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3rd International Conference on Innovative Academic Studies

September 26-28, 2023 : Konya, Turkey

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Investigation of the Effect of Mixing Direction on the Quality of Friction Stir Welding

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Abstract – Friction stir welding has become more popular compared to traditional welding methods because it allows for the joining of different types of materials in solid form without the need for additional material. With well-optimized welding parameters, it becomes easy and economical to create joints with an excellent microstructure and superior mechanical properties. Welding parameters depend on factors such as the geometry of the pin tool, rotation direction, rotation speed, feed rate, and vertical application force.

In this study, the effect of pin rotation direction on weld quality was investigated based on previous research. The rotation direction and tool geometry of the mixing tool are of primary importance in achieving homogeneous mixing of well-plasticized materials and consistent material flow. In welds created using this method, it is expected that the material will mix homogeneously in the junction area and fill the entire region equally. It was concluded that the direction of the stirring tool rotation is one of the key parameters that significantly influences the formation of weld microstructure and mechanical properties.

Keywords – Friction Stir Welding, Stirring Tool, Tool Rotation Direction, Microstructure, Mechanical Properties

I. INTRODUCTION

By adopting a more holistic approach to the development of the friction welding method, friction stir welding (FSW) has become widely used for joining different types of materials [1].

Traditionally, similar materials are combined by melting them under the influence of heat and pressure, followed by solidification to create an alloy. In these methods, the melted elements are transformed into thermo-mechanically useful shapes by allowing them to mix and form an alloy. However, the high heat exposure and energy consumption both increase costs and have adverse effects on the mechanical and microstructure properties of the materials. Additionally, the use of additional material close in composition to the main material in melting and pressure welding adds extra expenses to both the material and the process. Harmful particles and fumes produced during the melting process are another important consideration for both the environment and human health [2]. Friction stir welding (FSW), which has gained prominence over the past 40 years, is an energy-efficient and environmentally friendly technology. It appeals to a wide range of applications because it operates as a solid-state process, without the use of environmentally harmful materials [3, 4].

The most attractive aspect of FSW, compared to other welding processes, is its capability to weld alloys that are arduous or unfeasible to join using other methods. Since the FSW operates in the solid phase at temperatures lower than the melting point of the material being welded, it eliminates problems related to solidification mechanisms, such as second phases, pores, fragility and cracking. Furthermore, the lower process temperature allows for joints with reduced distortion and lower residual stresses compared to traditional welding methods. FSW is an energy-saving method as it doesn't require filler materials and typically avoids the use of shielding gas powder. Additionally, FSW is environmentally friendly, as it doesn't produce toxic smoke [5], arc flashes, spatter, or waste materials (such as slag and molten burrs) commonly associated with conventional welding methods [6-8].

It is a solid-state welding technique that eliminates the defects associated with traditional melting welding. It achieves this by utilizing the heat generated through the conversion of mechanical energy produced by mechanical friction at the interfaces of the work pieces into thermal energy, all without relying on electrical energy or other external energy sources [2, 9].

Friction stir welding technology; It was invented in 1991 by Wayne Thomas and his team. Its patent belongs to The Welding Institute (TWI) in Cambridge, England. It was first applied to the joining of aluminum alloys [10-12]. In later processes, FSW was used in the joining of high-strength Al-alloys, which are difficult to weld with other methods [6, 13, 14], thermoplastics, as a solid state method. is the welding process. In this new method, frictional pressure and heat are used to obtain error-free connections, Mg-alloys, Cu-alloys, Pb, Ti-alloys, steels [15-17] and thermoplastics, as a solid state method. is the welding process [6]. In addition, studies are carried out on the joining of composite parts such as polymer-polymer and metal-polymer [18].

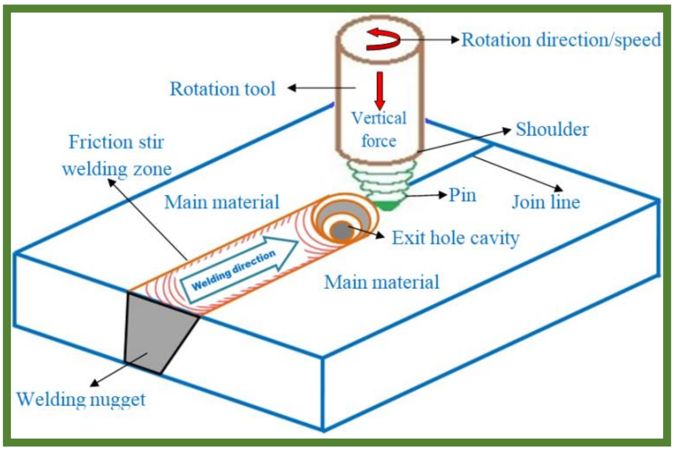

Fig. 1 Schematic of the FSW technique

The fundamental technique of FSW involves a pin tool positioned between the edges of the materials to be welded, rotating throughout the joint line. This specially designed pin tool includes a shoulder area. The heat generated during the mixing of the portion immersed in the material and the compression of the shoulder area is a result of the conversion of both frictional forces and plastic deformation work into heat. Importantly, this rotating tool is non-consumable and resistant to wear and high temperatures [17, 19]. This tool performs two key functions: heating the workpieces held under lateral pressure and moving the material to create the joint. Heating is achieved through friction between the workpiese and the tool, as well as the plastic deformation of the workpiece. This localized heating mellows the material round the pin. By the combined action of the rotation and translation of the tool, the material is moved from the front to the back of the pin. As a result of this stage, the softened materials transfer around themselves, and the plates blend together, forming a "solid-state" connection. Due to the varied geometric properties of the tool, the motion of material around the pin can be pretty complicated [17, 20]. During the FSW application, the material is exposed to intensive plastic deformation at high temperatures, resulting in the formation of thin and equiaxed recrystallized grains [21, 22]. FSP produces improved fine microstructure and superior mechanical properties in a wide variety of alloys [9].

II. MATERIALS AND METHOD

This study aims to elucidate the impact of the rotation direction of the mixing tool on the mechanical and microstructure features of welds in joints created using the FSW method, drawing insights from existing literature.

III. RESULTS AND DISCUSSION

Given that the FSW process lacks a melting and solidification mechanism, the primary determinant for achieving superior joining lies in the flow of plasticized material. One of the most fundamental factors influencing material flow is the geometry of the mixer pin assembly. This includes the geometry of the pin tool, the direction of rotation, and the orientation of the typically helical grooves in the plunge zone of the tool's tip, all of which can impact material flow.

During FSW application, the thermal and plastic behavior of the material flow around the rotating tool is crucial for a whole comprehension of the welding mechanism [23, 24]. In FSW, material flow occurs around the tool in two primary ways. The first involves material being transferred from the onward front side of the tool tip to the side in the direction of rotation as it rotates with the tool. Within the rotation zone, during the thermal interaction of the material at the tool tip, the material undergoes a spiral movement. This movement combines rotation and penetration into the material, followed by rising on the outside of the rotation zone. After these rotations, the material detaches from the tip, particularly on the advancing side, effectively exiting the rotational vortex. The second process involves dragging the material that fills the space between the pieces detached from the advancing side, drawing it from the retreating front side of the tool tip [25]. The joining region where the rotating tool motions in the same direction as the welding progress direction is generally referred to as the "advancing side", and the other region where the tool rotation is opposite to the welding direction is referred to as the "retreating side [26]. With this technique, it is possible to produce connections with minimal or no errors. For this reason, it is preferred in welding different light materials such as magnesium and aluminum, which are difficult to combine with other melting welds. Thanks to these superior features, it attracts great attention in the automotive, aviation and healthcare industries [16, 27]. Mixing tool pin geometries can be customized according to the specific purpose. Tool design is a crucial factor in FSW, and helical slotted pins are a common preference. The direction of material flow is closely tied to both the direction of rotation of the tool and whether the helices are right or left-handed. Figure 2 below illustrates the material transport scenarios in relation to clockwise rotation and the helical shapes of the tool.

Material flow has a great impact on the mechanical properties and microstructure of the welded joint. In the FSW process material flow behavior is of great importance in terms of optimizing process parameters, detecting welding faults, and controlling the mechanical properties and microstructure of joints. [28].

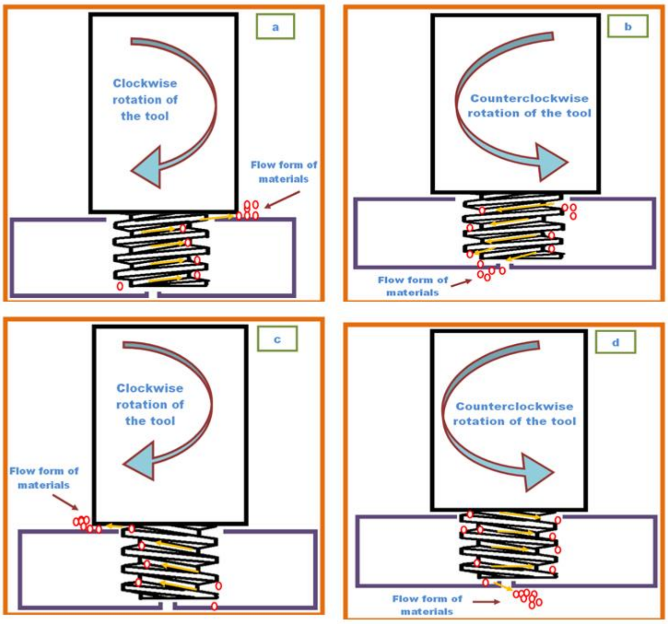

Fig. 2 Material transport based on tool rotation direction and pin helix configuration; a) Tool rotation clockwise with right-helix pin, b) Tool rotation counterclockwise with right-helix pin, c) Tool rotation clockwise with left-helix pin, d) Tool rotation counterclockwise with left-helix pin

The material flow during FSW represents the culmination of a complex mixing process. In this process, the material at the forward front side enters the rotation zone around the pin, undergoing significant plastic deformation in this region. Conversely, on the retreating front side, it is essentially extruded [25, 29, 30].

Throughout the material flow process, a crystallographic texture is established as material is periodically extruded or dragged from the heat-affected zone (HAZ) and the thermo-mechanically affected zone (TMAZ) towards the weld core (WNZ) region. This dynamic occurs with each rotation of the rotating tool positioned at the center of the weld suture [28, 31]. Therewithal, the plastic flow caused by intense slip near the pin surface greatly changes the crystal texture in WNZ [32, 33]. Material flow behavior is significantly affected by the welding parameters [34] and the geometry of the welding apparatus [35]. During the FSW application, the material in front of the welding apparatus undergoes initial heating and plasticization. It is then transferred from the front side to the back side under the influence of the rotating tool. Eventually, this material combines with the materials from the joined parts at the back, forming the weld seam's crystal texture. These two stages involve distinct thermo-mechanical processes, resulting in the acquisition of varying material properties. In the transfer process, the material is subjected to different properties due to the actions of the shoulder and the pin [25, 36]. That is, there are two varieties of material flow mechanisms in friction stir welding; "pin-driven flow" and "shoulder-driven flow". The etching contrast in these material flow regimes enables ring-patterned structures to form in friction stir welds to create a defect-free weld. [36]

As a result of this drive, there are vertical or vortex movements of the ring patterns formed in the rotation area induced by the transportation of the plasticized material. Therefore, material entering this region follows a progressive trajectory created by rotational movement, vortex flow, and translational movement of the aparatus. The material closer to the top of the weld is moved by the influence of the shoulder rather than by the teeth of the apparatus. The interaction between the upper side of the weld line and the regions dominated by moving materials at the bottom differs between welds made with the same apparatus but in a clockwise or counterclockwise direction [25].

- In FSW, lamellar rings are formed by the combined effect of the geometric shape of the pin-driven material flow and the vertical movement of the material due to shoulder interaction. The shoulder driven material is compressed between the advancing side main material and the pin driven material. Thus, the boundaries between the laminated rings formed in the material depending on the geometry of the pin are united [36].

Generally, high-strain hardening occurs in FSW due to the existence of recrystallized grains in the stirred zone (SZ) and TMAZ. This mechanism causes a decrease in both yield strength and tensile strength. The direction of rotation of the mixing tool and the geometry of the plunge pin has different effects on the material flow. Possible faulty material transport may adversely affect the micro-oil and mechanical properties of the welded connection. Process parameters that are not well optimized may not provide homogeneous material transport. Schematic views of possible material flow errors are shown in Figure 3.

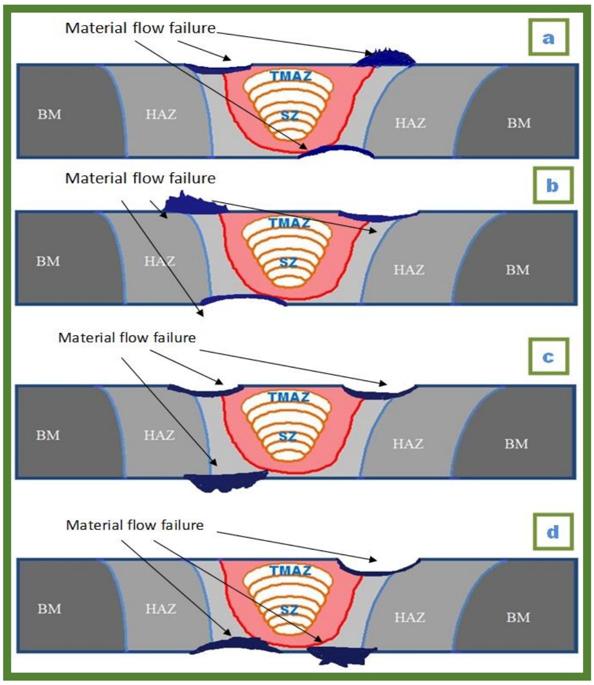

Fig. 3 Material flow errors caused by the rotation direction of the tool; a) Tool rotation clockwise with right-helix pin, b) Tool rotation counterclockwise with right-helix pin, c) Tool rotation clockwise with left-helix pin, d) Tool rotation counterclockwise with left-helix pin

For a welded connection, it is extremely important that the tool rotates at the appropriate speed, the rotating tool advances along the welding line at the appropriate speed, and the shoulder of the rotating tool contacts the welded parts to generate heat [37]. To illustrate, due to appropriate optimized welding parameters, a clockwise rotating left-hand threaded pin tool produces good welded joints and mechanical properties due to downward material flow near the pin surface. But clockwise rotation of the right-hand threaded pin tool produces worse joints because it causes upward material flow. As the stress setting decreases with increasing welding speed, yield and tensile strengths increase. Yield strength, as a function of grain size, increases with decreasing rotation speed, consistent with the Hall-Petch relationship. Both yield and tensile strength increase linearly with increasing welding step (ratio of welding speed to rotation speed). Pit-like ductile fracture mechanisms may occur between the SZ and TMAZ of the base metal. Welded connections made with a clockwise-rotating right-hand threaded pin set show higher yield strength than the left-hand threaded pin set, despite the formation of gap defects near the bottom face [16, 38]. The rotation and transverse direction of the tool affect the residual stress profiles according to the geometric constraints of the component. For example, if the rotation and traverse direction are changed, the stress profile is reflected along the vertical axis, and the maximal tensile stress occurs consistently on the onward side of the tool rotation direction [39].

Basically, when the threaded pin moves downwards with clockwise rotation, the helical groove of the pin also moves downwards. In this rotation state, when the gear profile dives into the material, it presses the material at the channel connection interface since the channel direction and the tool rotation direction are opposite to each other. In this case, the material becomes plastic easily without any material being expelled from the connection interface. In this welded case, the entire joint zone consists of a good plastic structure material without further visible defects such as porosity, air holes and voids [38]. When rotated counterclockwise, materials are pulled upward along the helical groove of the pin in the same direction. However, even though they are compressed by the shoulder, there is still space and other factors in the lower parts of the junction area. As a result, the mechanical properties of the weld are compromised.

IV. CONCLUSION

This study focuses on investigating the impact of stirring direction on the mechanical properties and microstructure of welds produced through the FSW method. FSW is a solid-state welding process used to join materials together, primarily metals. Here's a breakdown of the key points from the study:

The primary objective of the study is to understand how the direction of stirring during the FSW process influences the mechanical properties and microstructure of the resulting weld.

FSW is a welding technique that differs from traditional fusion welding methods like arc welding or gas welding. Instead of melting the materials, FSW uses a rotating tool to generate friction and heat at the joint interface. This heat softens the materials, allowing them to be mechanically mixed together, ultimately forming a strong, solid-state bond.

The study emphasizes the importance of achieving the desired microstructure and mechanical properties in the weld. A homogeneous mixing and joining zone are critical for the weld's quality. This implies that for FSW to be effective, the material needs to be evenly distributed across the joint.

FSW offers the advantage of joining both similar and dissimilar materials, provided that well-designed equipment and optimized welding parameters are used. This versatility makes FSW a valuable welding technique for various applications.

The study seeks to contribute to the understanding of how the direction of stirring in FSW impacts the quality of the weld, with a focus on achieving the desired microstructure and mechanical properties. This research can have implications for optimizing FSW processes and equipment for specific materials and applications, ultimately improving the quality and reliability of welded joints in engineering and manufacturing.

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