Review on Effect of Process Parameters - Friction Stir Welding Process

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Abstract - *The friction stir welding (FSW) process is a recent solid-state joining process to produce the permanent joint of two dissimilar metals. In this paper, the study of experimental the effects of tool rotation speed and welding speed on the tensile strength, Microstructure, Micro hardness properties during friction stir welding process. From the literature, it is understood that tool rotation speed and welding speed play an important role on the mechanical properties and weld quality. Important results reported by various authors are critically reviewed.*

Key Words: Friction Stir Welding, mechanical properties, weld quality, tool rotation speed, axial force and welding speed.

1.INTRODUCTION

Friction stir welding (FSW) is a solid state joining technique invented by The Welding Institute (TWI), Cambridge, UK, in 1991. The FSW process uses a, non-consumable cylindrical tool consisting of a shoulder, and a smaller diameter profiled pin, protruding from the tool shoulder. The rotating tool is slowly plunged into rigidly clamped work pieces. The shoulder makes intimate contact with the work piece surfaces. The pin is completely embedded within the through-thickness of the work pieces. However, it does not touch the bottom of the work pieces [1, 2].

It is observed from literature that friction stir welding is more advantageous such as good weld appearance, improve strength, ductility, resistance to corrosion, fine grain structure and welded surface as compare to other welding techniques. FSW machine consist of non-consumable rotating tool with probe or pin which is forced down into the joint line where the frictional heating is sufficient to raise the temperature of the material to the range where it is plastically deformed. Tool rotational speed, welding speed and tilt angle are the important influencing process parameters on tensile strength and hardness. The traversing force and side force are not considered as process parameters and only used for monitoring the process. Friction stir welding parameters have been selected based on acceptable mechanical, micro structural, fatigue and corrosion properties requirement to obtain efficient, defect free friction stir welded joints.

2. Historical Development of Friction Stir Welding

The friction stir welding (FSW) process was invented in 1991 by The Welding Institute (TWI) at Cambridge, in United Kingdom. It was further developed and was got patented by the Welding Institute. The first built and commercially available friction stir welding machines were produced by ESAB1 Welding and Cutting Products at their equipment manufacturing plant in Laxa, Sweden. The development of this process was a significant change from the conventional rotary motion and linear reciprocating friction welding processes. It provided a great deal of flexibility within the friction welding process group [1].

Since 1995 in Europe, Friction Stir Welding has been used in production applications. The first applications involved welding of extrusions to form paneling for marine applications. Since then, the process has been commercialized in many other applications, including rail car, automotive, aerospace, heavy truck, medical applications, etc. Today, the process is being transitioned into fabrication of complex assemblies, yielding significant quality and cost improvements. As the process is maturing, designers are taking advantage of the process, by designing the product specifically for the FSW process. The Friction Stir Welding is apparently quite new welding process as shown in Figure 1 and is a good process for particularly welding aluminum parts. The conventional rotary friction welding process requires at least one of the parts being joined to be rotated and has the practical limitation of joining regular shaped components, preferably circular in cross-section and limited in their length. Short tubes or round bars of the same diameter are a good example.

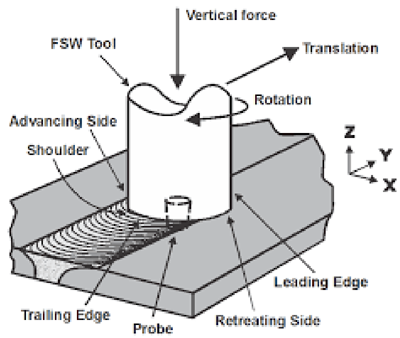


Figure 1: Mechanism of Friction Stir Welding

3. WORKING PRINCIPLE

3.1 Principle of Operation

In Friction Stir Welding, a cylindrical shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. The parts have to be firmly clamped onto the worktable in a manner that prevents the joint faces from being forced apart. Frictional heat is generated between the wear resistant welding tool and the material of the work piece as shown in Fig. 2 (b). This heat causes the latter to soften without reaching the melting point and allows passing of the tool along the weld line as shown in Fig. 2 (c). The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the two pieces [3].

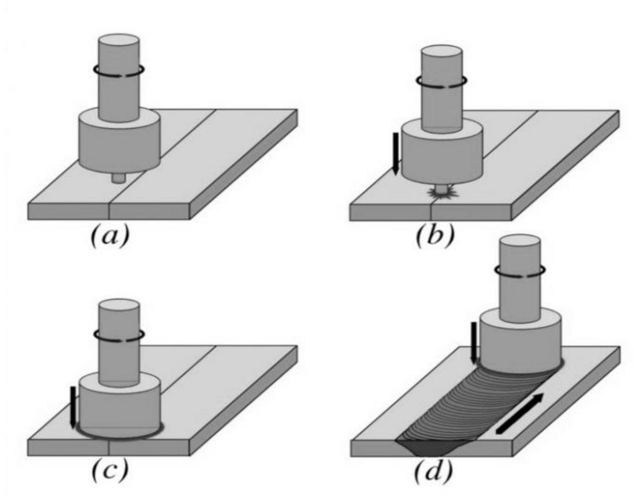
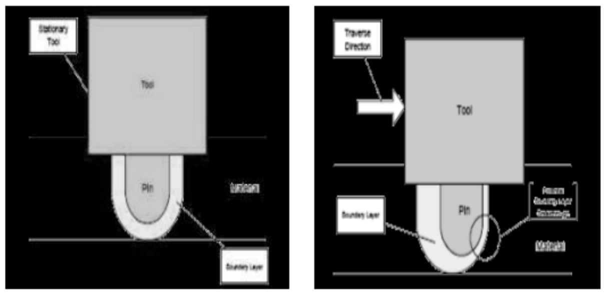


Figure 2: FSW Working Processes: (a)Starting position, (b). Start of joining, (c). Insert joining tool and (d). Joining [3,5]

3.2 Tool Rotation and Traverse Speeds

There are two tool speeds to be considered in friction-stir welding; how fast the tool rotates and how quickly it traverses the interface. These two parameters have considerable importance and must be chosen with care to ensure a successful and efficient welding cycle [4]. The relationship between the welding speeds and the heat input during welding is complex but, in general, it can be said that increasing the rotation speed or decreasing the traverse speed will result in a hotter weld as shown in Figs. 3 (a) and 3 (b).

Another end of the scale excessively high heat input may be detrimental to the final properties of the weld. Theoretically, this could even result in defects due to the liquation of low-melting-point phases (similar to liquation cracking in fusion welds). These competing demands lead onto the concept of a processing window: the range of processing parameters that will produce a good quality weld. Within this window the resulting weld will have a sufficiently high heat input to ensure adequate material plasticity but not so high that the weld properties are excessively reduced [4,5].



(a) (b)

Figure 3: (a) Tool Rotation and (b) Transverse Speed [4]

3.3 Tool Tilt and Plunge Depth

The plunge depth is defined as the depth of the lowest point of the shoulder below the surface of the welded plate and has been found to be a critical parameter for ensuring weld quality. Plunging the shoulder below the plate surface increases the pressure below the tool and helps ensure adequate forging of the material at the rear of the tool. Tilting the tool by 2-4 degrees, such that the rear of the tool is lower than the front, has been found to assist this forging process. The plunge depth needs to be correctly set, both to ensure the necessary downward pressure is achieved and to ensure that the tool fully penetrates the weld. Given the high loads required the welding machine may deflect and so reduce the plunge depth compared to the nominal setting, which may result in flaws in the weld. On the other hand, an excessive plunge depth may result in the pin rubbing on the backing plate surface or a significant under match of the weld thickness compared to the base material. Variable load welders have been developed to automatically compensate for changes in the tool displacement while The Welding Institute (TWI) has demonstrated a roller system that maintains the tool position above the weld plate [6].

3.4 Advantages and Disadvantages

The solid-state nature of FSW immediately leads to several advantages over fusion welding methods since any problems associated with cooling from the liquid phase is immediately avoided. Problem such as porosity, salute redistribution, solidification cracking is not a problem during FSW.

Advantages:

- Good mechanical properties in the as welded condition

- we could weld metal without melting it, maintaining its original properties despite the joining process
- we could weld together metals those previously could not be joined
- No consumables - conventional steel tools can weld over 1000m of aluminum and no filler or gas shield is required for aluminum.
- Welding Preparation not usually required
- Low environmental impact (no fumes) and low heat distortion
- No filler wire required

Disadvantages:

- Exit hole left when tool is withdrawn.
- Large down forces required with heavy-duty clamping necessary to hold the plates together.
- Less flexible than manual and arc processes (difficulties with thickness variations and non-linear welds).
- Often slower traverse rate than some fusion welding techniques although this may be offset if fewer welding passes are required.
- Critical tolerances.
- High investment.

4. EFFECT OF TOOL ROTATION SPEED

4.1. Tensile Properties

The tensile properties of the Aluminium alloy joints made with different welding conditions resulted in lowest tensile strength and ductility at lowest spindle speed for a given traverse speed. As the spindle speed increased, both the strength and elongation improved, reaching a maximum before falling again at high rotational speeds. At the optimum spindle speed, for a given traverse speed, the ductility of the nugget zone material was considerably greater than the parent alloy (18-24% compared to ~12%). [7]. In friction stir welding of AA1050 Aluminium alloy, the tensile strength decreased with increasing rotation speed and the elongation increased to a level similar to that for the base material, when the rotation speed was greater than 1000 rpm (Figure 2.1) [8].

The strength decreased with the increase in rotational speed regardless of the feed rate. The increase in strength with the decrease in the rotation speed was most likely to be due to the decrease in grain size at low rotation speed [9]

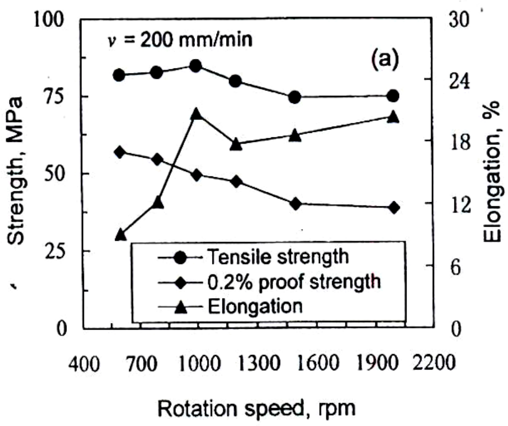


Figure 4. Effect of rotational speed on tensile properties [8]

Cavaliere et al. studied the effect of welding parameters on mechanical properties of AA6056 and found that the highest values of material ductility at the welding speeds of 40 and 56 mm/min and the lowest rotating speed. Ductility was decreased strongly as the rotating and the welding speeds were increased. The very different mechanical behavior of the FSW joints was also demonstrated by the strong variation in grain size and distribution [10].

4.2. Microstructure

Ma et al studied the effect of friction stir processing (FSP) on microstructure of cast A356 Aluminium alloy and found that FSP parameters had a significant effect on the macrostructure of the stirred zone. The lower tool rotation rates (300-500 rpm) produced a basin-shaped nugget with a wide top region. With increasing tool rotation rate, the nugget changes from the basin shape to elliptical. There was a macroscopically visible banded structure. The banded structure is characterized by a low density of coarse Si particles [11]. Increasing the tool rotation rate or the tool rotation-rate/traverse-speed ratio resulted in increasing the grain size in the processed zone. It indicated that the high tool rotation rate breaks up the Si particles and improved material mixing.

Jariyaboon et al reported that rotation speed affected the grain size in the nugget region of friction stir welded AA2024–T351. At a fixed travel speed, an increase in rotation speed increased the grain size due to the higher heat input. At fixed travel speed, a higher rotation speed created more fragmented particles while at fixed rotation speed, the travel speed had little or no influence on the fragmentation of particles [12].

The rotational speed appears to be the most significant process variable since it also tends to influence the translational velocity. This was due in part to a slightly elevated temperature difference at 800 rpm in contrast to

400 rpm tool rotation speed, which promoted grain growth [13].

The variation in appearance and volume fraction of the second phase particles of AA7010 alloy were investigated by Hassan et al (2002). As the rotational speed increased, the temperature within the nugget became higher and more uniform, as a result the volume fraction of coarse second phase particles decreased at different positions within the nugget zone region [14].

Grain growth drastically occurred at recrystallization temperature (> 0.5Tm, Tm being the absolute melting temperature) so that the grain growth in AA1050 alloy stir zone was promoted by an increase in process temperature or a decrease in cooling rate. The process temperature increased with increasing rotation speed of the welding tool [15].
Attallah et al (2004) evaluated mechanical and micro structural properties of friction stir welded AA2095 Aluminium alloy. They opined that weld nugget grain size depends on the welding parameters, where the grain size was found to increase with the increase of the tool rotation speed, since the heat input increased [16].

Won Bae Lee et al observed that the temperature of the stir zone in friction stir welded AA6005 alloys ranges from 458 °C to 480°C. These temperatures were sufficient to completely dissolve all precipitates and the cooling rate was sufficiently rapid to retain alloying elements in saturated solid solution. Precipitates were not observed in the stir zone, as a result of dissolution [17].

Scialpi et al analyzed the microstructural features of friction stir welded AA 6082-T6 Aluminium alloy and observed noticeable microstructure changes. Micrographs revealed that deformation in the TMAZ resulted in severe bending of grain structure. In this zone grain shape and dimensions evolution was quite evident [18].

Ying Chun Chen et al investigated friction stir welding of AA2219 Aluminium alloy and found that the metastable precipitates were dissolved and solutionized in the Aluminium matrix during FSW, but the stable precipitates were remained and prone to segregate in the high-strain region, thus resulting in visible bands of high and low particle density. Such visible bands form so-called "onion ring"- like morphology in the 2219-T6 weld. However, for 2219-O base metal, the precipitates exist in the form of stable state, and the number was large. So, large numbers of particles conceal the feature of the "onion ring"-like morphology in the 2219-O weld [13] .

Rodriguez et al (2005) studied the effect of FSW on commercial cast aluminum alloys A319 & A413 and found that the micro-dendritic cell structure of A319 was completely altered in the remixed FSW zone. Si plates and needles of A413 were largely broken and redistributed in the FSW zone. There is no apparent weld zone degradation [20].

4.3. Micro hardness

The hardness of the friction stir welded AA5083 stir zone decreased with increasing rotation speed. The increase in grain size led to the lower hardness value of the stir zone that was produced at the higher rotation speed [15].

Won Bae Lee et al investigated the FSW joints of AA6061 Aluminium alloy and they observed that the hardness of the stir zone increased with the tool rotation speed. A higher tool rotation speed resulted in the lower cooling rate because stir zone reached a higher temperature [17].

In friction stir welded AA7010 Aluminium alloy, when the spindle speed was increased, the hardness levels at the base of the weld increased more rapidly than at the top, so that the hardness values converge at high spindle speeds [7].

FSW joints of AA2024 Aluminium alloy had nearly constant hardness values within the nugget region and very low on the retreating side than on the advancing side. The minima were located at transverse locations that were approximately on a line drawn from the shoulder radius on the crown to the pin radius at the root of the weld [20].

The hardness profile in the age harden Aluminium alloy AA6063 strongly depended on precipitate distributions rather than on grain size. The minimum hardness region contained only a low density of rod-shaped precipitates, which led to the minimum hardness in that region accompanied by a loss of solute from the matrix. No precipitates could be detected in the softened regions because of dissolution of all precipitates during welding [15].

Friction stir welded AA 2024 joints exhibited a W-shaped hardness distribution that is characteristic of friction stir welds in precipitation hardening aluminum alloys, the weld nugget was significantly harder than the thermos-mechanically affected region immediately outside the nugget boundary A quite strong local softening of the AA7075 - T6 occurred because of the thermal action of the welding process [16].

In A319, micro hardness values of stir zone were higher than as cast metal. In A356, micro hardness values of stir zone were lower than as cast metal. These results show that the thermos mechanical treatment cycle of the friction stir processing had a hardening effect in A319 and a slight softening effect in A356 [21].

5. EFFECT OF WELDING SPEED

5.1 Tensile properties

As the welding speed increased, the width of the strained region and the value of the maximum strain decreased. The location of the maximum strain gradually moved to the retreating side from the advancing side of the joint (Figure 5). In other words, the fracture location of the joint made by AA1050 Alumiunium alloy gradually changed to the retreating side from the advancing side of the joint as the welding speed was gradually increased. The results described above indicated that the welding speed had a significant effect on the tensile properties and fracture locations of the joints [22].

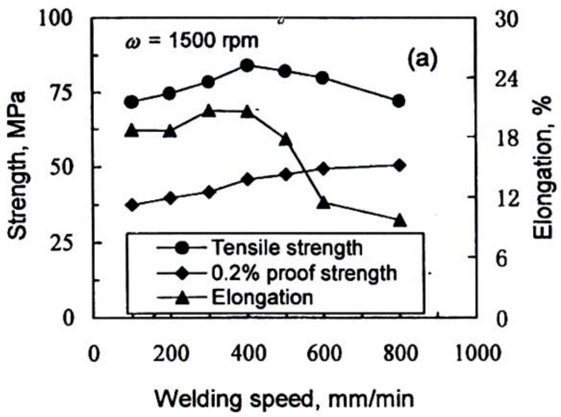


Figure 5 Effect of welding speed on mechanical properties

The ultimate tensile strength of AA5083 Aluminium decreased significantly when the traverse speed was increased. It was found by Peel et al that voids were formed due to poor consolidation of the weld interface when the tool traveled at higher traverse speeds, and hence lower heat inputs [23].

The tensile strength of as welded 6005 Aluminium alloy had a proportional relationship with welding speed (Won Bae Lee et al). Higher welding speeds were associated with low heat inputs, which resulted in faster cooling rates of AA5083 friction stir welded joint [17].

Colligan et al investigated the friction stir welded joints of AA 2519 alloy and the tensile results showed the progression in the transverse weld tensile strength, yield strength and elongation respectively, as a function of travel speed. Welds produced at higher speeds had tensile fractures in the stir zones, although tensile strengths were the highest observed and ductility was also high [24].

The tensile properties and fracture location of the joints were dependent on the micro hardness distributions and the weld defects of the joints. When the welding speed was slower than a certain critical value, the FSW produced defect-free joints. When the welding speed was faster than the critical value, welding defects were produced in the joints [25].

Ren et al studied the effect of welding parameters on tensile properties of friction stir welded Al-Mg-Si alloy and found that the increase in the traverse speed from 100 to 400 mm/min increases significantly the yield and tensile strengths of the FSW joints irrespective of the tool rotation rate [26].

Lee et al studied the friction stir welded A356 alloy and found the transverse tensile strength and yield strength of the friction-stir welded joints show the constant and almost same values in comparison to that of the BM regardless of welding speed. Sound joints were acquired below 187 mm /min welding speed [27].

5.2 Microstructure

The nugget region of friction stir welded AA2024-T35 showed a grain structure on a transverse vertical cross-section that was nearly uniform, with transitions to the base metal microstructure on both the advancing and retreating sides. In all cold, medium and hot welds, the transition was more abrupt on the advancing side of the weld. The mean grain size in the weld nugget decreased with increasing heat input. Based on results, it was inferred that the post welding nugget grain size variation was the result of a complex combination of static and dynamic re-crystallization and recovery processes [20]

Yutaka Sato et al investigated the effect of speed on microstructure and they inferred that the base material had an elongated coarse grain structure, while the stir zones consisted of equated grain structures. Grain size in the stir zone increased with an increase in heat input during FSW [16].

5.3 Micro hardness

Peel et al investigated the friction stir welding of AA5083 alloy and observed significant amount of softened material with the 50% reduced hardness around the weld line [23].

Liu et al observed a softened region occurred in the joints and was located at the weld zone and HAZ, and hence the tensile properties of the joints were lower than those of the base material. There was a minimum hardness zone on the advancing side of each joint and therefore the joint did not fracture on the retreating side but on the advancing side [8]. The result was still a decay of mechanical properties, this situation regards nugget zone, flow arm zone and TMAZ [28].

The fracture localization all-occurring at the HAZ/TMAZ boundary suggested that grain/sub grain structure, crystallographic texture, and precipitate overlaying could have contributed to the observed softening at this location [29].

Lee et al studied the friction stir welded A356 alloy and found that the base metal had a very wide range of hardness (Figure 6). The hardness of the SZ, in case of 87 and 187 mm/min welding speeds, was uniformly distributed and shows less variation. In contrast, the hardness of the SZ of 267 mm/min welding speed showed a very scattered value. The average hardness of the SZ slightly decreased with increasing welding speed [27].

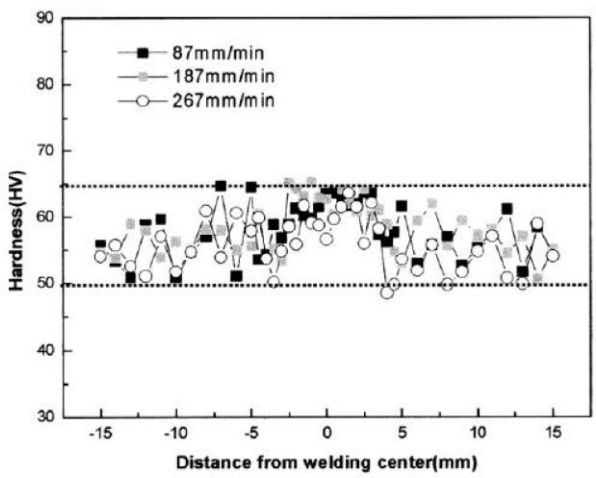


Figure 6. Effect of welding speed on micro-hardness

6. REVIEW SUMMARY

From literature review, it is observed that the friction stir welding process offers many advantages over fusion welding processes for joining Aluminium alloys. However, most of the reported research papers are focusing on FSW of wrought Aluminium alloys. Very few papers are found related to FSW of cast Aluminium alloys. Though this process shows more promise over fusion welding processes to join cast Aluminium alloys, the usefulness of this process is not yet explored by the researchers. Hence, many investigations have been carried out to make a systematic study to understand the effect of FSW process parameters on mechanical and metallurgical properties of cast Al alloys.

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