Research Annals of Industrial and Systems Engineering

www.raise.reapress.com

Res. Ann. Ind. Syst. Eng. Vol. 1, No. 1 (2024) 1–14.

Paper Type: Original Article

Dynamics of Friction Stir Welding as a Conventional Metal Joining Technique in Manufacturing Industries

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Citation:

Received: 20 May 2023 *Revised: 12 August 2023* *Accepted: 9 March 2024*	Ekanem, I. I., Bassey, M. O., & Ikpe, A. E. (2024). Dynamics of friction stir welding as a conventional metal joining technique in manufacturing industries. *Research annals of industrial and systems engineering,* ١ (١), 1-14.

Abstract

Metal joining procedures are essential in the manufacturing sector since they directly impact the strength and longevity of the end product. Arc welding and resistance welding, which are traditional welding techniques, have been extensively utilized for many years. Nevertheless, these procedures are constrained by limits in terms of the quality of the joints, distortion, and efficiency. Friction Stir Welding (FSW) technology has become a ground-breaking metal joining process in recent years, surpassing traditional welding procedures in terms of multiple advantages. This study aimed to investigate the potential of FSW technology in transforming traditional metal joining methods in the conventional production process. A thorough review was undertaken to examine the effects of FSW technology on traditional manufacturing processes. The review aimed to gather information on the concepts, applications, and advantages of FSW technology. Analyzing existing research in this area provided insights into the practical use of FSW across different sectors. In addition, there were a number of discussions with industry professionals to collect ideas on the difficulties and possibilities of incorporating FSW technology into traditional production processes. The results of this study indicated that FSW technology has the capacity to fundamentally transform metal joining methods in the traditional production process. FSW has several benefits, including enhanced joint integrity, less deformation, and increased productivity compared to conventional welding techniques. FSW may be easily incorporated into current manufacturing processes, reducing costs and improving product performance. Nevertheless, to fully use the advantages of FSW technology in traditional industrial processes, it is necessary to tackle some barriers, such as the high cost of equipment, the necessity for process optimization, and the requirement for operator training. Finally, using FSW technology can revolutionize metal joining methods, allowing product manufacturing to attain superior quality, efficiency, and cost-effectiveness.

Keywords: Friction stir welding, Manufacturing industries, Metal joining, Product performance.

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1 | Introduction

Welding is a widely used industrial process that involves joining materials by applying heat and pressure [1]. Friction Stir Welding (FSW) is a solid-state joining process that has gained significant attention in the manufacturing industry due to its numerous advantages over traditional welding techniques. This process involves using a rotating tool to generate frictional heat between the workpieces, which softens the material and creates a strong, defect-free weld [2]. The heat softens the material without melting, allowing the tool to stir the metal together and create a strong bond. This process is particularly beneficial for joining materials that are difficult to weld using conventional methods, such as aluminium, copper, and other nonferrous alloys. While FSW has been successfully used in various industries, some sceptics still question its effectiveness and reliability [3]. One of the main arguments against FSW is the initial cost of equipment and tooling. Critics argue that the high cost of purchasing and maintaining FSW machines makes it an impractical choice for many manufacturers, especially those with limited budgets. However, FSW proponents argue that this process's long-term benefits, such as reduced material waste and improved weld quality, outweigh the initial investment costs [4].

Another common criticism of FSW is the limited range of materials that can be effectively welded using this process. Some materials, such as high-strength steels and aluminium alloys, are more difficult to weld with FSW due to their high melting points and thermal conductivity. Critics argue that traditional welding techniques, such as arc welding, are more versatile and can be used on a wider range of materials. However, technicians specializing in FSW indicate that ongoing research and development efforts are continuously expanding the capabilities of this process, making it suitable for a broader range of materials [5]. One selling point of FSW is its ability to produce high-quality welds with minimal distortion and defects. Traditional welding techniques, such as arc welding, often result in residual stresses and distortion in the welded material, which can compromise the structural integrity of the final product. On the other hand, FSW produces welds with a fine microstructure and excellent mechanical properties, making it an ideal choice for applications where weld quality is critical [6].

While there are valid criticisms of FSW, the benefits of this process far outweigh its limitations. With ongoing advancements in technology and research, FSW is becoming an increasingly viable option for manufacturers looking to improve the quality and efficiency of their welding operations [7]. As more industries adopt FSW as a preferred welding technique, it is clear that this process has the potential to revolutionize the way we join materials in the future. As mentioned earlier, the operation principles of FSW involve using a rotating tool to generate frictional heat between the workpieces, which softens the material and allows for forming a strong bond without melting [8]. This highly efficient process produces high-quality welds with minimal distortion and defects. One of the key principles of FSW is using a specially designed tool that rotates at high speeds and applies pressure to the workpieces [9]. The rotating tool generates frictional heat at the workpiece interface, softening the material and creating a plasticized zone. As the tool moves along the joint line, it stirs the softened material, mixing the two workpieces and creating a strong bond. Unlike traditional welding techniques that rely on melting and solidification of the material, FSW operates in the solid state, eliminating the risk of defects such as porosity and solidification cracks [10]. This results in high-quality welds with superior mechanical properties, strength, and fatigue resistance. Furthermore, FSW is a highly versatile process that can join a wide range of materials, including aluminium, steel, and titanium [11]. This makes it an ideal choice for aerospace, automotive, and shipbuilding industries, where lightweight materials and high-performance welds are required.

The FSW operation principles involve using frictional heat and pressure to create a strong bond between workpieces without melting [4]. This solid-state joining process offers numerous advantages over traditional welding techniques, including high efficiency, superior weld quality, and versatility. As industries continue to demand high-performance welds with minimal defects, FSW will likely become an increasingly popular choice for joining materials [12]. Padhy et al. [13] presented a detailed flow diagram of FSW and processing technologies, as illustrated in *Fig. 1*. This study presents the revolutionizing trends of FSW technology in metal joining techniques and its impacts on conventional manufacturing sequences.

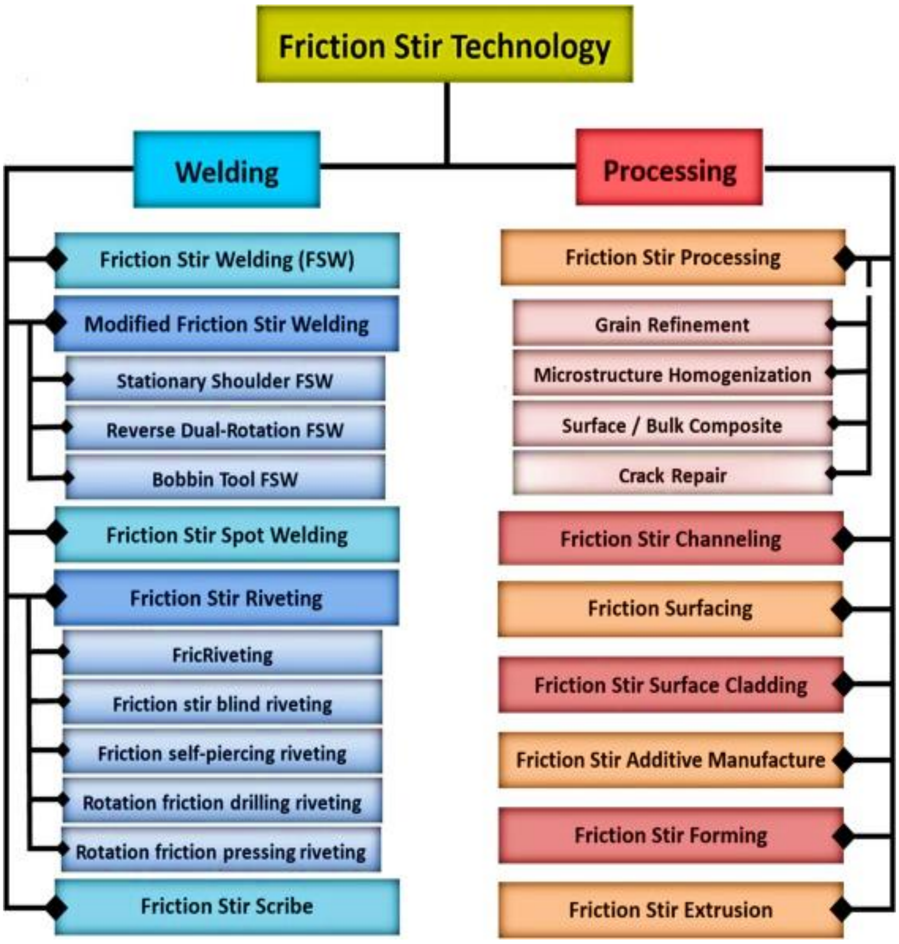

Fig. 1. Illustration of FSW and processing technologies.

2 | History of FSW

The history of FSW can be traced back to the early 1990s when TWI researchers, led by Wayne Thomas, developed the process as a novel method for joining materials [14]. However, FSW is an innovative welding technique that was entirely invented and patented by The Welding Institute in 1991 in the United Kingdom and has since been adopted by various industries for its ability to produce high-quality welds with minimal distortion and defects [15]. The initial concept of FSW was based on the idea of using a rotating tool to generate frictional heat and plasticize the material, followed by forging the softened material together to form a solid joint [16]. This innovative approach eliminated the need for melting the materials, resulting in a high-quality, defect-free weld with superior mechanical properties. Over the years, FSW has undergone significant development and evolution, leading to the establishment of various applications and advancements in the field of welding technology. One of the critical milestones in the historical development of FSW was the introduction of automated and robotic systems for welding [17]. This automation improved FSW's efficiency and accuracy and expanded its capabilities for joining complex geometries and materials.

Furthermore, the evolution of FSW has seen the development of new tool designs, materials, and process parameters to enhance the performance and versatility of the welding process [18]. Researchers and engineers have continuously optimized the FSW parameters, such as rotational speed, traverse speed, tool geometry, and tool material, to achieve superior weld quality and mechanical properties. The history, historical development, and evolution of FSW have demonstrated this innovative welding process's significant impact and potential. With its numerous advantages, including high strength, low distortion, and environmental friendliness, FSW has become a preferred choice for joining materials in various industries, such as aerospace, automotive, and marine [19]. As research and development in FSW continue to progress, it is expected that this solid-state welding process will further revolutionize the field of welding technology and contribute to the advancement of manufacturing industries worldwide.

3 | Advancement in FSW

Since its inception in the early 1990s, FSW has seen significant advancements and technological breakthroughs that have further enhanced its capabilities and applications. One of the critical milestones in advancing FSW technology was the development of specialized FSW equipment and tools [20]. In the early days of FSW, researchers and engineers had to rely on makeshift tools and equipment to perform the welding process. However, with the increasing demand for FSW in various industries, companies began investing in developing specialized FSW machines that could perform the process with greater precision and efficiency [21]. These machines are equipped with advanced features such as robotic arms, high-speed spindles, and real-time monitoring systems, which have significantly improved the quality and reliability of FSW welds. Another significant milestone in the development of FSW technology was the introduction of new materials and alloys that could be successfully welded using the FSW process [22].

Initially, FSW was limited to welding aluminium and its alloys, but researchers soon discovered that FSW could also be used to weld other materials such as steel, titanium, and even composites [23]. This opened up new opportunities for FSW in the aerospace, automotive, and shipbuilding industries, with high demand for lightweight and high-strength materials.

Furthermore, advancements in FSW technology have led to the development of new welding techniques and processes that have further improved the efficiency and effectiveness of FSW [24]. One such technique is using multi-pass FSW, where multiple passes are made over the same weld joint to achieve a stronger and more uniform weld [25]. Another technique is hybrid FSW, which combines FSW with other welding processes, such as laser welding or friction stir processing, to achieve even greater weld quality and performance.

The advancements in FSW technology have significantly impacted the welding industry and have opened up new possibilities for using FSW in various applications [26]. With the development of specialized equipment, new materials, and innovative welding techniques, FSW has become a versatile and reliable welding process that offers numerous advantages over traditional welding techniques. As FSW continues to evolve and improve, it is expected to play an even greater role in the manufacturing industry and contribute to developing new and innovative products.

4 | Types of FSW

Several types of FSW techniques have been developed to suit different applications and materials. These include the following:

I. One of the most common types of FSW techniques is the conventional FSW, where a rotating tool is plunged into the materials to be joined at a constant speed and pressure [27]. This technique is suitable for joining materials with relatively low melting points, such as aluminium and magnesium alloys. However, conventional FSW may not be suitable for joining materials with higher melting points or for applications requiring precise control over the welding process.

II. Another type of FSW technique is the stationary shoulder FSW, where the rotating tool is held stationary while the materials are moved relative to the tool [28]. This technique allows for better control over the welding process and is suitable for joining materials with higher melting points, such as steel and titanium alloys. Stationary shoulder FSW also allows for welding materials with varying thicknesses, as the tool can be adjusted to accommodate different material thicknesses.

III. A third type of FSW technique is the bobbin tool FSW, where a cylindrical tool with a threaded profile is used to join materials [29]. This technique is suitable for joining materials with complex geometries or applications requiring high precision. Bobbin tool FSW allows for better control over the welding process and can produce high-quality welds with minimal defects.

Several types of FSW techniques have been developed to suit different applications and materials. Each technique has its advantages and limitations, and the choice of technique will depend on the specific requirements of the welding application. By understanding the different types of FSW techniques available, manufacturers can choose the most suitable technique for their welding needs and achieve high-quality welds with minimal defects.

5 | Criteria for Selecting FSW

When selecting FSW as a joining method, it is essential to consider several criteria to ensure successful and efficient welding operations. These include the following:

I. One of the key criteria for FSW selection is the material being welded. FSW is particularly well-suited for joining nonferrous materials such as aluminium, copper, and magnesium alloys [30]. These materials have high thermal conductivity and low melting points, making them prone to distortion and defects when welded using conventional methods. As a solid-state process, FSW minimizes these issues and produces high-quality welds with minimal distortion.

II. Another important criterion for FSW selection is the thickness of the joined materials [31]. FSW is most effective for welding materials with thicknesses ranging from 0.5 mm to 25 mm. Thicker materials may require multiple passes or specialized equipment to achieve satisfactory weld quality. Additionally, the geometry of the materials should be considered when selecting FSW, as complex shapes and configurations may require customized tooling and fixturing to ensure proper weld formation.

III. The operating conditions of the FSW process, such as tool rotation speed, traverse speed, and applied force, also play a crucial role in determining the suitability of FSW for a particular application [32]. These parameters must be carefully optimized for the desired weld quality and mechanical properties. Additionally, the availability of skilled operators and proper training in FSW techniques is essential for successfully implementing the process.

The selection of FSW as a joining method should be based on a thorough evaluation of the material properties, thickness, geometry, and operating conditions. By considering these criteria, manufacturers can ensure the successful implementation of FSW and reap the benefits of this advanced welding technology.

6 | Components of the FSW Machine

The success of FSW largely depends on the components and parts of the welding machine. Each of these components plays a crucial role in the success of the FSW process. The spindle and welding tool generate the necessary heat and plasticize the material, while the workpiece fixture ensures proper alignment and stability [9], [33]. The drive system controls the movement of the welding tool, while the cooling system helps maintain the temperature of the machine components. The key components of FSW machines and their importance in achieving successful welds are highlighted as follows:

I. Spindle: the spindle is the rotating component of the FSW machine that houses the welding tool. It is responsible for providing the necessary rotational speed and torque to the tool during welding.

II. Welding tool: the welding tool is a key component of the FSW machine that directly interacts with the workpiece. It consists of a shoulder and a pin designed to generate frictional heat and plasticize the material being welded.

III. Workpiece fixture: the workpiece fixture securely holds the workpiece in place during the welding process. It is essential for maintaining proper alignment and preventing distortion of the workpiece.

IV. Drive system: the drive system of the FSW machine is responsible for controlling the movement of the welding tool along the joint line. It ensures consistent travel speed and pressure during the welding process.

V. Cooling system: the cooling system dissipates heat generated during the welding process and prevents machine components from overheating. It helps maintain the welding tool's integrity and prolong its lifespan.

The components of a FSW machine are essential for achieving successful welds. Proper selection and maintenance of these components are crucial for ensuring the quality and integrity of the welds produced. By understanding each component's importance and role in the welding process, manufacturers can optimize their FSW machines for maximum efficiency and productivity. A schematic view of the FSW process, as presented by Machniewicz et al. [34], is illustrated in *Fig. 2*.

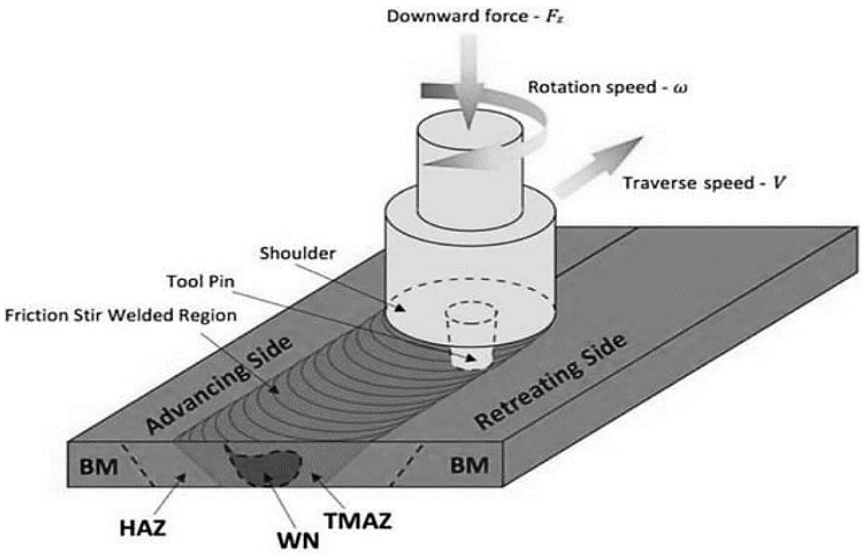

Fig. 2. Schematic view of the FSW process.

7 | Key Welding Parameters in FSW

In order to achieve successful FSW, it is essential to control key welding parameters that directly impact the quality of the weld. Therefore, proper control of these parameters is crucial for achieving high-quality welds. The key welding parameters in FSW are as follows:

I. One of the most critical parameters in FSW is the rotational speed of the tool. The rotational speed determines the heat input and material flow during welding [35]. A high rotational speed can lead to excessive heat generation, which may result in material softening and potential defects in the weld. On the other hand, a low rotational speed may not provide enough heat input for proper material flow and consolidation. Therefore, it is important to carefully select the rotational speed based on the material being welded and the desired weld quality.

II. Another important parameter in FSW is the traverse speed of the tool. The traverse speed determines the tool's rate of moving along the joint line, affecting the material flow and consolidation [36], [37]. A high traverse speed can lead to insufficient material mixing and inadequate consolidation, while a low traverse speed may result in excessive heat input and potential defects. Therefore, optimizing the traverse speed to ensure proper material flow and consolidation during welding is crucial.

III. Additionally, the plunge depth of the tool is a key parameter that influences the quality of the weld in FSW [38]. The plunge depth determines the depth at which the tool penetrates the workpiece, affecting the material flow and consolidation. A shallow plunge depth may not provide enough material mixing and consolidation, while a deep plunge depth can lead to excessive material displacement and potential defects. Therefore, it is important to carefully control the plunge depth to achieve proper material flow and consolidation in the weld.

Proper control of key welding parameters is essential for achieving high-quality welds in FSW. The tool's rotational speed, traverse speed, and plunge depth are critical parameters that directly impact the material flow and consolidation during the welding process. By carefully selecting and optimizing these parameters, welders can ensure the production of high-quality welds with minimal distortion and defects.

8|Preparation of Samples/Materials

One of the key factors determining FSW's success is the preparation of samples/materials before the welding process. Proper preparation of samples/materials is crucial in ensuring the quality and integrity of the weld joint [12], [39]:

I. The first step in preparing samples/materials for FSW is selecting the appropriate material [40]. The material should have good weldability and compatibility with the FSW process. It is important to consider factors such as the material's composition, thickness, and mechanical properties when selecting the material for FSW.

II. Once the material has been selected, the next step is to prepare the samples for welding. This involves cleaning the surfaces of the material to remove any contaminants such as dirt, oil, or grease. Cleaning the surfaces of the material is essential to ensure proper bonding between the materials during the welding process [41].

III. After cleaning the surfaces, the next step is clamping the samples in the desired configuration. Proper clamping is essential to ensure the samples are held securely during welding. Improper clamping can result in misalignment of the samples, leading to defects in the weld joint.

IV. In addition to clamping, it is preheating the samples/materials before welding [42]. Preheating helps reduce the material's thermal gradients, which can lead to distortion and residual stresses in the weld joint. Preheating also helps soften the material, making it easier to deform during welding.

Preparing samples/materials for FSW is a critical step in ensuring the success of the welding process. Proper selection of materials, cleaning of surfaces, clamping of samples, and preheating of materials are essential steps in preparing samples/materials for FSW. By following these steps, welders can ensure the quality and integrity of the weld joint, leading to strong and durable welds.

9|Materials Commonly Welded Using FSW

While FSW can be used to weld a wide range of materials, certain materials are commonly welded using this technique [43], [44]. These are as follows:

I. One of the most common materials welded with FSW is aluminium and its alloys [45]. Aluminium is a lightweight and corrosion-resistant material widely used in aerospace, automotive, and marine industries. FSW has been successfully used to weld aluminium alloys of varying thickness and composition, producing welds with excellent mechanical properties and high strength.

II. Another type of material commonly welded with FSW is magnesium and its alloys [46]. Magnesium is also lightweight with a high strength-to-weight ratio, making it ideal for applications where weight reduction is critical. FSW has been proven to be an effective welding technique for magnesium alloys, producing welds with high strength and good fatigue resistance.

III. Titanium and its alloys are another material commonly welded with FSW [47]. Titanium is a high-strength material with excellent corrosion resistance, making it suitable for applications in the aerospace and medical industries. FSW has been used to weld titanium alloys, producing high-strength and good ductility welds.

IV. In addition to aluminium, magnesium, and titanium, FSW can also be used to weld other materials such as copper, steel, and composites. Copper is a highly conductive material commonly used in electrical applications, and FSW has been successfully used to weld copper alloys. Steel is a widely used structural material in various industries, and FSW has been shown to produce high-quality welds in steel components.

Composites, made from two or more different materials, can also be welded using FSW, allowing for the joining of dissimilar materials with different properties.

FSW is a versatile joining technique that can be used to weld a wide range of materials, including aluminium, magnesium, titanium, copper, steel, and composites. By utilizing FSW, industries can benefit from high-quality welds with minimal distortion and defects, making it a preferred welding technique for various applications.

10 | Applications of FSW

The applications of FSW are vast and diverse, ranging from aerospace and automotive industries to shipbuilding and construction. The applications of FSW are highlighted as follows:

I. One of the key advantages of FSW is its ability to join dissimilar materials, such as aluminium and steel, which are traditionally difficult to weld using conventional methods [48]. This makes FSW an attractive option for industries that require the joining of different materials to create lightweight and durable structures. For example, in the aerospace industry, FSW is used to join aluminium alloys to construct aircraft components, such as fuselage panels and wing structures. The resulting joints are strong, reliable, and fatigue-resistant, ideal for high-stress applications.

II. Another important application of FSW is in the automotive industry, where it is used to join aluminium components for lightweight vehicle construction [49]. By using FSW, automakers can reduce the weight of vehicles, improve fuel efficiency, and enhance overall performance. Additionally, FSW produces high-quality welds with minimal distortion and porosity, improving automotive components' structural integrity and longevity.

III. In the shipbuilding industry, FSW is employed to join thick aluminium and steel plates to construct ships and offshore structures [3]. The process produces welds with excellent mechanical properties, such as high strength and toughness, which are essential for ensuring the safety and reliability of marine structures. Furthermore, FSW offers significant cost savings compared to traditional welding methods, as it eliminates the need for filler materials and reduces post-welding operations.

IV. FSW joins aluminium and steel components in the construction industry to fabricate architectural structures, such as bridges, buildings, and stadiums [50]. The process allows for the creation of complex geometries and joints with superior mechanical properties, making it an attractive option for structural applications requiring high strength and durability.

The applications of FSW are vast and diverse, spanning various industries requiring high-quality, reliable, and cost-effective joining solutions. With its ability to join dissimilar materials, produce high-quality welds, and offer significant advantages over traditional welding methods, FSW continues revolutionizing how metal components are joined in modern manufacturing processes.

11 | Advantages of FSW

The advantages of FSW include joint quality, cost, energy savings, economics, safety and waste management, as illustrated in *Fig. 3*.

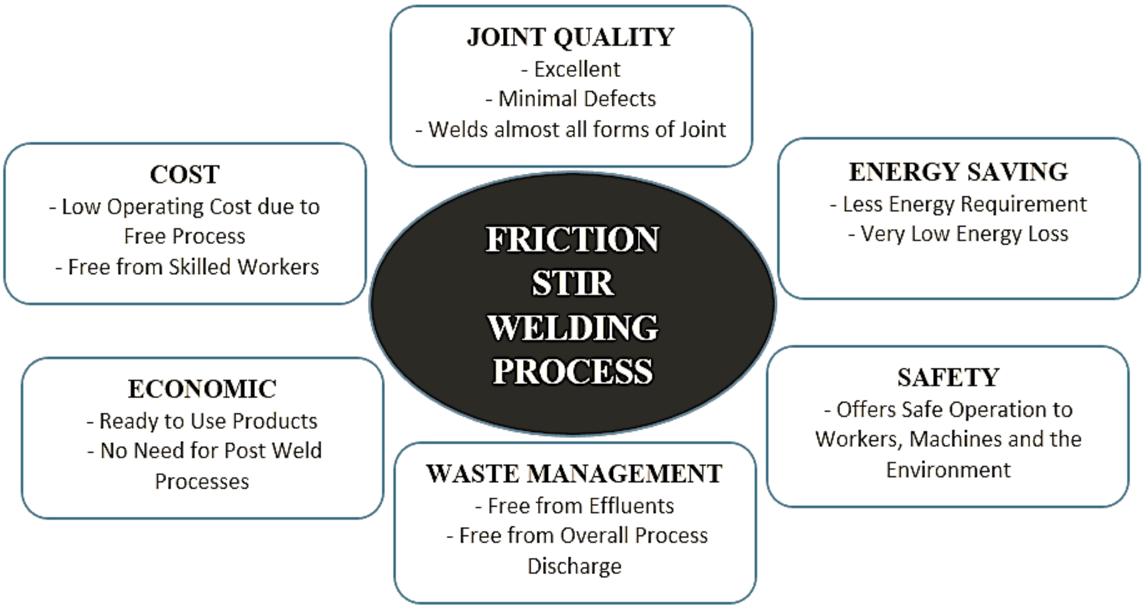

Fig. 3. Advantages of the FSW process.

In recent years, FSW has gained popularity in various industries due to its several advantages highlighted as follows:

I. One of the main advantages of FSW is its ability to produce high-quality welds with minimal defects.

II. Unlike traditional welding methods, FSW does not involve using a filler material or shielding gas, which can lead to porosity and other defects in the weld. This results in stronger, more reliable joints less prone to failure.

III. Additionally, FSW offers improved mechanical properties compared to conventional welding techniques. In other words, FSW can produce welds with superior mechanical properties, including high strength, fatigue resistance, and flexibility. The absence of a molten weld pool in FSW results in a finer grain structure and reduced distortion in the workpiece. This leads to higher tensile and fatigue strength and improved corrosion resistance in the welded joint.

IV. FSW is a versatile process that can be used to join a wide range of materials, including aluminium, steel, and titanium. FSW can join materials of different thicknesses and compositions, making it a versatile option for a wide range of applications. This makes it ideal for applications in industries such as aerospace, automotive, and shipbuilding, where lightweight materials and high-performance welds are required.

V. Another advantage of FSW is its environmental friendliness. Since FSW does not produce fumes or gases, it is a cleaner and safer welding process than traditional methods that rely on consumable electrodes and shielding gases. This makes FSW a more sustainable option for manufacturers looking to reduce their environmental impact.

FSW offers numerous advantages over traditional welding techniques, including high-quality welds, improved mechanical properties, versatility, and environmental friendliness [51], [52]. As industries continue to adopt FSW for their welding needs, it is clear that this innovative process will play a significant role in the future of manufacturing.

12 | Disadvantages of FSW

Like any other welding technique, FSW has drawbacks that must be considered before implementation. The disadvantages of FSW techniques are as follows:

I. One of the main disadvantages of FSW is its limited applicability to certain materials. FSW works best with materials that have good thermal conductivity and can be easily softened, such as aluminium and its alloys.

However, FSW may be less effective when it comes to materials with high melting points or low thermal conductivity, such as steel and titanium. This limitation restricts the range of materials that can be welded using FSW, making it unsuitable for certain applications.

II. Another disadvantage of FSW is the equipment and tooling costs associated with the process. FSW requires specialized machinery and tools, such as a high-powered spindle and a rotating shoulder, which can be expensive to purchase and maintain. Additionally, the complex nature of FSW equipment makes it difficult to set up and operate, requiring skilled technicians to ensure proper welding parameters are met. These costs can be prohibitive for small businesses or industries with limited budgets, making FSW less accessible compared to other welding techniques.

III. FSW has limitations in terms of joint design and geometry. The process is best suited for welding flat or slightly curved surfaces, making welding complex shapes or structures challenging. This limitation can be a significant drawback for industries that require intricate welds or joints, as FSW may not be able to meet their specific requirements. Additionally, the lack of flexibility in joint design can limit the overall strength and durability of the weld, leading to potential structural issues in the long run.

IV. FSW also has some limitations, such as requiring specialized equipment and skilled operators.

While FSW offers numerous advantages, such as high weld quality and minimal distortion, it also has several disadvantages that must be considered. These include limited material applicability, high equipment costs, and restrictions in joint design and geometry [53]. Despite these drawbacks, FSW remains a valuable welding technique in certain applications where its benefits outweigh its limitations. However, it is essential for industries to carefully evaluate the pros and cons of FSW before deciding to implement it in their manufacturing processes.

13 | Conclusion and Recommendations

The existing studies on FSW have provided valuable insights into the process and its applications in various industries. The research has shown that FSW offers numerous advantages over traditional welding techniques, including improved mechanical properties, reduced distortion, and enhanced weld quality. Additionally, studies have demonstrated the potential for FSW to be used in various materials, from aluminium and steel to composites and even dissimilar materials. Despite the many benefits of FSW, challenges still need to be addressed. One of the process's main limitations is the difficulty of welding thick sections and the complexity of tool design and optimization.

Furthermore, there is a need for further research to fully understand the effects of process parameters on the microstructure and mechanical properties of the weld. Overall, the findings from existing studies highlight the potential of FSW as a viable alternative to traditional welding methods. By addressing the current limitations and continuing to research and develop the process, FSW has the potential to revolutionize the welding industry and open up new possibilities for joining materials in a wide range of applications. As researchers continue to explore the capabilities and limitations of FSW, it is important to consider some recommendations based on this study to improve the process further and expand its applications:

I. One key recommendation based on this study is the importance of optimizing process parameters to achieve high-quality welds. This study has shown that parameters such as tool rotation speed, traverse speed, and tool geometry significantly impact the mechanical properties of FSW joints. By carefully controlling these parameters, researchers can improve the strength and durability of FSW welds, making them suitable for a wider range of applications.

II. Another important recommendation is the need for further research into the microstructural evolution during FSW. The microstructure of FSW joints can vary significantly depending on the process parameters and material properties. By better understanding how the microstructure evolves during FSW, researchers can develop strategies to optimize the process and improve the mechanical properties of the welds.

III. Additionally, the importance of Post-Weld Heat Treatment (PWHT) in improving the properties of FSW joints cannot be ignored. PWHT can help relieve residual stresses, improve the microstructure, and enhance the mechanical properties of the welds. By incorporating PWHT into the FSW process, researchers can further enhance the performance of FSW joints and make them more suitable for demanding applications.

The recommendations based on findings from existing studies on FSW emphasize the importance of optimizing process parameters, understanding the microstructural evolution, and incorporating PWHT. By following these recommendations, researchers can continue to improve the capabilities of FSW and expand its applications in various industries. Further research in these areas will be crucial for advancing the field of FSW and unlocking its full potential.

Author Contribution

The authors have equally contributed to this study.

Funding

The study received no funding.

Data Availability

The authors will supply the supporting information upon request, free from any unjustified limitations, which form the foundation of the conclusions presented in this article.

Conflicts of Interest

The authors declared no conflicts of interest regarding this work.

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