Friction Stir Welding and Processing on Aluminium Alloys

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Abstract

This study summarizes the main conclusions from a thorough review of studies on friction stir welding (FSW) of various aluminum alloys. In many applications, joining different materials is frequently a practical solution because it allows the use of more expensive materials only when absolutely necessary. Due to the significant physical and chemical incompatibilities between the materials to be joined, fusion welding, however, poses significant challenges in sectors like shipbuilding, electronics, aerospace, and automotive. Fusion welding can still cause problems like porosity formation, solidification cracking, and chemical reactions when working with dissimilar materials, despite careful design, planning, and control of operational parameters and filler metals. Friction stir welding, in contrast, provides a promising substitute by allowing the joining of various aluminum alloys, ranging from soft to hard, without the disadvantages of fusion welding. Numerous studies and experiments on the welding behavior of aluminum alloy products have been inspired by their growing technological and financial significance in industrial applications. To ensure the best outcomes, these investigations take a variety of factors into account during the welding process. This review aims to increase understanding of FSW of aluminum alloys by conducting an analysis of the existing literature. The results of various studies shed light on how different parameters affect the welding process and final weld quality. To comprehend how they affect weld characteristics and mechanical properties, factors including rotational speed, traverse speed, axial load, tool geometry, and material choice have been studied. The review emphasizes the need for additional research and development to get around these obstacles while also highlighting the difficulties and restrictions encountered in FSW of aluminum alloys.

Keywords— *FSW- Friction stir welding, Tool Material, Tool Geometry, Welding zones, Low-Cost Welding***.**

Introduction

Due to its ability to get around several problems with fusion welding, friction stir welding (FSW) has become a popular method for joining soft materials like aluminum alloys. However, the creation of affordable and robust tools that can reliably produce strong welds is necessary for its commercial viability with harder alloys like steel and titanium. The performance of the tool, the caliber of the welding, and the cost-effectiveness are all significantly influenced by the design and selection of the resource materials [1]. For a variety of materials, including both soft and hard alloys like titanium, different steels, and aluminum, FSW has demonstrated excellent weld quality. In the FSW process, a specially made tool is rotated and slid between two workpieces while the material is heated at the same time. Frictional heat is produced as the tool moves along the joint line, softening the material. As the softened material from both workpieces come into contact, heat and pressure combine to form a strong weld joint. Comparing this solid-state welding method to traditional fusion welding techniques, there are a number of benefits. The lack of a melting phase is one of FSW's main benefits [2]. FSW works in the solid state as opposed to fusion welding, which involves melting and resolidifying the base material. This avoids problems with fusion welding that frequently arise, such as solidification cracking and porosity formation [3]. Fine-tuned microstructures and enhanced mechanical properties in the weld zone are also produced by the solid-state nature of FSW. FSW is also a very adaptable method that can be used on a variety of materials, including softer alloys of aluminum as well as harder metals like steel and titanium [4]. The method is renowned for its ability to join disparate materials with little distortion and without the use of extra consumables like filler wires. This makes it particularly helpful in sectors like aerospace and automotive manufacturing where it is common practice to weld materials that are not compatible. Designing the tool correctly and choosing the right materials are essential for successful FSW [5]. The equipment used for welding must be able to withstand the high temperatures and mechanical strains involved. Due to their high-temperature strength, wear resistance, and chemical stability, ceramics, tungsten-based alloys, and other cutting-edge materials are frequently used to fabricate FSW tools [1][6]. Additionally, to achieve particular welding goals, the tool geometry and configuration are optimized. Heat generation, material flow, and weld quality are influenced by variables like tool shoulder diameter, pin profile, and rotational speed. The durability and effectiveness of FSW tools for difficult alloys like titanium and steel are being improved through intensive research and development efforts to enhance tool design and material selection [7][8][9].

TABLE 01: PHYSICAL PROPERTIES OF ALUMINIUM [18]

Density (g/cm^3)	**2.7**
Melting Point (°C)	660
Tensile Strength (N/mm^2)	150
Electrical Conductivity (10^{6}S/m)	34
Thermal Conductivity (W/m*K)	210
Thermal Expansion (10^{-6}/m)	23.5

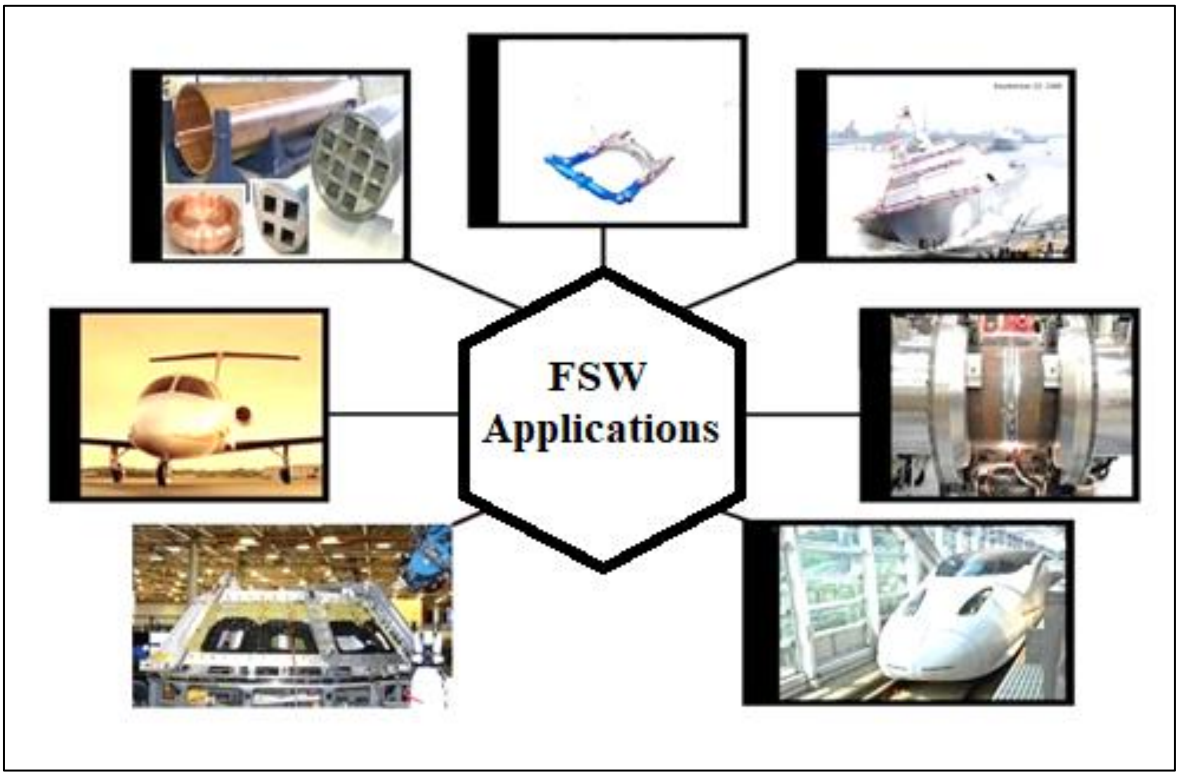

FIGURE 01: INDUSTRIAL APPLICATIONS OF FSW [18]

Friction stir welding has added importance in the flight path, railways, and shipbuilding businesses, particularly production of aluminium alloys, since its invention at TWI in 1991[10]. The technique generates frictional heat in the workpiece using heat resistant tool. A spinning apparatus with a body and a probe is used in this solid-state joining method. In the z-direction, the shoulder put on down force on the workpiece surface. Plunging the probe into the plasticized substance, Friction produces heat and results plastic distortion in a tinny layer beneath the end surface of the shoulder. The revolving probe draws the adjacent material along, plasticizes it, and mixes it in the stir zone, resulting in a frictionless bond [11] [12].

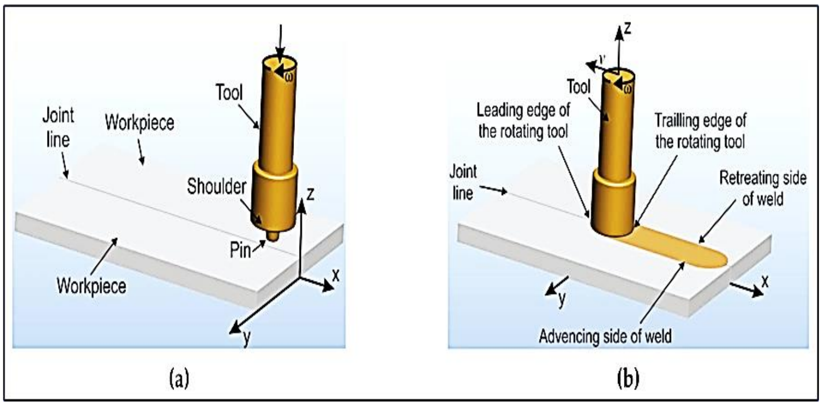

FIGURE 02: PRINCIPLE OF WORKING

Figure 02 shows a working principle of actual friction stirs welding. The tool had crucial part in this method since tool has two basic functions: (a) To heat the plates through friction, and (b) To move the material to make the joint. The friction among tool and workpiece heats the base material, which leads to plastic deformation. Material in contact with the tool's pin is automatically fiery and softened, and material migration from the tool's front to back side is consistent. Due to less energy usage, environment friendly, and versatile in nature, this technique is regarded as most important process advancement in welding of metals from the last era [14]. FSW uses significantly less energy than traditional welding processes. Because no gas or flux is utilized, the method is environmentally beneficial. Because the joining procedure hasn't used any type of filler material, that is major problem with fusion welding. This welding, unlike traditional friction welding, can be employed on different joints as butt, lap, T-butt along with filler joints etc. [13] [15].

This technology is referred as LOW-COST WELDING due to some benefits as below [16]:

- Welding was done utilizing a milling machine's vertical spindle attachment.
- It employs simple, non-consumable, and cost-effective tooling.
- The material can be joined without the use of any filler material or shielding gas.
- Welding requires less energy because the joining material is soft.
- For holding the work piece, no specific purpose or expensive fixture is required.

The following welding zones are noticed during the process, as indicated in figure 03:

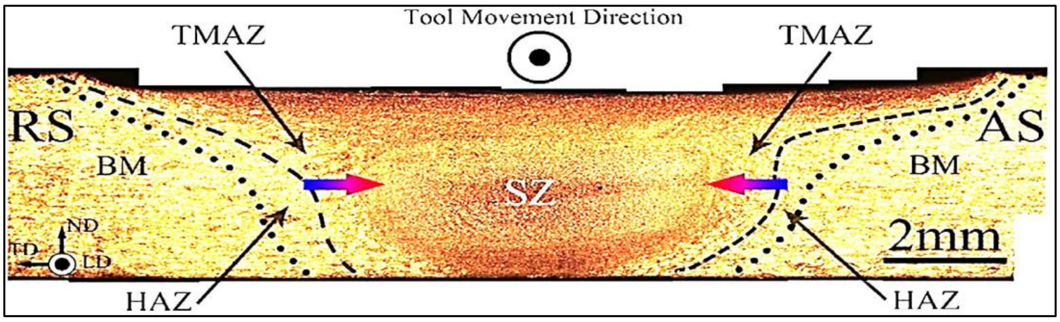

FIGURE 03: WELDING ZONES IN FSW [18]

- The nugget zone (NZ): After the stirred zone cools down, the NZ is created. The place where the two metals are being joined are firmly connected together is a crucial area. An intriguing phenomenon known as "onion rings" can be seen in the nugget zone. These onion rings have a fine grain texture that has undergone recrystallization, which increases the strength of the weld joint [6] [17].
- The heat-affected region (HAZ): During the welding process, HAZ is exposed to a significant amount of heat without experiencing any plastic deformation. A change in the material's properties occurs in this area as a result of the tool's frictional heat on the material's microstructure. The grains, however, are largely unaltered in the HAZ because there is no plastic distortion there [17].

- The thermo-mechanically affected region (TMAZ): A region that experiences significant distortion as a result of welding is known as the TMAZ. There are significant changes to the metal's microstructure in this area as a result of thermal and mechanical effects. Near the stir region, the TMAZ grains elongate and display a distorted pattern. The TMAZ experiences plastic deformation in contrast to the HAZ. Recrystallization does not take place in this region, though, due to insufficient deformation strain [17].
- The base metal (BM): The portion of the workpiece that is unaffected by the welding parameters is referred to as the BM. This area still has its original microstructure and characteristics. It acts as a standard against which to compare the alterations that take place in the other regions throughout the welding process [6].

Assessing the integrity and quality of a friction stir weld requires a thorough understanding of these various regions. In determining the overall effectiveness and dependability of the welded joint, each region's properties and characteristics are crucial. High-quality friction stir welds can be produced by carefully controlling the process and optimizing the welding parameters to produce the desired microstructural changes and mechanical properties in the various regions [18].

TABLE 02: KEY BENEFITS OF FSW

Metallurgical benefits	Environmental benefits	Energy benefits
• Solid phase process • Low distortion of workpiece Good dimensional stability and repeatability • No loss of alloying elements • Excellent metallurgical properties in the joint area • Fine microstructure • Absence of cracking • Replace multiple parts joined by fasteners	• No shielding gas required • No surface cleaning required • Eliminate grinding wastes • Eliminate solvents required for degreasing • Consumable materials saving, such as rugs, wire or any other gases	• Improved materials use (e.g., joining different thickness) allows reduction in weight • Only 2.5% of the energy needed for a laser weld • Decreased fuel consumption in light weight aircraft, automotive and ship applications

I. FSW TOOLS

Tools for FSW (Friction Stir Welding) are essential to the efficiency and success of the welding process. Two key elements that have a significant impact on the overall performance of FSW experimentation are the tool design and material choice. This section will examine the significance of tool selection, including tool geometry and material options. When it comes to FSW, the quality and strength of the final weld are largely determined by the tool geometry. The welding process's heat generation, material flow, and overall stability are all directly impacted by the tool's shape and design. Depending on the unique requirements of the welding application, different tool geometries, such as cylindrical, tapered, or threaded, can be used. For example, cylindrical welding equipment is frequently used for general-purpose welding, whereas tapered welding equipment is appropriate for welding thicker materials or when additional material mixing is required [19]. The geometry of the tool selected should be compatible with the specific welding goals and the materials being joined. The choice of appropriate materials for FSW tools is equally significant. To withstand the high temperatures and mechanical stresses involved in the process, the tools need to have specific qualities. Typically, materials with high strength, excellent wear resistance, and good thermal conductivity are used to create FSW tools [3]. High-speed steels, tungsten alloys, and polycrystalline cubic boron nitride (PCBN) are frequently used materials in tool manufacturing. These materials provide the toughness required to withstand the challenging FSW conditions, ensuring increased tool life and reliable welding results. The choice of tool material also depends on the materials being joined [18]. When welding dissimilar materials, such as aluminum and steel, the tool material should be carefully selected to reduce the formation of undesirable intermetallic compounds and ensure proper mixing of the materials. Additionally, coatings or surface treatments can be applied to the tool to improve its functionality, such as lowering friction and preventing the adhesion of the welded material [14][25].

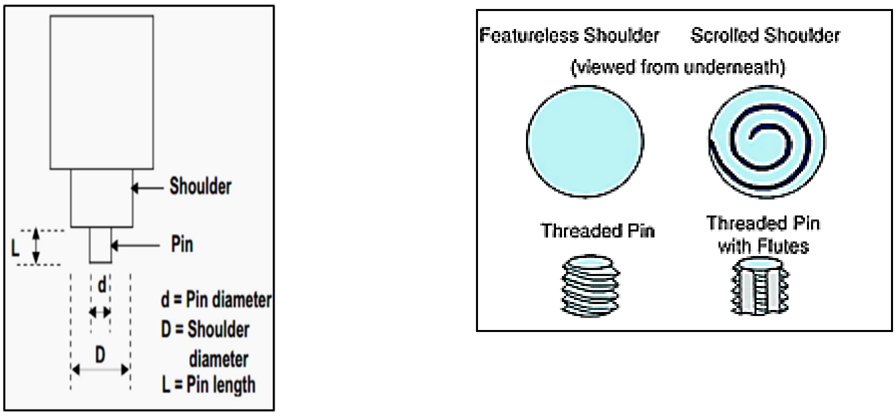

FIGURE 04: SCHEMATIC DRAWING OF FSW TOOL [2]

3.1 Tool selection

The probe and the shoulder are the two main components that make up a welding tool used in friction stir welding (FSW). The material of the welding specimen determines the choice of shoulder size. The tool probe's shape is crucial because it has a direct impact on a number of variables, such as the rate of heat generation, the transverse load, torque, and the tool's thermal-mechanical environment. The dimensions of the tool pin, the shoulder length and diameter, and the FSW tool's effectiveness must all be considered. For greater pressure to be applied to the two plates being joined, a larger shoulder provides a larger area for welding. Due to the high friction involved in the process, the shoulder quickly heats up as the probe is inserted between the connection line of the workpieces. The probe, which ideally has a flat base, is produced and used frequently. The flat probe design's disadvantage is the sizeable force needed during the plunging phase, though. The softened zone expands and the deformed material contracts as the shoulder quickly heats up once it comes into contact with the workpiece. The quality of the weld is ultimately impacted by the profile of the tool pin or probe, which is crucial to the flow of plasticized material. Researchers and practitioners can optimize the welding process by carefully considering the dimensions and design of the shoulder and probe in FSW tools. Heat generation, material flow, and weld quality can all be directly impacted by the choice of shoulder size, probe shape, and tool pin profile. To ensure successful and effective friction stir welding operations, it is crucial to strike a balance between the needs of the particular welding application and the capabilities of the tool design [4]a[20].

Tool shoulder helped layer-by-layer flow of material, whereas pin aided bulk flow. Cylindrical pin increases material flow as compare with triangle or tri-fluted tool pin.

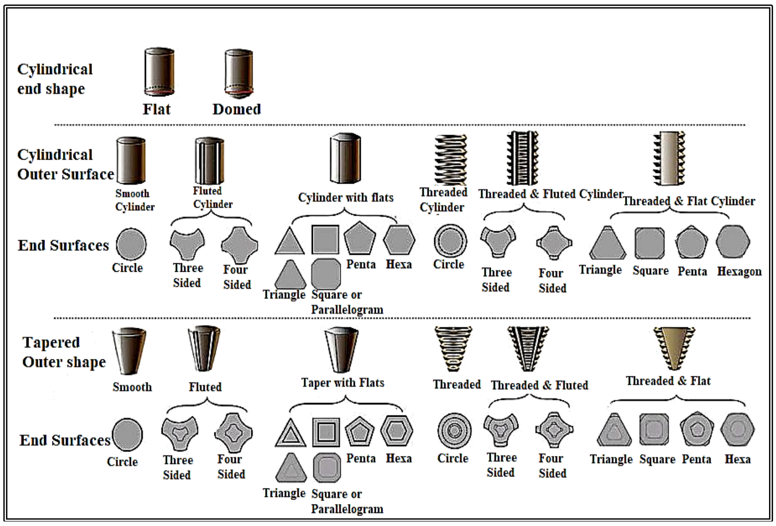

FIGURE 05: SHAPE OF FSW TOOLS PROBE

In addition, several tool pin shapes are commonly employed in the FSW process. These are quite beneficial for uniform material mixing inside the weld region. Figure 05 represent the various structures of the probes. These probe configurations are generally used to determine the friction welding of a variety of materials, such as aluminium as soft to steels as hard [21].

3.2 Tool material selection

Table 03 lists some of the tool materials that can be used to make appropriate welds. While welding of aluminium alloy, copper alloy, and magnesium alloys, tool steel is used more commonly. These materials are readily available, machinable, and resistant to thermal fatigue. Welding of some alloys, tool steels are resistant to abrasion and distortion. High carbon high chromium tool steels, gives more tool wear resistance and are accessible in several tool steel grades, are commonly used for aluminium alloys [20].

TABLE 03: TOOL MATERIAL AND ITS USE [18]

Sr. No.	Tool Material	Thickness (mm)	Weld material
I	Tool Steel, Tungsten carbide	<12	Aluminium and its alloy
II	Tool Steel, Tungsten carbide	<6	Magnesium and its alloy
III	PCBN, Tungsten Alloy	<50	Copper and its alloy
IV	Tungsten Alloy	<6	Titanium alloy
V	PCBN	<6	Nickel alloy

II. JOINT DESIGN

Tool rotational speed (rpm) and transverse speed (mm/min) are two crucial factors that friction stir welding (FSW), a durable welding process, depends on. These factors are crucial in figuring out the strength and caliber of the welding joint. The improved weld quality and improved mechanical properties result from the tool rotation's facilitation of material movement and mixing from the advancing side to the retreating side. High friction develops between the tool and the workpiece as a result of the transverse movement of the tool along the joint line during the welding process. Heat, produced by this friction, is essential for producing a weld without flaws. The welding process can be negatively impacted by excessive heat, especially for materials with high melting points like steel, copper, and titanium. Preheating is frequently required to soften the materials and allow for proper material flow during the welding process in order to ensure successful welding of these materials[22].

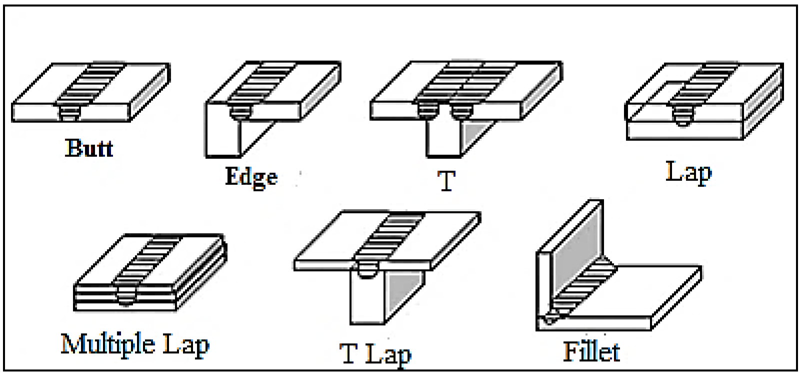

FIGURE 06: JOINT CONFIGURATION FOR FSW

On the other hand, cooling becomes crucial for substances like magnesium and aluminum that have low melting points. The mechanical integrity of the weld may be harmed by the growth of grains that have recently recrystallized as a result of excessive heat. As a result, efficient cooling techniques are used to reduce the rate of excessive grain growth and to keep the joint's desired microstructure and mechanical strength. Depending on the unique requirements of the application, different types of joints can be formed using FSW. The butt joint and lap joint are the two most frequently used joint arrangements. To avoid any misalignment during the welding process, two plates are aligned and set on a backing plate with a firm clamp. Two plates that are to be joined overlap their edges in a lap joint. These joint arrangements, which are popular across many industries, provide excellent strength[23].

The various joint configurations that can be achieved through FSW are illustrated in Figure 4.1. These set ups are adaptable and can be made to suit particular welding requirements. One benefit of FSW is that special surface preparation is frequently not needed for these joint types, simplifying the welding process and cutting down on prep time and expenses. In general, FSW offers a trustworthy and effective welding technique for a variety of materials and joint configurations. Welders can achieve the best mixing, heat generation, and material flow by carefully controlling the tool rotational speed and transverse speed. The choice of preheating or cooling techniques depends on the melting point of the material and the desired weld characteristics. The butt joint and lap joint configurations offer sturdy joints without the need for thorough surface preparation. FSW has expanded its applications in a number of industries, including the automotive, aerospace, and marine sectors, through ongoing research and development. With benefits like better weld quality, less distortion, and improved mechanical properties, it is a desirable option for joining various materials. Further developments in tool design, process optimization, and joint configurations are anticipated as knowledge of FSW processes and parameters continues to grow, which will increase the use of FSW in the manufacturing sector[24].

CONCLUSION

This study presents a comprehensive analysis of the friction stir welding (FSW) technique, which has demonstrated successful applications in joining materials ranging from soft aluminum to hard titanium using traditional milling machines. The investigation considers various parameters such as spindle speed, weld speed, axial load, tool shoulder and probe design, tilting angle, and plate thickness, all of which play crucial roles in achieving high-quality welds.

Based on the extensive review, the following conclusions have been drawn:

1. Increasing spindle speed (RPM), weld speed (mm/min), and axial load (KN) generally enhance tensile strength until a saturation point is reached, beyond which further increases tend to diminish it.
2. Higher spindle speeds and axial forces result in increased percentage elongation, indicating improved ductility, while higher welding speeds have the opposite effect, reducing percentage elongation and, thus, reducing ductility.

3. The D/d ratio, representing the ratio between the tool shoulder diameter (D) and tool probe diameter (d), significantly influences welding strength. Optimal D/d ratios have been identified as critical factors for achieving strong welds.
4. The shape and design of the tool probe have a substantial impact on submerged FSW, underscoring the importance of careful selection to ensure desired welding outcomes.
5. The welding zone exhibits greater hardness compared to the heat-affected zone due to grain recrystallization. This emphasizes the need for precise control over welding parameters to achieve the desired balance between strength and hardness.
6. In comparison to typical FSW techniques, the use of water as a cooling medium has been shown to minimize residual strains in the stir zone, indicating its potential for improving the overall quality of welds.
7. The majority of studies have primarily focused on aluminum alloys in the 1000, 6000, and 2000 series. Limited attention has been given to aluminum alloys in the 5000 and 7000 series, and even less research has been conducted on alloys in the 3000 and 4000 series. Therefore, further investigation is needed to broaden our understanding of FSW characteristics in these less-studied aluminum alloys.

This research provides valuable insights into the effects of different parameters on the quality and strength of FSW. By carefully considering and controlling factors such as spindle speed, weld speed, axial load, tool design, and cooling medium, researchers and practitioners can optimize the FSW process to achieve high-quality welds across a wide range of materials. Future studies should focus on expanding the knowledge base regarding FSW in less-explored aluminum alloy series to further enhance its applications in various industries.

FUTURE SCOPE

There is lots of work can be done related to this process with taking some different parameter for the process and study that new process to get some of new results. There are following points which are considered as future scope of study.

- Research on 3000and 4000 series aluminium alloy gives some new results.
- The heat produced during experiment is very high therefore study on the machine parameters after welding is also the good way of research.
- The cost of tool is more because when we use the tool having threads, once the tool used for the process then it can’t be used about two or three more processes because the material of the previous one get deposited in the threads of the pin and tool must be changed for further processes.
- The energy cost of welding for aluminium alloy is less but if we use this process for hard alloys then it will take more cost than any other process.
- FSW uses in various sectors such as fuel tanks in spacecraft, rolling stocks, military vehicles, marine appliances, helicopters tail, cold plate in high power electronic devices etc.

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