Effect of Welding Parameters on Mechanical Properties of Friction Stir Welding of Dissimilar Metals- A Review

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Abstract. This review article summarizes the extensive research works carried out on welding parameters (tool rotational speed, traverse speed, pin profile, axial force and tilt angle) effect on mechanical properties of FSW of dissimilar alloys. Extensive studies were being carried out by joining different materials using friction stir welding for different automobile and aerospace applications. FSW process takes place in the solid stage below the melting point of the metals to be joined and numerous materials including, aluminum, bronze, copper, titanium, steel, magnesium, and plastic can be welded. FS welded joints gives more strength and toughness when compared to fusion welded joints. FS welding technique is being used in many research institutes and production companies in the world.

Keywords: Friction stir welding, tool rotational speed, traverse speed, tilt angle, axial force, mechanical properties.

1. Introduction

The Welding Institute (TWI), England, U.K. developed FSW process which is used for joining lightweight materials [1]. FSW is a novel process to weld numerous metals and alloys in solid state condition providing good mechanical properties when compared to the welds formed by fusion processes. The properties of the FS welded samples depend upon the parameters like tool rotational speed, traverse speed and geometric conditions of tool. [2, 3]. A conventional NC operated friction stir welding machine (FSW-3T-NC) used for FSW process is shown in Figure 1.

Figure 1: Friction stir welding machine.
Process parameters are to be examined critically since they are key factors for optimizing the process [4]. Material mixing, weld integrity and mechanical behaviour are influenced by the welding process parameters [5]. Plasticization and the material flow in FSW is controlled by the mechanical properties of base material underneath the action of rotating tool [6]. The molten material movement is determined by the probe design which also amends weld strength and characteristics. Tool design plays a key role in gaining weld strength and in tool geometry optimization [7]. AA1xxx metal matrix composite and the AA6xxx alloy were welded using FSW and the effect of FS weld parameters on the strength and properties of the welded joints were investigated [8]. Higher hardness is obtained than that of base materials in the investigation of FS welding of AA6xxx and AA5xxx alloys. The material flow which decides the strength of the dissimilar joints is directed by the pin profile of the tool [9]. FSW of heat treatable AA7xxx and AA6xxx alloys was done and had been found that material mixing and mechanical behaviour are influenced by the process parameters [5]. 2xxx and 6xxx alloys were joined using FSW in similar and dissimilar combinations. Results showed that fracture took place in the partially deformed zone of alloy 6xxx side where the sudden drop in hardness was observed. This occurred due to localized plasticity on the partially deformed zone of 6xxx, which took place due to joining of two dissimilar material with large strength mismatch [10]. AA 1xxx plates were joined using single and double pass friction stir welding. Highest hardness is seen in double pass bottom flat plates due to fine grain refinement which is improved by thickness ratio of plate and rotational speed [11]. Aluminium alloys AA5xxx and AA7xxx were fabricated by FSW and it was observed that parameters like plunge depth of the tool, rotational speed, weld traverse speed and D/d ratio influence the ultimate tensile strength [12]. Highest strength of the welds was obtained at 6000 rpm, 45 mm/min, 11kN and 1.5° using two tungsten-based tools in FS butt welding of AISI 316 L stainless steel plates [13]. Double-sided FSW was done with aluminium alloy plate under various rotational and welding speeds. High quality joints are formed with a steady flow of plastic material at a constant welding speed and lower rotational rate [14]. Increase in rotation and travel speeds in a constant proportion leads to higher tensile strength and ductility of the welded joints. The weld material exhibits higher strength than ductile base materials at the Mg/Al interface due to the presence of intermetallic compounds [15]. The joint strength will be low if the material flow is not good and liquidation is high which occurs due to more heat generation through increased rotational and traverse speeds [16]. Rolled AA7075 aluminium plates of 12mm thickness were friction stir welded and it is found that higher fracture toughness properties are observed for the welded joints treated with solutionizing followed by artificial aging cycle [17]. Decrease in fracture toughness is observed in friction stir welded TA5 titanium alloy due to the crack propagation related to microstructure and texture of the joint [18]. Increase in fracture toughness is observed with decrease in input of heat and speed of the spindle in FS welded API X80 [19]. Table 1 exhibits the result of strength of FS welded joints effected by different welding parameters.

2. Applications of Dissimilar friction stir welding

Current applications involve use of different types of material based on its functional performance. Industries like marine, aerospace, and transportation which requires high strength lightweight structures can be benefited from dissimilar FSW. Design of aerospace and ship structures can be flexibly designed by FSW of dissimilar high strength and corrosion resistant alloys [20][4]. Many constructions need for joining of dissimilar materials and clad material. FSW has good possibility for joining dissimilar aluminium alloys [21]. Aerospace industry uses FS welded high strength Al alloys as large tanks for satellite launch vehicles. Light alloy wheels and fuel tanks of high volume production in automotive industry uses FSW [22]. Modern Trent aero engines that drive Airbus A380 and the Boeing 787 uses friction stir welding [23]. The body of airplane is 20% of the aluminium alloy and AA2024, AA6061 and AA7075 are three dissimilar aluminium alloys which are commonly used in aerospace applications [24].
3. Effect of welding parameters on mechanical properties of friction stir welded joints

3.1. Effect of tool rotational speed
Rotational speed of the tool is a key weld process variable because it tends to influence the translational velocity [25]. It is observed that mixed flow region in FS welded AA5xxx-H111 and AA6xxx-T6 joints is affected by rotational speed and traverse speed. Uniform hardness disparity across the joint through metal plastic flow and mixing of base material alloys gives higher strength to the weld joint [26]. Tensile strength increases at rotational speed of 800 to 100rpm and with constant weld traverse speed of 120mm/min in FS welded AA5052-O alloy plates and the strength of the weld decreases as the rotational speed is increased from 1000 to 3000rpm [27]. Higher rotational speeds with a constant weld traverse speed generates heat input rapidly. Cavities are formed due to the turbulence flow caused by fluidity of the metal because of excess heat input. [28]. Higher rotational and traverse speeds will leads to defected weld joints because of lesser metal flow and higher liquation [29]. Higher rotational speeds with lower weld traverse speeds will lead to excessive heat generation which caused the weld metal to melt [16]. The rotation of the tool in counter clockwise direction was not able to produce a defect free and complete joint [30]. Higher rotational speed up to a certain value will improves impact energy of the welded joints and further increase will cause the strength to decrease as the heat generation causes grain refinement at weld zone [31]. The tensile strength (TS) of the FS welded joints depends upon the tool rotational speed [32]. 5083-H116 aluminium alloy and HSLA-65 steel sheets were butt welded and observed that the lesser rotational speed with high weld traverse speed lead to poor material flow around the rotating pin and contributed to lack of fill void formation [33]. Different pin profiles and rotational speeds were used to FS weld the IS:65032 Al alloys. Higher tensile properties are obtained for the joints fabricated at 1300 rpm than the joints produced with other rotational speeds, without the concernment of weld traverse speed and pin profile [34]. Rotational speed with other parameters like pin profile, weld traverse speed and tilt angle are considered as insignificant in case of FS welded AA5454 and AA7075 alloys [12]. Tensile strength which exhibits variation through weld traverse speeds and rotational speeds seems to be related to the energy of the welded joints found in the investigation of EN AW-2024 T351 aluminium alloy welded joints [35]. Increasing the rotational speed leads to improvement of tensile and impact energies. Higher rotational speed and low feed rate leads to rapid solidification of the grains because of rapid generation of heat in FSW of AZ31B Mg alloys [36]. FSW on the dissimilar AA5058 alloy and polycarbonate (PC) sheets had been investigated and found that tool's rotational speed mainly controls the joint strength and the fracture mode [37]. Insufficient heat and inadequate material flow and mixing is caused due to departing of tool quickly which is occurred through low heat generation caused by Low tool rotation and higher feed rate [38]. Rotation of the tool generates the frictional heat due to stirring effect and allows the base materials to mix and plasticized. Tool spindle speed effects the material deformation rates of tool shoulder and pin [39]. When the rotational speed of the tool was increased, the generated heat was higher and excess material flush was noticed along with deposition of some base material to the FSW tool shoulder and cavities formation can be seen in the weld zone of the joints [40][41].

3.2. Effect of tool traverse speed
The traverse speed shows more impact on efficient strength of f FS welded AA8011 alloy components. Substantial increase in traverse speed leads to good quality welded joint with excellent joint properties [25]. Generation of heat, joining of materials and straining amount in FSW are influenced by the tool traverse speed [42]. Plastic flow region development is influenced by the welding speed and mixed flow region is not appeared in the welded joints fabricated at highest and lowest weld traverse speeds [43]. Welded joints with good mechanical and microstructural properties can be produced with low traverse speed high heat treating effect [44]. Better joining of the metals with less material straining condition is obtained with weld traverse speeds at low rate and generation of heat due to the friction and distortion was high and vice versa [42]. The welding parameters, in
particular the welding speed, have a great influence in the type of material flow that is produced [45]. Weak joints are formed due to generation of less heat at low rotational speed to weld traverse speed ratio, and increases as it results in less material flow [46]. With increasing the tool traverse speed, cross sectional defects like steel large fragments are caused which leads to lower tensile strength. Further increase of traverse speed leads to tunnel and voids kind of defects which gives less tensile strength [30]. More feed rate in FSW causes poor material flow resulting in a deep groove at the joint of lower strength [40]. Tensile strength is improved to a maximum value with high weld traverse speed and will be decreased with further increase in weld speed as the frictional heat generation is increased and decreased respectively. Voids in the joints are presented because of insufficiency in heat and less material flow in weld areas with short exposure period with higher weld traverse speeds [47]. Intermetallic compounds layer thickness will be reduced through shortening of high temperature period which occurs through high weld traverse speed [48]. AA6061 and AA7075 aluminium alloy plates are joined successfully in butt position using friction stir welding technique with two stir pins which have different geometry (cylindrical and triangular). Tensile strength linearly increased with increasing traverse speed [49]. Decrease in downward force (Fz) and increase in longitudinal force (Fx) is attained with increase in tool rotational speed which does not affect transverse force (Fy) [27]. Strong joining of the materials can be obtained due to the metal flow from rear side to front side of the tool pin as the pin eliminates the metal surface caused by the tool rotation [42].

3.3. Effect of tool pin profile

Tools used in FSW with different pin profiles are shown in Figure 2. Weld joint strength and characteristics are varied by tool pin design which controls the movement of the liquified material. Tool design in FSW is significant as it helps in improving the strength of the welded joints. FSW tool consists of body, shoulder and pin (probe) and tool design also optimizes the geometry of the tool [45]. FSW tools with different pin profiles are used to weld AA5xxx-H111 and AA6xxx-T6 alloys and highest tensile strength of 273MPa is obtained at 950rpm with tool which has straight square pin tool due to mixing of alloys and high plastic flow which leads to homogeneous disparity of hardness along the joint [43]. Al–Mg–Cr–Mn (AA 5052-O) alloy was FS welded and was found to be defect free having good tensile strength produced by using a straight cylinder profiled tool. Stirring and mixing of material and increasing its temperature around the rotating tool pin is affected by the tool rotational speed [27]. J. Guo mentioned that the microstructural evolution and the material flow during welding were complex and mainly dependent on the tool geometry and the process parameters [8][50][2]. Sadeesh P et al. found that maximum tensile strength and defect free welds were obtained for the joint formed with cylindrical threaded and squared pin out of the profiles used (cylindrical threaded pin, straight cylindrical pin, taper pin, straight squared pin and straight stepped pin) [51]. Higher temperatures were produced with conical probe with three grooves and uniform material mixing in the weld zone is occurred with square frustrum tool pin in welded joints of 6xxx and 7xxx alloys. Generation of heat in FSW is influenced and affected by the tool pin profile and geometry which produces good material flow [52].

![Figure 2: Tools with different pin profiles](image-url)
3.4. Effect of axial force
Axial force plays a key part in FSW of dissimilar alloys as mentioned by Ramamoorthi et al. As the tool pin rotates and moves the plasticised metal towards retreating side, the tool shoulder pressure affects the tool pin penetration leading to good material flow. So, as the axial flow increases, the strength of weld increases and decreases with further increase in the force [53]. Gerbson de et al. mentioned that the production of flash can occur with high axial force, as this improves the heat input and allows the formation of a larger amount of plasticized material, and because of the instability of the application of axial force [54]. Application of axial force leads to plasticization and flow of the material with appropriate temperature which in turn produces good and defect free welded joints as mentioned by R. Srinivasan et al [55]. Axial force applied and tool pin movement and direction influences the flow of material which experiences the plastic deformation [56].

3.5. Effect of tilt angle:
The tool tilt angle is significant in dipping the tool pin with appropriate depth into the materials to be joined improving the devolution of the plastically deformed material by producing the sufficient heat required [57]. Tool should be tilted to enable a gradual increase of forging pressure [56]. The tool tilt angle also influences the surface appearance of the weld [58]. Shallow plunge depths produced due to large tilt angles reduce the contact area between tool shoulder and base materials so that the plasticized material cannot be transferred effectively from front to rear side of the tool with less heat generation leading to decrease in the weld strength and defective welds [59][60].

3.6. Effect of welding parameters on microstructure
Different microstructural zones are formed in FSW because of its asymmetric nature [56]. The different zones are heat affected zone (HAZ), thermo-mechanically effected zone and nugget zone or weld zone which is shown in Figure 3.

![Figure 3: Zones in friction stir welding.](image)

The stirring action of the FSW has produced a fine recrystallized structure at the stir zone. Homogeneous distributions of the fine grains are found at the stir zone. The intermetallic compounds which are appeared in the weld zone significantly influence the weld joint strength [61]. The equiaxed grain structure in the weld nugget zone is depicted in Figure 4.
Sevvel et al have found that, the solidification of the weld zone was occurred rapidly due to higher rotational speed and low feed rate during welding of AZ31B-Mg plates. This rapid solidification leads to strengthening of weldments without defects [36]. Umasankar Das et al. welded AA6101 and AA6351 plates and stated that too much rise in the rotational speed declines the impact energy because of the high produced heat and grain refinement at the weld zone [31].

Table 1: welding parameters effect on strength of FSW joints

| S.No | Authors and year | Material used                          | Inference                                                                                                                                  | References |
|------|-----------------|----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|------------|
| 1    | Peng chen et al. (2021) | 2195-T8 Al-Li alloy                   | Grain refinement strengthening is decreased with increase intoil rotational speed.                                                             | [62]       |
| 2    | Yadong Zhao et al. (2021) | 1060 aluminum/AZ31B magnesium          | An increase in the overlap ratio from 50 % to 75 % caused the maximum tensile shear force of the joint at 70mm/min tool traverse speed and 1500rpm tool rotational speed. | [63]       |
| 3    | M. Sucharitha et al. (2021) | AZ31 magnesium alloy                   | Tool rotational speeds of 1120rpm and 900rpm produces welded joints with higher tensile strength and hardness.                              | [64]       |
| 4    | Devender kumar et al. (2020) | AA6061/SiC Aluminum Matrix Composite    | Tilt angle of the significantly influences the tensile strength of the weld joint besides tool rotational and travers speeds                  | [65]       |
| 5    | S. Dharmalingam et al. (2020) | AA7475-AA8011                          | Defect free welded joints are attained at higher rotational and traverse speeds.                                                              | [66]       |
| 6    | D. Wu et al. (2020)       | Al-Cu aluminium alloys                 | Sound weld joint is obtained by adjustable-gap bobbin tool pin and tool traverse speed of 120-240mm/min.                                    | [67]       |
Tool pin profile with triangular pin produces the best metallurgical and mechanical weld properties among the other pin profiles used in FSW.

The material flow and heat input in FSW of materials with different yield strengths is influenced by tool pin profile.

Lower lap-shear failure loads were occurred with decrease in the width of the weld nugget zone resulted through higher tool rotational speeds.

The tool tilt angle significantly effects the weld stir zone volume, increase in temperature and development of shear band in the weld zone.

Wormhole defect on the advancing side can be avoided by the tool tilt angle which improves the material flow.

Good microstructural and mechanical properties were obtained in the welded joints produced with an axial force of 5kN.

4. Conclusion:
In this review, mainly the influences of welding conditions on mechanical properties have been investigated. Major conclusions drawn includes as follows.

1. The tool rotational speed has a significant effect on tensile strength of the FS welded joints.
2. Excess material liquation and less material flow gives low strength welded joints.
3. Formation of plastic flow region is affected by traverse speed and welded joints produced at lowest and highest tool traverse speeds does not show the mixed flow region.
4. Strength of the weld, movement of molten metal were altered and determined by the tool pin design.
5. The tool pin plunge depth into the base material during welding is achieved through applied axial force which influences the temperature and quantity of plasticised metal during FS welding.
6. Defective welds are produced due to large tilt angles which reduces the generation of heat and movement of metal flow.
7. The microstructural zones in friction stir welding are weld zone, heat affected zone and thermo-mechanically affected zone.
8. The strength of the FS weld is also affected by the microstructure which is affected and altered by rotational speed.
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