speed, heat input will be extreme and can cause tunnel defect while having the high welding speed results in poor plasticization of metal. The tool tilt angle must be prior to be set at 2-4º which affects the weld quality and impact better at mechanical property. The mixing of material will be better in this tilt angle.

Shows the impact of different parameters on grain size and formability in AA5083 aluminium alloy. No cracks or porosity was visible while observing the cross-section of weldment and fine equiaxed grains were found in microstructure testing. They found that for the present alloy, the hardness increases slightly with the decrease in grain size in the stirred zone, which occurs due to recrystallization due to excessive plastic deformation. They concluded that the ductility can be improved while changes in combination of R_t and V and with lowering the friction heat flow, the formability in friction stir weld (Hirata et al. 2007). Investigates the suitability of friction stir welded but joints of AA2024-T3 and AA7075-T6 aluminium alloy. They found that the weld strength of the weldment is lower than the base material due to lesser thickness ratio of dissimilar welds. The grains in unmixed zones were fine equiaxed which shows that it goes to dynamic recrystallization. They discussed that the flow of material through the advancing side to retreating has been uniform (Avinash et al. 2014). Trying to predict the size of grain and tensile strength of friction stir welded joints and to establish the empirical relationship between them. By using response surface methodology (RSM), they developed the empirical relationship and identified the vital process parameters by analyzing the predicted value and actual value for tensile strength; they found out that with the narrower confidence interval, the precision rate would become higher (Rajakumar et al. 2010). Using Taguchi's technique, trying to find out the optimized process parameter for joining of

AA6061-AA7075 with friction-stir welding. With Taguchi's L9 algorithm, they got the better parameters from the higher tensile strength welded sample. It was also analyzed from the S/N ratio where "Larger is Better" was desirable. Through this study, it was recommended that in all aspects, rotational speed contributes more and is the key feature for getting the best results. The contribution of different process parameters such as number of passes and rotating speed is shown in Figure 4 (Ugrasen et al. 2018). Studied and investigated the mechanical and thermal behavior while doing the friction welding on Al-Al, Cu-Cu and Al-Cu couples. Through a scanning electron microscope, no voids or defects can be seen which indicates the proper mixing of aluminium and copper with 800rpm of rotational speed and 60mm/min of feed rate. They found that at low rotational speed, poor tensile strength can be seen at similar and dissimilar joints but at the above parameters, the UTS value of 64.81 N/mm^2 would achieve which was good and higher than other experimental trials. Table 2 describes the several welding parameters having impact on mechanical properties of friction welded joints (Rane et al. 2018).

Found through their experimental results that low rotational speed will be required for thick sheets due to necessity of lower heat input. Whereas, the welding speed and axial force was required to be increase in thickness with increase of aluminium sheets due to the variation in microstructural grains and joint strength. If the rotational speed puts too high, coarse grain will form with worm-hole type defect. While if welding speed is not sufficient then it causes lack of fill defect. For better productivity, 6mm to 15mm aluminium sheets would be compatible for commercial applications which maintains the mechanical and microstructural properties (Mallieswaran et al. 2021).

Inquired into material flow for the use of plasticine as an analog in friction-stir welding. They observed the weld deformation features while comparing at low tool rotational and feed rates where original interface is clearly perceptible and little mixing is formed (Liechty et al. 2007).

Scrutinize the microstructural characterization of 304 stainless steel and st37 steel during friction stir welding. They reported that the st37 became recrystallized at the stirred zone due to high heat input and shows the large ferrite grains while the 304SS shows small austenitic grains when dynamic recrystallization occurred in the stirred zone (Jafarzadegan et al. 2012).

Trying to make a defect free friction stir weld through a mathematical model of magnesium alloy. They found that at high welding speed and constant rotation speed, pores were made at the welding line. But it was avoided by a mathematical model with less welding speed and constant welding pressure (Zhang et al. 2006). Investigates the impact of different welding parameters on dissimilar welded joints through various resources such as optical and scanning electron microscopy and tensile test. The 430 stainless steel and AA6061 material had been taken for research study and with friction stir welding the joint were made. They concluded that the microstructural property variates highly from the vital parameter tool offset, for those which have tool offset zero, shows maximum tensile strength with better joint efficiency. The variation in temperature of microstructure during welding is shown in the form of graph at Figure 5 (Zandsalimi et al. 2019).

TABLE 2. Different parameters influenced in friction welded joint

Sr. No.	Authors	Work Material	Influencing Parameters	Outcomes
1	Hirata et al. 2007	AA5083	Rotational and Welding speed	Grain size increased with increase in welding speed and vice-versa in rotational speed, At lowest speeds, the tensile strength was at highest
2	Avinash et al. 2014	AA2024T3 and AA7075-T6	Rotational and traverse speed	At rotational 1450rpm and traverse 82mm/min, highest strength of 262MPa was achieved, at low rotation, the grains were large and elongated
3	Rajakumar et al. 2010	AA6061-T6 (Al-Mg-Si)	Axial force, Rotational and welding speed, tool pin profile	Increase in grain size occurs in fall of tensile strength, at 95% CI the highest 2tensile strength obtained was 199MPa and lowest was 195MPa
4	Ugrasen et al. 2018	AA6061 and AA7075	Number of welding passes, welding and tool rotational speed	At midrange of rotational with single pass, exhibits the higher tensile of 110MPa, S/N ratio shows the optimum range of parameters which was 650 to 850rpm, The hardness shows maximum at low rpm
5	Rane et al. 2018	Aluminium and Copper	Cylindrical tool, transverse speed, tool speed	At lowest and highest rpm the sample become failed, the optimum range of parameter were found to be 850 to 1100 rpm which show 146MPa of strength, Lower the feed rate smooth the surface
6	Mallieswaran et al. 2021	AA5083 and AA6082	Tapered cylindrical, Flat cylindrical	Different thickness sheets were tested by source of strength, hardness and fractographs. The 3mm sheets sustains the higher load with a tapered pin profile, heat input required to be high for thick sheets.

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7	Liechty et al. 2007	Non-Sulphurated Plasticine (NSP), Roma Plasticine	Threaded pin, Smooth Pin	Through thermal testing and compression testing, the qualitative flow of stress was found during FSW which was similar to metals.
8	Jafarzadegan et al. 2012	304SS and St37 Steel	Tilt angle, welding speed	Due to high heat input of increased tool rotation, the area of stirred zone increase, Onion rings were made due to increased grain size at aluminium, higher rpm shows higher tensile strength and hardness
9	Zhang et al. 2006	AZ31 (3% Al. and 1% Zn.)	Varying welding speed with same rotational speed	To avoid the voids and defects, the welding speed was kept to be constant with larger value of tool rotaion and welding pressure. Pore was produced when welding and rotational speed were kept at constant
10	Zandsalimi et al. 2019	430SS and AA6061	Tool offset, Rotational speed	For optimization, the main influencing parameter was tool offset. With the increased heat input, the thickness becomes increased, steel parts becomes micro crack
11	Kranthi et al. 2021	AA5083 and AA6061	Feed, Rotational tool speed	At high tool rotation, the temperature increases and thus the width of the stirred zone increases. At mid rpm, the highest tensile was achieved 198MPa. At high rpm, the ring becomes small without any corrosion factor

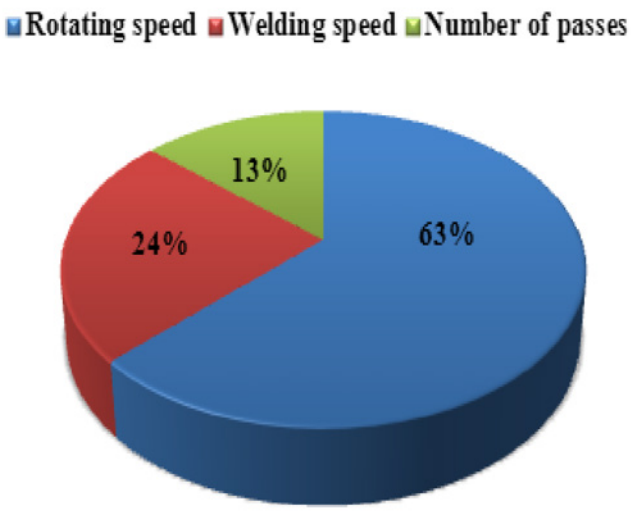

FIGURE 4. Contribution of process parameters (adapted from Ugrasen et al. 2018)

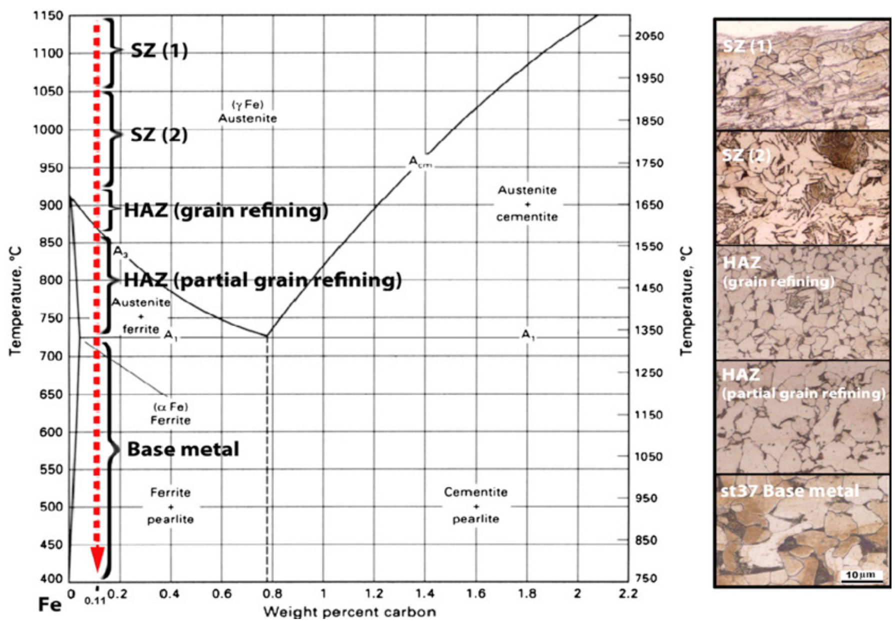

FIGURE 5. Observations from Jafarzadegan et al. 2012 which shows the temperature of various microstructures.

The steel shows the micro voids which have lower hardness. This occurs due to the heat treated condition of aluminium and steel. It shows that at interface, the hardness at HAZ is lower than that of aluminium and faces the negative impact of micro voids. Trying to highlight the influence of process parameters on mechanical property and material flow by using dissimilar AA5083-AA6061 material. The normal tensile test and notch tensile test shows a difference in strength even at different parameters. The researcher found that at 1150rpm, the superior tensile strength was shown to be 198MPa and at the notch test it was at 1450rpm with joint efficiency 69%. They also observed that the onion ring layer was decreased at high rpm with improving corrosion resistance. The microhardness of traverse speed and rotational speed at dissimilar aluminium alloy is shown in Figure 6. It depicts the variations in traverse speed and rotational speed with the outcome of hardness values 84.4 HV and 87.9 HV for AA5083 and AA6061 respectively. The minimum hardness occurred at HAZ region due to coarse grain and dissolution of second phase at AA6061. The average hardness value was shown at higher traverse speed due to loss of work hardening behavior of AA5083. While at stirred zone, higher rotational speed shows lower hardness value due to large grain size and prolonged thermal exposure (Kranthi et al. 2021.

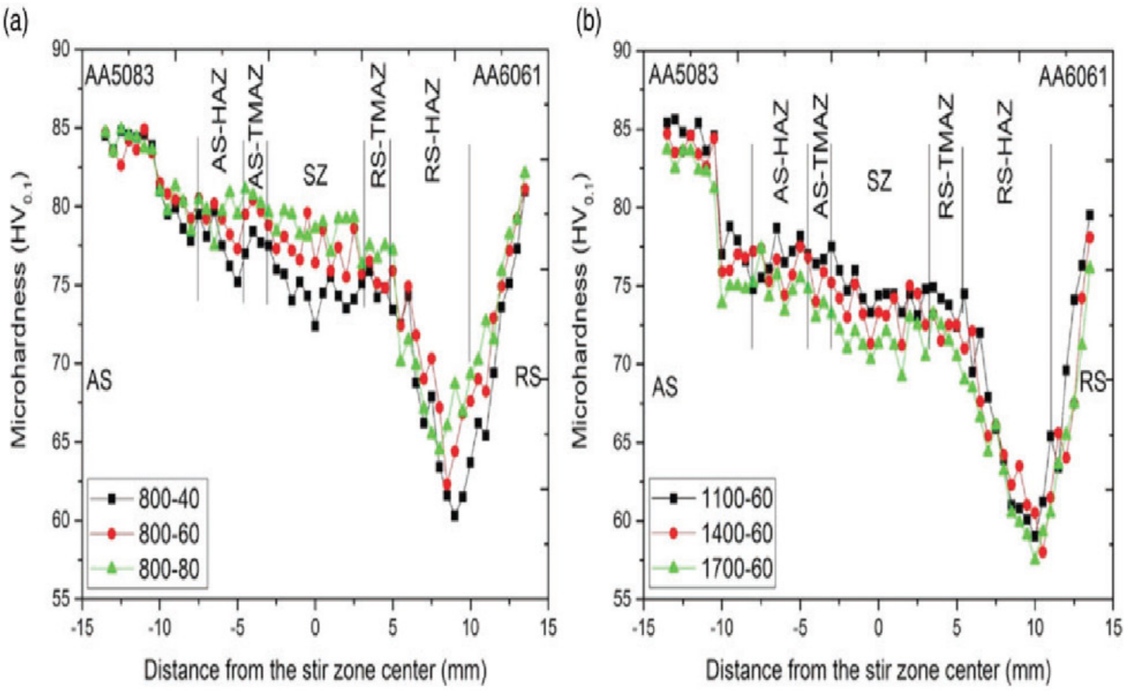

FIGURE 6. The figure shows the microhardness of AA5083-AA6061 at varying (a) traverse speed and (b) rotational speed respectively (adapted from Kranthi et al. 2021)

COMPARISON OF FRICTION STIR WELDING TO OTHER ARC WELDING

For joining the metals, welding is the first preference which all do as it provides the same strength as of its parent metal while being used in a diverse variety of applications. Its use could have occurred in several places from outside premises on rural farms to inside locations such as manufacturing laboratories and factories. Friction stir welding (FSW) has emerged as one of the vital alternative technologies which has good potential to be used in major industries like automobiles, aerospace, shipbuilding and can be used in high strength alloys. The materials being light in weight like aluminum, magnesium, etc. can be frequently used in transport and other industries. As the tool rotates and moves along the workpiece with the joining of plates, the softened material would extrude around the tool. The heat generated in the joint area is typically about 80-90% of the melting temperature. Gas tungsten arc welding is a type of arc welding in which a tungsten electrode is used to produce the heat and weld the two metal pieces. The electrode is non-consumable in nature. The welding torch for GTAW is greatly designed for manual and automatic torch is, manual torch consists of the handle from the centerline which consist of tungsten electrode to variate. Friction welds possess more joint strength and superior in microstructural grains as compare to GTAW and GMAW. The comparison done by researcher shows the 38% reduction in the tensile strength of GTAW welded joints while the FSW performs highest tensile strength and yield strength. In terms of hardness, GTAW also becomes low from FSW as due to improper welding heat input and usage of lower hardness filler metal. Also the presence of Silicon contaminates the welded joints and hence reduces the hardness in GTAW welded joint. Gas metal arc welding (GMAW) is a process in which a consumable electrode is used and through the electric power supply, an arc is generated between electrode and workpiece which melts the metal and causes it to join. But in most of the conditions, if we compare friction welding from arc welding above regarding the mechanical and microstructure property, the friction becomes more suitable and optimum as the heat generation during welding is low and balanced. Due to high heat input in GTAW and GMAW, there will be more chances of making defects with low mechanical strength. Scrutinize and try to find out the variation in fatigue strength of friction-stir welds altered by welding speed. The researcher found that the friction welded aluminium alloy shows higher pulse rate than arc welds with higher ductility. As due to high heat input, the material becomes less sensitive and shows better mechanical properties. They concluded that the TIG and MIG welds don't show better fatigue strength than Al-Mg-Si 6082 alloy which were independent of welding speed (Ericsson et al. 2003). Trying to show the variation in tensile strength of AA6061 while effecting the welding process on aluminium joints and to compare the arc welding with friction-stir welding. In their research study, they used AA4043 filler grade for the gas metal arc welding. Through their research, it is clearly shown that the superior tensile strength at friction welded specimen was 295MPa. They found that the joint efficiency of friction welded samples is 74% while it was 49% and 63% for metal inert gas and tungsten inert gas welded joints respectively. Also, the hardness shown is more for friction-stir as the motion of the tool generates high shear stress and is made of very fine grain structure (Lakshminarayan et al. 2009).

TABLE 3. Comparison of Friction welding to GTAW and GMAW

Sr. No.	Author	Work Material	Influencing Parameters	Conclusions Made
1	Ericsson et al. 2003	AA6082 (Al-Si-Mg-Mn)	Axial force, welding speed, rotational speed, depth of penetration	The FS weld shows high tensile strength followed by TIG. The alloy with T4 aged high shows a maximum of 291MPa tensile strength. At low welding speed, the flow and mixing of material become adequate
2	Laksminarayanan et al. 2009	AA6061, AA4043 filler material	Shoulder and pin diameter, rotational and welding speed, axial force, pulsating current	Higher tensile strength shown by FS weld which was 249MPa with 86VHN hardness. Due to fast heating and cooling at GTAW, dendritic structure was formed
3	Kulekci et al. 2010	AA6061-T6 (Al-Mg-Si-Cu), AA4145 filler material	Tilt angle, tool speed and transverse speed, voltage	Less the heat input, smaller the impact at areas where hardness varies. Due to less HAZ at GMAW, the mechanical properties were low compared to FSW. FSW made the quality welds
4	Balasubramanian et al. 2011	AA2219-T87	Gas flow rate, current, voltage, tool speed, Threaded pin tool, axial force,	FSW shows the joint efficiency of 73% with 243MPa of tensile strength which was higher than the other two. Fine equiaxed grains were made

Scrutinize the comparison of variation of mechanical properties to gas metal arc welding and friction-stir welding at welded joints of material EN AA6061-T6. For the experimental runs of friction-stir, the semiautomatic milling machine is used while for metal inert gas, it was MIG-350 semiautomatic. They found that the welded samples were broken from heat affected zones for friction and showed the maximum tensile strength of 270MPa but the strength decreased for metal arc welding for about 23%. The microstructure shows the rough surface for MIG specimen and fine grains at friction sample. Overall, the heat generation and balancing at friction stir is the superior quality which enhances its mechanical properties (Kulekci et al. 2010). Worked upon AA2219 to make butt joints and studied the impact of gas tungsten arc welding, electron beam welding and friction-stir welding on mechanical properties of aluminium alloy. They used individually welding machines for the related welding processes. In their research study, they found that the friction-stir shows the highest tensile strength of 343MPa which shows the lowest reduction from base metal. The maximum reduction of 50% was shown by tungsten inert gas welding joints with 243MPa (Malarvizhi et al. 2011). Pointing towards the joint efficiency, friction stir specimen shows 73% which is highest in class. The microstructure study of welded specimens shows fine equiaxed grains due to consistently recrystallization caused by the heating process.

CASE STUDIES OF FRICTION STIR WELDING

Investigates the suitability of processing the tailor welded blanks during friction-stir welding. The joints were created by phase transformation and undesirable changes in microstructure could be seen. They reported that with the increase in the thickness ratio, the increase in temperature would be seen near the HAZ area on the advancing side (Buffa et al. 2006). Scrutinize and try to show the influence of friction-stir welding on AA7075. They concluded that a nugget zone with 2-4μm grain size was shown when recrystallized and concentric flow lines were observed (Rhodes et al. 1996). Trying to show the impact on tensile strength of different welding parameters at pulsed current tungsten inert gas at AA6061. The basic influencing parameters which the researcher used were peak current, pulse on time, pulse frequency and base current. From their experimental work and calculations, they came to the conclusion that tensile property variates according to peak current and pulse frequency and they are indirectly related, if one increases then other also increases or vice-versa. However, it is totally polar for other parameters i.e. for base current and pulse on time, they have an inverse relation to tensile properties which was noticed by researcher (Kumar et al. 2007). The case studies of several researchers at friction stir welding and other processes are shown at Table 4. The various zones at macrostructure made during friction stir welding are shown in Figure 7.

TABLE 4. Case study of various researcher about influencing parameter used during friction stir welding

Sr. No.	Author	Experimental Material	Different parameters used at welding	Observations
1	Buffa et al. 2006	AA7075-T6, H13 steel for tool material	Cylindrical pin, tool rotation and welding speed	Poor material flow and mixing due to the thick plate at the advancing side. Due to large value of nutting angle, the mechanical strength of joint become less
2	Rhodes et al. 1996	AA7075-T6, Thickness 6.4mm	Tool design, travel speed, tool rotation speed	At weld nugget, the density of dislocating the parent metal was very low. The grains would be recrystallized
3	Kumar et al. 2007	AA6061-T6 and AA4043 weld metal	Pulsed current, voltage, non-consumable filler	The pulsed current enhances the tensile strength and aluminium was broken from the weld region. Hardness also comes more than continuous current.
4	Ramaswamy et al. 2020	AA6061-T6, ER4043 as filler with 1.2mm diameter, Thickness was 3mm	Filler wire, current, wire feed, frequency, welding speed	Due to pulsating current, hardness exhibits more. The range was between 76 to 250A with 150 HZ. The tensile strength was improved by 15%
5	Gomathisankar et al. 2018	AA6061-T6 square plate with 6mm thick	Dwell time, tilt angle, rotational and welding speed	The hardness and tensile strength was achieved to be 44VHN and 229MPa with most influencing parameter welding speed
6	Devaiah et al. 2017	AA5083-H321 and AA6061-T6 with 5mm thickness	Taper cylindrical threaded tool, tilt angle, welding and tool speed	With the macrographs, some dimples were found which were due to plastic deformation. Higher tensile strength at midrange of rotational speed welding speed. Slow speed shows the reduction at mechanical properties
7	Elatharasan et al. 2020	AA6061-T6 and AA5083-H111	Transverse speed, pentagon, polygon, and cylindrical pin profile, rotational speed	At 1250rpm, the tensile strength shows better joint strength. At 95% certainty level, the influencing parameter shows the efficient strength
8	Akinlabi et al. 2012	AA5754 and C11000 copper	Rotational speed, feed rate, threaded pin	Onion rings were found at lower rpm and feed. The micro voids were present at lower rpm due to insufficient heating
9	Devaiah et al. 2018	AA5083 and AA6061	Tilt angle, welding speed, tapered threaded cylindrical tool	The most influencing parameter was rotation speed which gives 63% of contribution. The optimum parameter range was between 1000 to 1200rpm with 80mm/min feed
10	Moreira et al. 2009	AA6061-T6 and AA6082-T6	Travel speed, tilt angle of 2.5º, M5 threaded pin tool, gage length	Due to some impurities involved in aluminium, more flash was generated and lower the value of hardness. The dissimilar joint produce 64% of joint efficiency

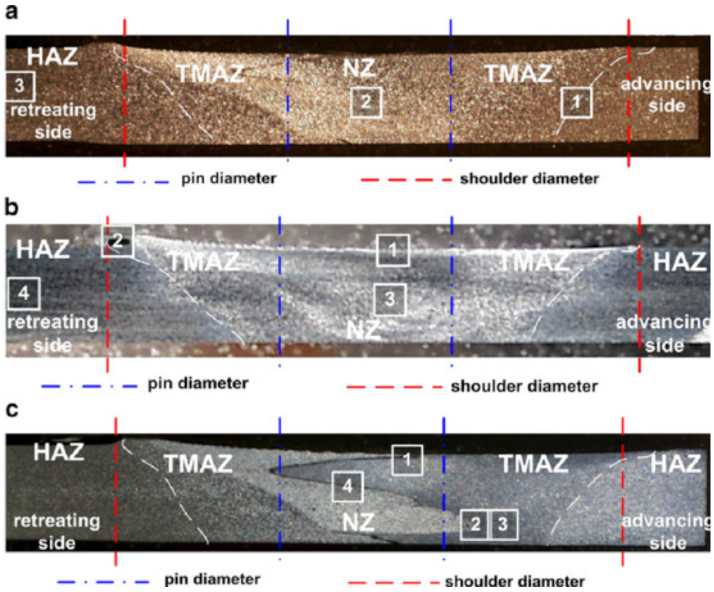

FIGURE 7. Macrostructure observation shown from Moreira et al. 2009 of friction welded joints of (a) AA6082-T6, (b) AA6061-T6 and (c) dissimilar weld.

Ramaswamy et al. [51] describes the impact of different parameters on the mechanical properties of AA6061-T6 during gas metal arc welding. The thickness of material was kept to be thin and the parameters were constant current, pulsed current, cold metal and pulsed cold metal transfer taken. Through their research study, they found the 15% growth in tensile strength at pulsed core metal transfer (PCMT) parameter while low in constant current variant. The hardness is also recorded to be highest for pure-cold metal transfer at weld metal and HAZ. This caused the narrow zones at the advancing side and retreating side as compared to other joints. Used complex proportional assessment (COPRAS) for optimizing the best welded parameters which enhances the mechanical property of AA6061-T6 during friction-stir welding. After determining and evaluating the optimum parameters using COPRAS and ANOVA, they reach a conclusion with different mechanical properties. They said that the most remarkable parameter which influences heavily on properties is welding speed as it varies the heat generation and recrystallization. The actual data of optimum level were rotational speed at 460rpm, welding speed at 25mm/min, dwell time at 2 min and tool tilt angle of 1.5º (Gomathisankar et al. 2018).

Using tapered threaded cylindrical pin profile, author was trying to find out the impact of welding speed at dissimilar AA5083 and AA6061 welded joint properties. With the 5mm of thickness, friction stir welding was used as due to thermal diffusivity and high heat generation, the fusion process doesn't able to achieve such mechanical properties. Though their research study observed that increasing the welding speed at limit, better weld quality could be achievable. They also added that at 1140 rpm, the fine grains at microstructure and higher tensile strength was accomplished and hence the best parameter with weld speed 80mm/min at tilt angle 2.6º (Devaiah et al. 2017). With improvising grey relation analysis, trying to find out the optimum parameters as joining the different alloys of aluminium where one is heat treated and other is not. Using ANOVA technique, response surface method, the properties of the welded joint of AA6061 and AA5083 were observed doing friction stir welding. With the 95% confidence level at regression analysis, they came to the result that the highest and lowest tensile strength was achieved by threaded cylindrical and hexagonal pins respectively. For, different pin profile the ANOVA shows 95% of certainty level and with GRA the optimized parameters were selected and come with great output (Elatharasan et al. 2020). Scrutinize the characterization of dissimilar material to be joined by friction welding which are AA5754 and C11000 copper. With the scanning electron microscopy, the welded joints at different parameters were observed. From their research study, they found the reduction in thickness at 650rpm at different feeds, but at high feed of 340mm/min, large voids as defects were shown which resulted in low material mixing. When the analysis of 1200rpm was taken, no reduction in thickness with good material mixing was found. They concluded that at highest feed, no joints were fused and showed the maximum number of voids with low-material mixing (Akinlabi et al. 2012). Using Taguchi, trying to optimize the process parameter at friction stir welded dissimilar joints of AA5083 and AA6061. As per using the L9 array of Taguchi and optimization technique of ANOVA, the significant role of each parameter was observed. After the confirmation test to the welded sample, the researcher concluded that the value observed of yield strength has become approximated to predicted value which was 213MPa. They said that the parameter rotation speed sustains the most influencing parameter followed by traverse speed (Devaiah et al. 2018).

Scrutinize the characterization of welding properties of dissimilar friction welded AA6061-T6 and AA6082-T6 aluminium alloys. The two different alloys were made and tested on different parameters for analyzing the strength, grains and various aspects of testing. The researcher observed that the AA6082 shows lower strength and hardness as compared to others. The intermediate zone shows the proper mixing of material at the nugget zone. The load sustain capability of AA6061 would always be shown from the results due to higher tensile strength and less plastic deformation (Moreira et al. 2009).

Through their experimental work, trying to observe the impact in macro and microstructure of different welding parameters at friction welded joints of AA7075-T6 and AA6061-T6. The researcher used different pin profiles for comparing the fusion between two plates at the same parameters. They found the tapered cylindrical profile to be superior as it provides approximate fusion and gives 206MPa of tensile strength. The microstructure reveals the fine equiaxed grains at nugget zone for AA6061 while AA7075 shows the rolling flow along the direction of the tool (Ravikumar et al. 2014). Trying to achieve the peak tensile strength through the optimization of tool parameters and friction stir welded joints in AA7075-T6. Through their experiments, attempts have been made to analyze the relationship between process and tool parameters with the help of regression analysis and ANOVA technique. From their observations, the researcher concluded that the tool rotation speed is the most sensitive parameter as compared to others and exhibits higher strength of 376MPa at 1440rpm. They explained that material which has lower in strength should be welded at higher rotation speed unless it will result in the tensile strength to lowest Rajakumar et al. 2010). Took a 7mm thickness of AA6063 plate through which they tried to optimize the welding parameters at friction stir welding. With the use of scanning electron microscopy testing Taguchi method, they analyze the distribution of composites and precipitates made and to compare with the base material composition. They concluded from their research study that the optimum parameter was axial force which contributes 49% of the total through which the maximum tensile achieved is 102MPa with 41 S/N ratio (Ganapathy et al. 2017).

Analyze the effect of tool heating on the friction welded aluminium joint. Different types of pin profile such as cylindrical tapered, square, cylindrical with full thread were used to define the changes in mechanical and microstructural properties of dissimilar AA6061-T6 and AA7075-T651 joints. From their research study, they found that the threaded with intermittent flat surface and full thread perceives the highest axial force and the tunnel defects were also minimized. There was improvement in microhardness as adequate mixing of material was there in the stirred zone (Garg et al. 2019). Trying to find out the influencing parameters in the friction welding of copper and AA6061-T6. The design of tool pin profile kept to be threaded cylindrical and welding parameters were tilt angle, rotational speed, tool offset to analyze the impact on mechanical properties. They found that if we increase the tool pin offset from low to high, the axial load decreases due to the pin displacement towards the aluminium side. They concluded that the taper tool was not acceptable for the dissimilar welding of copper and alloy due to not proper mixing of material at the nugget zone. They observed that the joint strength becomes reduced due to the presence of intermetallic compounds at stirred zone (Mehta et al. 2015).

There are several challenges associated with Friction Welding. Without the adequate heat input there could be chance of marking cracks and porosities inside of weld which can directly reduce the fatigue life. Remedies would be the use of chemical ingredients which prevents local melting and provides better control. However, they found the challenges for the detection of weld defects. They told that with the crucial welding parameters, plunging force should also be considered to a nominated value which makes a defect free weld (Wahab et al. 2019).

As per the section 5 of this manuscript, it was studied that how researchers found the friction welding to be superior from other arc welding. However, the benefits of friction welding is the welding nature as it provides fine, equiaxed grains with uniformly distribution without generating excessive heat. Also, it prevents from harmful emission of gases and light. Friction is now priorly used in aerospace, marine and transportation industries over arc welding, where aluminium is the most preferable material.

Trying to observe the microstructure variation on dissimilar AA6061 andAA7075 during friction stir welding. With the using of K-type thermocouple, they measured the temperature at six different positions and optimize the result. The microstructure at nugget zone shows the fine grains towards AA7075, hence grain density and strength becomes high as compare to AA6061. As per the temperature measurement, third position at 4.6mm penetration provides maximum temperature at advancing side (Godhami et al. 2019).

With near net shape forming technique trying to went through the development done at friction stir processing. Mechanical properties of superplastic forming and different variables such as tool rotation, travel speed, tool geometry and multiple pass were optimized. Due to breaking of secondary phase particles, a fine and without porosity processed aluminium as well as magnesium alloy was found which enhanced its mechanical properties. The multi-pass also impacts the mechanical properties (Patel et al 2019).

Analyze the temperature distribution at AA2014 experimentally and statistically during friction stir welding. With using various welding parameters such as tool rotation, welding speed, tilt angle the temperature were analyzed at eight different positions by using K-type thermocouples. Through experimental values, the ratio of tool rotation and welding (N/v) is directly depends on temperature i.e. with increasing the N/v ratio, temperature increases. The temperature at advancing side would founded to be higher due to the initial heat input. They found the most vital welding parameters as tool tilt angle through statistically analysis (Chaudhary et al. 2019).

CONCLUSION

The numerous studies regarding the tool design, welding parameters, comparison of FSW with arc welding process and several case studies, the following important conclusions are made:

1. The influence of tool geometry shows the great impact at mechanical and microstructure properties. Several researcher in their study shows the square pin profile which exhibits higher tensile strength and less deformation.
2. Several literature survey has been done in this study from various researchers with different experimental values and parameters. The outcomes and recommendation have been insert and preferred in this review paper.
3. Welding parameters play a significant role for perfectly joining a similar or dissimilar weld. Through this study, it has been concluded that the rotational speed will be the supreme welding parameter which possess the capability to change microstructure grains and mechanical strength. Welding speed also has a major role with different tool pin profile and tool tilt angle.
4. Many investigations have been carried out to compare the FSW and other arc welding processes and therefore it is considered to show the conclusion of various researcher in the prescribed format. Due to adequate heat supply during welding, the microstructural and mechanical properties are superior in FSW joints.
5. FSW is not only limited to aluminium alloys. Friction welding can also be applied to weld the stainless steel material and copper alloys. Through case studies, it is clear that dissimilar joint of aluminium with copper and steel can be frictionally welded.

ACKNOWLEDGEMENT

This work was supported by the AKGEC, Ghaziabad, Uttar Pradesh.

DECLARATION OF COMPETING INTEREST

None

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