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A Review on Mechanical and Metallurgical Characterization of Friction Stir Welding Joints

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ABSTRACT

The behaviour of mechanical characteristics of Aluminium, Magnesium, Copper and their alloys, when welded by the friction stir welding (FSW) method, is described in this work. Because of its solid-state nature, the FSW approach differs from conventional fusion welding processes. FSW is now widely utilized since it has numerous applications in a wide range of sectors. In the beginning, this technique was used to combine workpieces made of similar materials. Later, as technology progressed, it was also utilized to weld different metals and alloys together. Because of the widespread usage of this welding technology in industries, a study of the behaviour of mechanical and metallurgical properties is presented in this work. This study also explains the fundamentals of the FSW approach. In addition, this study discusses the various uses of FSW in different applications. Threaded pin profiled tool produced defect free FSP region and showed superior tensile properties in double pass. The micro hardness analysis of the welded specimens shows an increase in micro hardness in the welded region. The joints fabricated by double passes have shown higher ultimate tensile strength as compared to the joints fabricated by single pass and this trend is common for all the tool profiles.

Keywords: Friction stir welding, Mechanical Properties, Hardness, Tensile Properties

INTRODUCTION

Welding enables the fabrication of material portions that would be difficult to shape using other methods. The weldable sections are made separately, and then the parts can be united using appropriate welding procedures. Due to technological advancements, demand for complicated shape products that cannot be created in one unit or are expensive is rapidly increasing. The FSW procedure might be regarded as a significant advancement in welding technology for combining similar or even dissimilar workpieces. Because FSW does not develop the surface imperfections as other fusion welding processes do, it can produce higher-quality welds. Metals and alloys that are difficult to weld can now be easily welded using the FSW process.

The FSW technique was invented recently and is now employed in a variety of production industries, including high-speed trains [1, 2], manufacturing ships [1, 2, 3]. construction [3], and the marine [4, 5] and aerospace industries [6, 7, 8]. In recent years, some variations in this procedure have been developed to increase weld quality. The dual rotation FSW, for example, was developed in which the probe and shoulder rotate independently [9]. This difference in FSW allows for a change in direction or speed between the probe and the shoulder. The twin stir method, in which two tools are utilized on opposite sides of the workpiece, is another modification in FSW. This adjustment allows for a more symmetrical weld, as well as a reduction in the magnitude of the reactive torque, which can be regarded advantages over other friction stir welding processes. Similarly, research is being carried out on spot welding using the FSW technique for various metals and materials. As a result, it is reasonable to conclude that progress in the field of FSW has been rapid. The friction stir welding technology has received almost 2100 patent applications to date [12].

FSW PROCESS

The FSW process for joining materials has seen rapid expansion in recent years all around the world. The Welding Institute in the United Kingdom created the FSW technique in 1991 [13]. Figure 1 depicts the FSW procedure. Friction stir welding is based on a simple notion. Two plates are generally kept together under varied welding circumstances. A non-consumable tool with a pin and shoulder rotates rapidly while also moving along the joint line of workpiece materials. For the FSW process, the choice of tool material and shape is a critical constraint. The tool is spinning at a high rpm, and the tool pin is inserted between the plate joint lines. It generates a lot of friction between the tool shoulder and the workpiece, which causes it to heat up [14]. Plastic deformation of workpieces around the tool occurs as a result of extreme heat. The tool rotates at a high rpm while traveling along with the plates, transferring the plasticized material and combining the plates' materials. Another function of the tool shoulder is to prevent the debarring of plastically deformed material by forcing it downward. The advancing side is the welding side when the welding direction is parallel to the tool's rotational direction, and the retreating side is the welding side where the welding direction is perpendicular to the tool's rotational direction [15]. Due to the combined action of tool rotation and linear tool movement, the plastically deformed material moves from the front to the backside of the tool employed in FSW. Because the workpiece materials were not found in a molten condition during the whole process, the junction created is classified as a solid-state joint in FSW [16, 17]. In the FSW process, there are three separate microstructure zones to consider. Stir zone (SZ), heat affected zone (HAZ), and thermomechanical affected zone (TMAZ) are the names of these three zones, respectively [18]. Various researchers are considering diverse tool forms for various FSW applications around the world. FSW tools with a cylindrical shape are used to weld thin sheets, whereas those with a conical shape are used to weld heavier plates. More sophisticated shaped welding equipment was required for the lap welding application. In the case of lightweight alloys, the FSW process has many advantages over other welding procedures. FSW is widely utilized in the aerospace sector (cryogenic fuel tanks for spacecraft and wings), the marine business (hulls, marine and transport structures), and the construction industry (lightweight materials and pipelines).

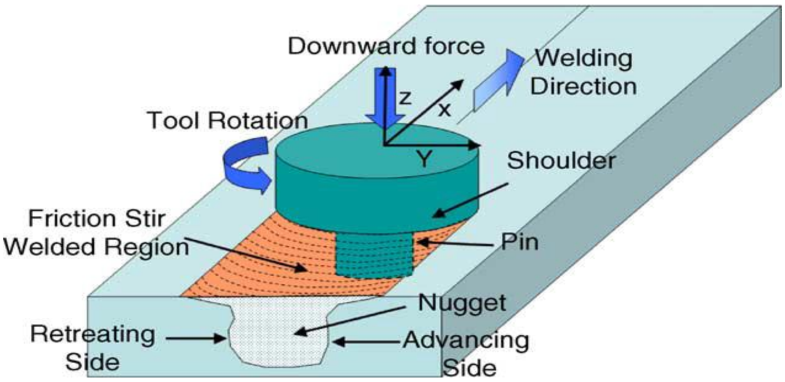

Figure 1 Schematic drawing of Friction Stir Welding [3]

EFFECT OF PROCESS PARAMETER ON FSW

The FSW process is a complicate phenomenon. Tool rotations, tool geometry, join configuration, linear tool speed, and tool pin dept are the primary process parameters that affect the FSW process. The temperature distribution over the tool shape is likewise influenced by these parameters. In the FSW approach, the temperature peak is much lower. In the FSW approach, too geometry plays a significant role. An earlier study by many researchers has shown that the geometry of the FSW tool plays a vital role in the flow of plasticized material from the front to the backside of the tool, as well as directing the linear velocity of the FSW tool [19]. Hattingh et al. [20] investigated the effects of various tool settings on the FSW of Mg alloy, including profile, material, and shoulder size. The visual view of the FSW tool utilized for his inquiry is shown in Fig. 2. According to Weglowski and Pietras [21], the FSW process has two fundamental functions: heating of the workpiece material and flow of the plastically deformed material. The tool pin is plunged in the workpiece material until its shoulder comes into contact with the workpiece's surface. Researchers have also discovered that the friction between the workpiece materials and the tool is the primary source of extreme heat created during FSW. The tool's design and proportions play a significant effect in the heating phenomena. The tool pin's height and depth are other important factors in the FSW process. During the FSW process, the tool shoulder surface is always in contact with the workpiece's surface. The correct tool pin depth can be used to accomplish this condition. It shouldn't be too shallow or deep. If the tool pin depth is too shallow, the tool shoulder may not make contact with the workpiece's surfaces, resulting in less movement of plastically deformed material in the weld pool [22]. The tool shoulder sinks into the parent material when the tool pin depth stays large. When other elements such as the weld tool linear speed, angle, and coefficient of friction are held constant, the maximum temperature and torque values increase with tool rotation speed [23]. In addition, when the tool rotation speed increases, the axial pressure rises as the relative velocity between the tool and the material rises. According to previous study, when the tool's linear welding speed is raised while the other parameters stay constant, the torque increases significantly.

For various welding processes, welding configurations such as butt joint and lap joint are commonly employed. Two independent metal sheets of similar thickness are fitted together and correctly held with each other during the friction stir welding process of the butt joint. The revolving FSW tool is put into and runs along the connecting line of two workpiece plates. It's worth noting that the tool shoulder should make contact with the workpiece plate's surface before producing a weld. Both parent material sheets are overlapped in a lap joint welding setup. After inserting the upper plate, the tool is vertically inserted into the bottom plate, and the FSW tool then runs along the joint line, producing the junction in a lap configuration.

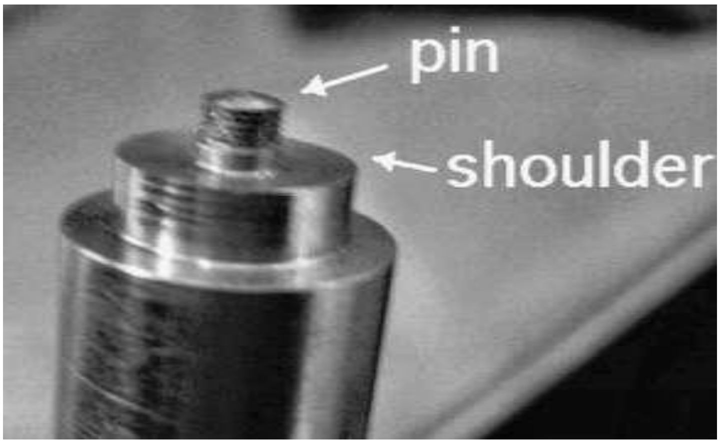

Figure 2. Schematic drawing of the FSW

MECHANICAL PROPERTIES OF FSW JOINT

The mechanical properties of FSW joints depend on the development of microstructure during the welding procedure, and available literature indicates that FSW joints result in significant microstructure progress in the weld pool. As a result, the mechanical characteristics of welds are mostly altered as a result of this. So, different mechanical properties of the parts produced by the FSW technique are reviewed in this paper.

Tensile Properties

Previous research has shown that increasing tool rotating speed or decreasing welding speed increases welding joint strength [24]. The investigation on the FSW of the AZ31BH24 Mg alloy was done by Pareek et al. [25]. They demonstrate that as the rpm of the FSW tool increases, the tensile strength of the weld increases dramatically, but on the other hand, Lim et al. [26] investigate FSW on AZ31B-H24 alloy and according to them, there is no significant changes occur on the tensile strength of welds with changing the rpm of tool used. On the AZ31 Mg alloy, Park et al. [27] study the FSW approach. They used a tool with a rotational speed of 1230 rpm and a linear tool speed of 90 mm min-1 and discovered that the ultimate tensile strength and yield strength were marginally lower. The maximum tensile strength of the weld was attained when the rotating speed of the FSW tool fluctuated between 1240 rpm and 1750 rpm, according to a study done by Nakata et al. [28] with AD91D Magnesium alloy. Padamanabham et al. [29] utilized a variety of tool materials and found that a welded junction with a large diameter FSW tool shoulder of 18 mm and a threaded outline on the tool pin had the highest tensile strength. For their experiments, they used a variety of steel materials, including HSS, high carbon steel, mild steel, and stainless steel.K. Elangovan et al. [30] found that employing square FSW tool pin geometry with a tool rotating speed of 1600 rpm resulted in the highest tensile strength. With a tool speed of 1600 rpm, the welded junction has improved tensile characteristics, regardless of the tool pin profile design. K. Elangovan et al. [31] aim to increase the joint efficiency by investigating the FSW of an AA6061 alloy joint. Different welding conditions have a significant impact on fracture locations and mechanical qualities, according to H. J. Liu et al [32]. They found that the welded joint's UTS is 82 percent, which is equal to workpiece material at 1500 FSW tool rotations per minute and a linear tool speed of 100 mm per minute.K. Elangovan et al. [33] attempt an investigation on three welded joints and shows that the joint fabricated by FSW process have extra strength value and this strength value is 32% to 34%when related to gas metal arc welding technique (GMAW) and approximately 15% when related to gas tungsten arc welding (GTAW) technique. He also discovered that in a gas metal arc welding joint, a low hardness value of 58 VHN was attained, whereas, in an FSW technique, a maximum hardness value of 85 VHN was obtained. When compared to GMAW and GTAW joints, the production of small, uniformly dispersed grains is the major reason for the improved tensile qualities of FSW joints. Chowdhury et al. [34] found that raising the strain rate increases the YS and UTS of the weld. Fujii.et al [35] investigated the process of FSW on three distinct carbon steel alloys with varying percentages of carbon, namely IF steels, S12C, and S35C steel, and discovered that when the tool's linear speed exceeds 200 mm per min, the tensile strength of the weld decreases somewhat. Zhang et al. [36] joined the two different alloy materials i.e., titanium alloy and aluminum alloy by the FSW technique. The results show that if the FSW tool rotates at 1200 revolutions min-1 and the linear speed of the tool is kept within 60 mm min-1, then the welded joints of good quality could be obtainable. The maximum tensile strength of the joint obtained was equal to 265 MPa. P. Xue et al. [37] examined the FSW on aluminum and copper plates having 3mm thickness. The welding of aluminum and copper by normal fusion welding is not easy because of the creation of brittle intermetallic compounds in the heat-affected zone [38]. The larger pin diameter of 8 mm and tool rotational speed of 600 rpm were used. The welding joint failed in the region of the weld pool towards the Al side when a tensile load of 2680 N was applied.

Hardness

In most cases, the magnitude of the hardness of the joints created by welding operations should be higher than the parent material under all conditions. Zhang et al. [39] investigated the FSW of various magnesium alloys and discovered that massive intermetallic compounds are broken down, resulting in a considerable increase in hardness. As a result, the hardness around the weld pool should be higher than the hardness in other weld zones. Xie et al. [40] came to the same conclusion. The effect of varying tool rotating speeds on hardness is shown by Singarapu et al. [41]. Microhardness increases as the value of FSW tool rpm are increased, but its magnitude gradually diminishes. This could be attributed to two factors: I the minor particles of intermetallic compounds are responsible for the increase in hardness; and (ii) the minor particles of intermetallic compounds are responsible for the increase in hardness. (ii) The grain size in the weld pool is smaller than the grain size in the source metal, which has a substantial impact on the tensile strength of the FSW joints. FSW of AM60 alloy was also reported to provide similar results by Esperza et al. [42]. Using FSW tool rpm of 800 and linear weld speed of 100 mm min-1, Xie et al. [43] investigated the FSW method on ZK60 Magnesium alloy and obtained flaw-free weld. They also discovered that the weld pool had a lower hardness value than the parent workpiece material. The heat-affected zone of the weld was where the FSW joint fractured. Sunil et al. [44] used FSW to combine the AZ31 and AZ91 Mg alloys and discovered the hardness variation in the stir zone. It was caused by the coexistence of Mg17Al12 and AZ31 phases. W. Wang et al. [45] investigated FSW on the AZ31 Mg alloy and discovered that the hardness value increased marginally when compared to the base metal. They also discovered that as the tool rotational speed increases, the grain size in the stir zone increases. They also discovered that increasing the value of FSW tool rotation min-1 from 800 to 1200 boosted joint efficiency. Don Hyun Choi et al. [46] used a gas torch as an external heat source to determine the hardness of high carbon steel SK5. A total of two instances were obtained. The hardness of the parent metal is 200 HV. The hardness value in the first case without the use of a gas torch is 850 HV, whereas the hardness value in the second case with the use of a gas torch is 750 HV. The discrepancy in hardness value is due to the weld pool having a distinct martensite structure. Thomas W.M. et al. [47] used the FSW technique on low carbon chromium alloy steel and discovered that the average hardness values in the HAZ and TMAZ areas were 230 HV and 280 HV, respectively, whereas the base material had a hardness value of 158 HV. Fujii H et al. [48] studied the FSW technique on carbon steels with various carbon concentrations, including IF steel, S20C, S50C, S35C, and S12C, as well as the microstructure and mechanical properties of FSW joints. They discovered that at a tool rotation min-1 of 400 and altering tool linear speed, the value of hardness in the weld pool is higher than the parent material. It was also discovered that changing the linear speed of the tool material had no significant effect on the hardness of the welded joints. In the case of carbon steel, however, changing the welding speed has a considerable impact on hardness. They also discovered that when the welding speed is changed, the value of hardness within the weld stir zone remains constant for S12C steel. FSW is also used to attach two separate workpieces. Shojaeefard M.H. et al. [49] used FSW to combine metal sheets of brass and AA5083 Al alloy with a thickness of 2.5 mm. They employed the Taguchi optimization technique to determine the optimum level of process parameters and discovered that tool rotational speed is critical for heat generation. They also discovered the high hardness value in the weld pool's centre. L. Zhou et al. [50] studied the effects of adjusting the tool rotational min-1for the FSW technique of titanium alloy at a tool linear speed of 75 mm min-1on mechanical properties. The hardness value declined as the tool rotational speed increased, and it was found to be lower in the weld stir zone. Similarly, the hardness of a weld nugget is affected by the traverse speed, as H. Liu et al. [51] discovered. They discovered the lowest hardness value in the stir zone because dynamic recrystallization (DRX) was not fully developed in the weld nugget at higher traverse speeds, resulting in a lower hardness value.

CONCLUSION

This article provides a summary of the development of the FSW process in recent years, as well as changes in the mechanical characteristics of the weld as a result of changing the values of various parameters such as tool rotation speed (rpm), tool linear speed (mm min-1) and tool shape selection. The following are some key conclusions:

Because of the small grain development in the weld pool, the parent material's microstructure changed after welding.

The creation of distinct zones such as the weld stir zone (SZ), heat affected zone (HAZ), and thermos-mechanically affected zone (TMAZ) occurs during the FSW process. The microstructural properties of each zone vary. The tool's form is a significant consideration. Other process variables like tool pin depth and spindle angle have an impact on post-weld mechanical qualities.

The quantity of grain refining that occurs in the weld pool has a substantial impact on the variance in hardness value.

FUTURE OUTLOOK

The researchers have mostly used the lap and butt joint design for the FSW process. Other sorts of joint designs should be required to be worked on. The flow of plastically deformed material in the nugget zone is a complicated phenomenon that needs further investigation. The amplitude of residual stresses generated during FSW should be minimized by using different welding parameters, and the weld mechanical characteristics can be improved by heat treatment after the welding process. As a result, researchers should concentrate their efforts on this area.

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