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A Brief Review of Friction Stir Welding Techniques for Flange Joint Configurations in Similar and Dissimilar Alloys

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Abstract

Emerging as a transformative technology, friction stir welding (FSW) has proven to significantly enhance the integrity of flange joints, particularly in demanding applications such as offshore and automotive environments. This welding method effectively minimizes defects commonly associated with traditional techniques, ensuring superior mechanical properties in the welded joints. Studies demonstrate that FSW produces weldments with strength values comparable to the base materials, thereby meeting the stringent requirements of industries that operate under harsh conditions, especially offshore structures, where resistance to corrosion and high fracture toughness is paramount. This paper concisely reviews FSW applied to flange joints, focusing on dissimilar material combinations such as aluminum and steel. The influence of tool geometry, process parameters, and joint configurations on weld quality and mechanical properties is discussed. Furthermore, as industries shift from mass production to mass customization, adopting techniques that streamline manufacturing processes becomes essential. Prospects for FSW lie in its potential application across various materials and complex designs, facilitating innovations such as part consolidation in automotive manufacturing. Ultimately, FSW merits further exploration as a viable solution for enhancing flange joint performance in diverse sectors. Key challenges and future research opportunities in the industrial adoption of FSW for complex flange geometries are also identified.

Keywords: Friction Stir Welding, Flange Joint, Mechanical Properties, Industrial Implementation.

1. Introduction

The advancement of welding technologies is crucial in addressing the demands for more efficient and reliable joining methods in various industrial applications. As of recent market analyses, the global friction stir welding (FSW) market is projected to reach 1.23 billion USD by 2030, growing at a compound annual growth rate (CAGR) of approximately 7.1% from 2023, driven by rising adoption in aerospace, automotive, and marine sectors [1-2].

Among these technologies, FSW has emerged as a promising alternative due to its ability to produce high-quality welds with reduced thermal distortion. The specific application of FSW to flange joints presents unique challenges, particularly in terms of the complexity of weld paths and the need for precisely engineered fixtures to maintain alignment during the process. As current research emphasizes, developing optimal welding parameters, such as rotation speed and tool profile, is essential for maximizing mechanical performance [2]. Furthermore, innovative methods like combining FSW with traditional techniques have shown potential in enhancing welded joints' microstructure and mechanical properties, thus improving overall performance [3-5]. This essay explores these aspects, focusing on optimizing FSW for flange joints to meet industrial standards.

We emphasized the research gap in applying FSW to complex flange geometries, particularly when dealing with dissimilar material combinations. Figure 1 illustrates a cause-and-effect (fishbone) diagram that

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systematically categorizes the key factors influencing the quality of FSW flange joints. This diagram is a diagnostic tool used to identify root causes of defects or performance limitations in flange joint applications and is structured around six primary branches: Tool Design, Process Parameters, Material Properties, Fixture and Clamping, Operator Skill, and Environmental Conditions.

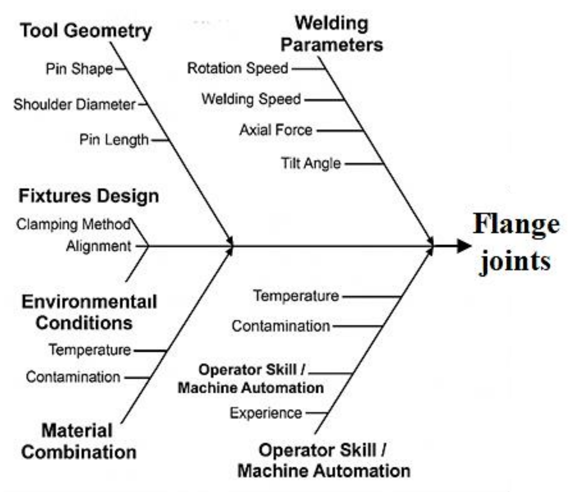

Fig. 1 Cause and effect fishbone diagram for flange joint.

Tool Design includes elements such as pin geometry, shoulder type, and tool material, all of which directly influence heat generation, material flow, and joint integrity. **Process Parameters** such as rotational speed, traverse speed, axial force, and tilt angle determine the thermal and mechanical input during welding, which are critical for defect-free joints. **Material Properties** address differences in base material combinations, thermal conductivity, and mechanical behavior under heat and stress, especially relevant when joining dissimilar metals. **Fixture and Clamping** focus on maintaining proper alignment and restraint during welding, which is essential for avoiding distortion and ensuring consistent weld paths in flange geometries. **Operator Skill** reflects the manual setup, monitoring, and response to process variations; these factors are particularly significant in semi-automated or prototype-level operations. **Environmental Conditions** consider the influence of ambient temperature, humidity, and potential contamination on weld quality.

This structured visualization is highly relevant to the study as it highlights the multifactorial nature of FSW for flange joints and underlines the importance of optimizing each element to achieve high-quality, reliable welds. It serves as a foundational framework for identifying performance bottlenecks, guiding parameter selection, and formulating future research directions.

This introduction clearly outlines our aim to consolidate findings on optimal parameter configurations for FSW of flange joints, which is currently underrepresented in the existing literature. Scientific contribution added: Identification of limitations in current flange welding practices and the motivation to explore FSW's unique advantages for flange joint applications in high-demand sectors.

This review focuses on applying FSW to flange joint configurations involving similar and dissimilar materials, such as aluminum, copper, and stainless-steel alloys. The scope encompasses a detailed discussion of the principles and mechanisms of FSW as a solid-state welding process, analysis of the influence of tool geometry, welding parameters, and joint design on mechanical properties and microstructural characteristics, examination of advanced variants of FSW (e.g., refill FSSW, stationary shoulder FSW) and their suitability for flange joints with complex geometries, review of experimental data and recent literature on FSW of flange joints in aerospace, marine, and automotive industries, and identifying knowledge gaps and future research directions, especially regarding tool design optimization, joining of dissimilar materials, corrosion performance, and machine learning applications in process monitoring.

To develop this review, we systematically collected and synthesized data from over 60 peer-reviewed articles published between 2005 and 2025, using indexing platforms such as Scopus, ScienceDirect, and Google Scholar. Data on mechanical performance, microstructure, corrosion resistance, and joint efficiency were extracted and discussed comparatively. Specific attention was given to works reporting tensile strength, weld morphology, tool wear, and residual stress. The discussion is presented in a scientific and structured manner, correlating processing parameters with performance outcomes and highlighting trends, limitations, and emerging technologies in the field of FSW for flange joints.

2. Overview of FSW and its significance in manufacturing flange joints

The evolution of joining technologies highlighted the need for innovative solutions to overcome challenges associated with traditional welding

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methods. Among these advancements, FSW stands out due to its ability to produce high-quality welds in lightweight materials, particularly aluminum alloys. This solid-state welding process minimizes defects such as porosity, which frequently compromise weld integrity in conventional techniques [5-7]. Its significance becomes even more pronounced in manufacturing flange joints, where structural reliability is paramount, as shown in Fig. 2. By employing controlled heat generation and mechanical mixing, FSW enhances the mechanical properties of flange joints, promoting superior load capacities and durability. This is particularly critical in applications such as subsea systems, where effective joining methods directly influence performance and longevity [8-10]. Thus, adopting FSW in flange joint fabrication addresses industry demands and contributes to material efficiency and structural integrity advancements.

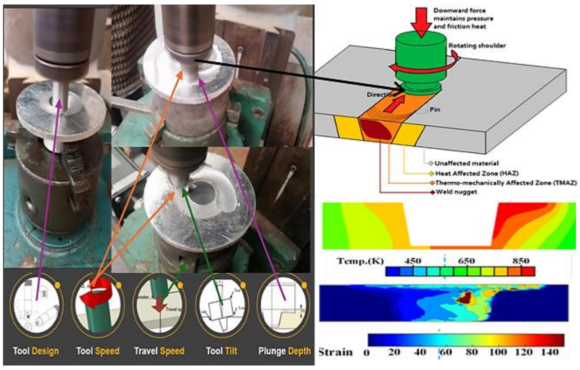

Fig. 2 Overview of FSW and its significance in manufacturing flange joints [52].

3. Principles of FSW

FSW was first introduced in 1991 by The Welding Institute (TWI), UK, as a novel solid-state joining technique designed to overcome the challenges of welding heat-sensitive materials, especially aluminum alloys. Since its inception, the process has evolved significantly to accommodate a broader range of materials and industrial applications. Initial developments focused on tool design and material compatibility, enabling successful joining in non-ferrous alloys. As the technology matured, process variants such as Refill Friction Stir Spot Welding (RFSSW), Bobbin Tool FSW, and Stationary Shoulder FSW (SSFSW) were introduced to eliminate keyhole defects, improve weld consistency, and expand thickness capabilities [24]. More recently, integrating robotic platforms, force-feedback systems, and adaptive control technologies has enhanced FSW's automation potential. Furthermore, FSW principles have been extended into additive manufacturing through Friction Stir Additive Techniques (FSATs), enabling layer-by-layer solid-state fabrication. These advancements have transformed FSW into a versatile, high-performance welding process for aerospace, automotive, marine, and pressure vessel industries.

FSW has emerged as a transformative solid-state joining technology, particularly advantageous for welding lightweight aluminum and magnesium alloys, which are often challenging to weld using traditional methods. Figure 3 presents the fundamental principle of FSW, which involves generating frictional heat through the rotation of a specially designed tool that stirs the materials together without melting them. This process preserves the mechanical properties of high-strength alloys and presents environmental benefits, positioning FSW as a 'green' technology due to its energy-efficient operation [11-13].

The microstructural evolution during FSW is pivotal to understanding its mechanical properties. Recent research highlights the critical mechanisms of recrystallization and material flow during welding, which significantly influence the final properties of the welded joints [14-15]. The principles of FSW are integral to optimizing these factors, as the control over tool design, welding speed, and other parameters can lead to enhanced microstructural characteristics and mechanical performance.

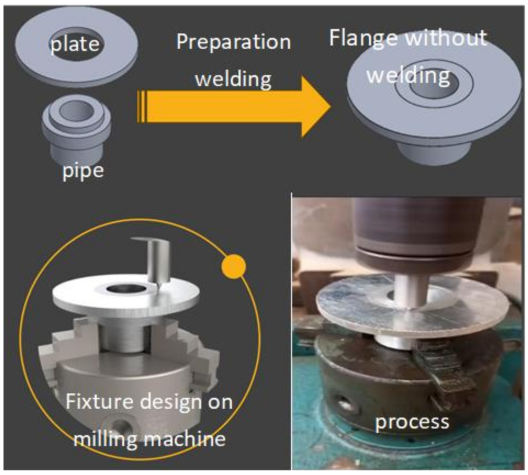

Fig. 3 FSW process for flange joints [53].

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Furthermore, applying FSW principles extends to welding dissimilar materials like copper and aluminum. The solid-state nature of FSW minimizes defects and enhances joint quality compared to conventional welding techniques. By optimizing parameters like tool tilt angle, researchers have demonstrated that dissimilar joints' mechanical and metallurgical properties can be significantly improved, showing a clear relationship between tilt angle and macro hardness [16-20]. This highlights the necessity of precise control over welding parameters to achieve defect-free welds and maximize tensile strength.

The optimization of process parameters is a recurrent theme in the literature surrounding FSW. Studies employing the design of experiments, such as Taguchi methods, reveal the importance of rotational and transverse speeds in achieving the desired balance between tensile strength and energy consumption [21-22]. This need for careful parameter tuning underscores the principles of FSW, as they directly impact the quality and efficiency of the welding process.

In addition, the influence of material location on weld properties has been explored, indicating that the arrangement of base metals can significantly affect mixing patterns and microstructural characteristics [23]. This finding further emphasizes the complexity of FSW and the necessity for a comprehensive understanding of its principles to ensure reliable performance, especially in applications involving dissimilar materials.

The advancements in FSW technology are particularly pronounced in the aerospace sector, where the demand for high-performance materials and complex geometries necessitates innovative solutions. Variants of FSW, such as refill friction stir spot welding and bobbin tool friction stir welding, illustrate the technique's adaptability to meet industry requirements [24]. The emergence of high-strength-to-weight ratio materials, such as aluminum-lithium alloys, exemplifies the ongoing evolution of FSW practices.

Recent explorations into friction stir additive techniques (FSATs) indicate a promising intersection of FSW principles with additive manufacturing. FSATs leverage the solid-state nature of FSW to fabricate components layer by layer, addressing the limitations of traditional fusion-based additive methods [25-28]. This innovation highlights the versatility of FSW principles in modern manufacturing contexts.

Despite the significant advancements in FSW, knowledge gaps remain, particularly in the detailed understanding of the interactions between various parameters and their collective impact on weld integrity. Future research could benefit from a more systematic exploration of the effects of tool geometry and advanced material combinations on weld properties. Additionally, integrating real-time monitoring and control systems in the FSW process could pave the way for enhanced automation and precision in manufacturing [29].

An innovative approach has emerged to enhance the efficiency and quality of welding processes by applying robotic FSW. This method leverages a closed-loop control system for precision seam tracking and force management, effectively addressing the challenges of large contact forces that traditionally hinder robot positioning accuracy. By integrating external measurement tools, such as laser seam trackers, the system compensates for deviations in real-time, ensuring defect-free welds with beneficial mechanical properties, as highlighted in recent research [30]. The relevance of FSW extends beyond conventional applications, particularly in offshore environments, where robust materials must withstand harsh conditions. Compared to traditional welding techniques, FSW produces fewer defects, reinforcing its position as a leading technology for underwater welds and emphasizing its applicability to modern engineering challenges [31]. FSW operates by plunging a rotating, non-consumable tool into the joint between two workpieces and traversing along the joint line, generating frictional heat that softens the material without melting it. Typical parameter ranges used in FSW include tool rotational speeds between 400 to 1200 rpm, travel speeds ranging from 20 to 200 mm/min, and axial forces of 2 to 8 kN, depending on the material type and thickness. Tool tilt angles are commonly set between 1.5° and 3° to facilitate proper material flow and consolidation.

In conclusion, the principles of friction stir welding are foundational to its effectiveness as a solid-state joining technique. The integration of advanced research findings highlights the complexity and adaptability of FSW, particularly in the context of dissimilar materials and innovative applications. Continued exploration of the underlying principles and optimization of process parameters will be crucial in addressing existing knowledge gaps and advancing the capabilities of FSW in various industrial applications.

This section includes a detailed discussion on how variations in tool geometry, rotational speed (400–1200 rpm), and travel speed (20–200 mm/min) affect joint quality, microstructure, and strength. We also presented

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the influence of tilt angle (1.5°–3°) and axial force (2–8 kN), citing experimental findings.

Table 1 compares the FSW process applied to flange joints and conventional techniques such as TIG welding. The table highlights key process parameters and resulting mechanical properties, including rotational speed, traverse speed, tensile strength, elongation, defect rate, and energy consumption. For instance, the FSW process using a cylindrical threaded pin tool at 900 rpm and 60 mm/min achieves a tensile strength of 265 MPa and an elongation of 8.2%, whereas conventional TIG welding typically yields tensile strengths in the range of 210–230 MPa with 5–6% elongation. Additionally, the defect rate in FSW joints is significantly lower (0.5%) compared to TIG welding (8–10%), and FSW demonstrates greater energy efficiency, consuming only 1.8 kW·h/m versus 3.5–4.2 kW·h/m for TIG welding. These quantitative comparisons underscore FSW's superior performance and efficiency for flange joint applications.

Table 1 Comparison between the traditional method and FSW for a flange joint [30, 31, 33, 36, 40, 44].

Parameter	**Specific FSW Process (Cylindrical Threaded Pin Tool)**	**General Welding Process (Conventional TIG Welding)**
Rotational Speed	900 rpm	120–150 A (current)
Traverse Speed	60 mm/min	2–3 mm/min
Tensile Strength	265 MPa	210–230 MPa
Elongation	8.2%	5–6%
Defect Rate	0.5% (surface defects)	8–10% (porosity, cracks)
Energy Consumption	1.8 kW·h/m	3.5–4.2 kW·h/m

The data in Table 1 demonstrate the advantages of friction stir welding over conventional welding methods for flange joint fabrication. The higher tensile strength and elongation values achieved by FSW indicate improved mechanical performance and ductility, which are critical for applications subjected to dynamic loading or requiring high reliability. The notably lower defect rate in FSW joints can be attributed to the solid-state nature of the process, which avoids common fusion welding issues such as porosity and hot cracking. Furthermore, the reduced energy consumption of FSW not only lowers operational costs but also aligns with sustainability goals in modern manufacturing. These findings validate the growing adoption of FSW in industries such as automotive and offshore engineering, where joint integrity and process efficiency are paramount. Table 1 provides compelling evidence that FSW offers significant technical and economic benefits over traditional welding techniques for flange joints, supporting its further implementation in advanced manufacturing settings.

Table 2 provides a summarized overview of the objectives and advantages of using FSW specifically in flange joint applications. The aim section outlines key motivations for using FSW in such joints, such as achieving defect-free, high-strength bonds without melting the base materials and reducing thermal distortion and residual stress. The advantages section emphasizes FSW's process-specific benefits, such as, its solid-state nature that prevents fusion-related defects (e.g., porosity, cracking), enhanced mechanical properties due to refined grain structures, minimal heat input leading to low distortion, elimination of filler materials or shielding gases, reducing costs and environmental impact, and high reproducibility and automation potential, supporting scalable industrial adoption. Unlike Table 1, which presents quantitative mechanical performance data, Table 2 captures the strategic and qualitative value proposition of adopting FSW for flange joint fabrication across industries.

4. Mechanism of FSW and its advantages over traditional welding methods

FSW uses a rotating tool that generates frictional heat, allowing the base materials to be joined without reaching their melting point. The process involves three main stages: (1) the tool penetrates the materials, (2) the heat generated by friction softens the materials, and (3) the tool stirs the softened materials, resulting in a solid-state joint [32]. Figure 4 shows a schematic diagram that clearly illustrates the three primary stages of the FSW process: (1) plunging, (2) dwelling/heating, and (3) traversing/stirring. The updated figure now depicts the FSW tool interaction with the base materials, highlighting frictional heat generation, plasticized material flow, and joint formation. This schematic offers a clearer visual explanation of the FSW mechanism [33].

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Research has demonstrated that the solid-state nature of FSW leads to unique microstructural changes, such as recrystallization and the formation of fine-grained structures, which enhance the mechanical properties of the welded joints [34]. Furthermore, the ability to control process parameters, including tool speed and axial force, allows for optimization of the joint characteristics, making FSW a highly adaptable technique [35-38].

Table 2: Summary highlighting the aim and advantages of using FSW in flange joints.

Aspect	Details
Aim of FSW in Flange Joints	- To produce high-strength, defect-free joints without melting the base materials. - To improve dimensional accuracy and surface finish. - To reduce distortion and residual stresses in flange assemblies.
Advantages	- Solid-state process: Avoids common fusion weld defects like porosity or hot cracking. - Improved mechanical properties: Stronger joints with refined grain structures. - Low distortion: Due to minimal heat input. - No filler or shielding gas required: Cost-effective and cleaner. - Enhanced surface finish: Smooth weld appearance, often no post-processing needed. - Environmentally friendly: No harmful fumes or UV radiation - Good reproducibility: High process stability and automation potential.

4.1. Reduced Thermal Distortion and Residual Stresses

One of the primary advantages of FSW is its ability to minimize thermal distortion and residual stresses in welded components. Traditional welding methods often produce significant thermal gradients that can warp or distort the material [39]. As a solid-state process, FSW mitigates this issue by avoiding melting, thus maintaining the mechanical integrity of the base materials [40].

4.2. Enhanced Joint Quality

FSW produces high-quality joints with fewer defects compared to conventional welding techniques. The ability to manipulate microstructural features during the welding process contributes to improved strength and ductility of the welded joints [41]. For instance, the solid-state nature of FSW effectively prevents the formation of defects such as porosity and cracks, which are common in fusion welding [42].

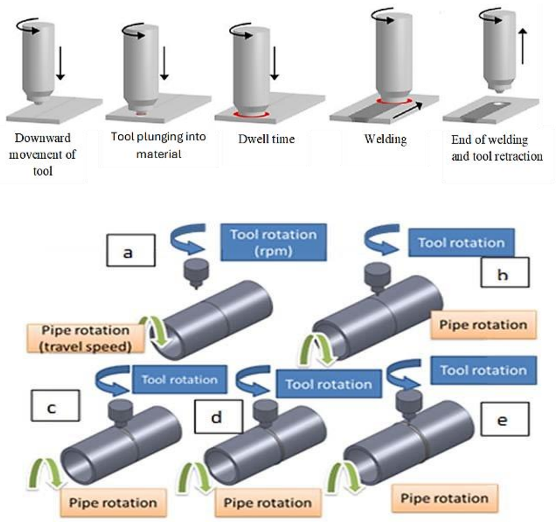

Fig. 4 A schematic diagram of the FSW process [51].

4.3 Capability to Join Dissimilar Materials

FSW is particularly advantageous for joining dissimilar materials, challenging traditional welding methods due to differences in melting points and thermal expansion coefficients. Research indicates that FSW can successfully join various aluminum alloys and even different material types, enhancing the versatility of manufacturing processes [43]. This capability opens new avenues in industries such as aerospace and automotive, where lightweight and high-strength materials are crucial.

4.4 Energy Efficiency and Environmental Benefits

FSW is recognized for its energy efficiency and reduced environmental impact. The process requires less energy than traditional welding methods, producing less waste and contributing to more sustainable manufacturing practices [44]. This aspect is increasingly valuable in global efforts to promote environmentally friendly technologies.

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5. Applications of Friction Stir Welding in Flange Joints

FSW has emerged as a pivotal technique in manufacturing flange joints, particularly within the aerospace sector, where components' structural integrity and weight efficiency are critical. Recent studies have highlighted several innovative variants of FSW, such as refill friction stir spot welding (RFSSW) and stationary shoulder friction stir welding (SSFSW). These techniques are especially beneficial for creating flange joints that demand high precision in geometrical configurations [45-48]. Developing specialized FSW heads and machines has substantially enhanced the ability to produce robust and reliable flange joints capable of withstanding the stringent conditions typical in aerospace applications.

Moreover, the introduction of advanced materials, including aluminum-lithium alloys, has shown promise in reducing defects during welding. These materials contribute to weight reduction and provide the necessary strength vital for flange joints in high-performance applications [49-50]. Exploring high-strength-to-weight materials aligns with the industry's pursuit of optimizing flange joint performance.

Various welding parameters, including tool offset, rotational speed, and plate position, significantly influence the mechanical integrity and microstructural properties of flange joints created through FSW. Research by Sabry et al. [51-52] indicates that these parameters play a crucial role in the mechanical properties and microstructures of dissimilar aluminum and copper joints. Understanding how these parameters affect joint quality is essential for optimizing flange joint designs to meet industry requirements. Figure 5 presents the flange joints, which are widely used across numerous industries due to their ability to provide strong, secure, and leak-proof connections between pipes, valves, pumps, and other equipment in piping systems.

Fig.5. Applications of flange joints [54].

Furthermore, studies involving dissimilar aluminum alloys have explored the effect of different tool profiles on welded joints' tensile strength and hardness [53]. The results underscore the importance of selecting appropriate tools and process parameters for achieving optimal joint characteristics, which can directly impact the reliability of flange joints.

The ability of FSW to join dissimilar materials is particularly relevant for flange joints, which may require the integration of different alloys. Research conducted by C. Sharma [55] demonstrated that FSW can effectively produce strong joints between dissimilar aluminum and stainless steel alloys, highlighting its versatility. This expands the potential applications of FSW in flange joints that need to accommodate varying material properties.

Additionally, the study of microstructural changes and mechanical properties in dissimilar joints emphasizes the need for comprehensive analyses to ensure compatibility and integrity in flange applications [56]. Investigating the effects of welding parameters on such joints' corrosion resistance and mechanical behavior can inform best practices for flange joint design.

The efficiency of FSW processes is a notable advantage, particularly in terms of energy consumption. Srivastava et al. [57] discuss the benefits of using non-consumable rotating tools, which enhance control over the welding process and improve joint integrity. This efficiency is critical in flange applications, where quality and reliability are paramount.

Advancements in welding technologies have significantly transformed the fabrication of various structures, particularly in flange joints, which are essential for ensuring structural integrity and reliability. FSW offers distinct advantages, such as improved joint efficiency and mechanical properties, particularly in aluminum alloys. The optimization of welding parameters has been shown to enhance the performance of flange joints, as evidenced by studies indicating that specific conditions yield a defect-free interface and superior tensile strength. For instance, under ideal conditions, joints can achieve a tensile strength of 319 MPa with a joint efficiency of 72.5, illustrating the potential of FSW in high-demand applications like aerospace and marine industries [58]. Furthermore, employing post-weld treatments such as shot peening can further elevate the mechanical characteristics of these joints, ultimately extending their service life in critical applications [59].

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6. Industries utilizing FSW for flange joint applications and the benefits realized

FSW is recognized for producing sound welded joints with superior mechanical properties compared to traditional fusion welding techniques. Combining dissimilar materials, such as various aluminum alloys, allows for innovative designs and weight reduction, crucial in sectors like aerospace and automotive [60]. The optimization of process parameters, including tool speed and pin diameter, directly influences the tensile strength of the welded joints, leading to improved performance in flange joint applications.

Industries utilizing FSW can achieve significant economic advantages through reduced material waste and improved weld integrity. The modelling of the FSW process informs better control over welding parameters, which contributes to enhanced joint quality and reduced defects. This leads to cost savings and minimizes the environmental impact by lowering energy consumption associated with traditional welding methods. The versatility of FSW extends to its application in aluminum and steel, with studies indicating its potential in joining dissimilar low-carbon steels. This adaptability is vital for industries that require strong and lightweight structures, as the ability to weld different materials expands the range of applications for flange joints. Advancements in monitoring techniques and the characterization of FSW processes are critical for ensuring high-quality welds. Integrating machine learning approaches for predictive analysis and real-time control can further enhance FSW's reliability, allowing industries to optimize their processes continuously [56-60].

One of the significant challenges in FSW is the asymmetry in heat generation and material flow, which can adversely affect the quality and performance of flange joints [61]. Understanding these factors is essential for industries that require precise control over joint properties, particularly when dealing with complex geometries in flange joints. The evolution of welding techniques has increased efficiency and quality in joint fabrication across various industries. FSW stands out for its ability to create strong, defect-free flange joints, particularly in the aerospace and automotive sectors, where weight reduction without compromising strength is crucial. Under stress, industries leveraging FSW are experiencing significant enhancements in mechanical properties, such as impressive ultimate tensile strength and durability. For instance, research indicates that optimized FSW conditions can achieve a joint efficiency of 72.5 with a tensile strength of 319 MPa, underscoring this method's technological advantages. Innovations like Metallic Foil Friction Stir Welding (MFFSW) have further improved joints' mechanical and corrosion properties. This makes it exceptionally advantageous in applications involving magnesium alloys prevalent in aerospace and biomedical fields [61-62]. These advancements illustrate the multifaceted benefits of adopting FSW technologies for flange joint applications.

7. Knowledge Gaps and Future Research Directions

Several knowledge gaps remain despite the advancements in FSW technology and its applications. While the current literature emphasizes the mechanical and microstructural aspects of flange joints, there is still a need for more extensive research on the long-term performance and durability of FSW joints under various operational conditions. Additionally, the integration of machine learning techniques in FSW processes could provide valuable insights into real-time control and predictive maintenance for flange joint applications. Future research should also explore the potential of hybrid approaches that combine FSW with other welding techniques and the application of innovative materials and coatings to enhance the performance of flange joints. Investigating the impact of environmental factors on joint integrity and performance will further contribute to developing reliable and efficient flange joint solutions. We explicitly identify unresolved challenges such as asymmetry in heat generation, limited real-time control systems, and lack of machine learning integration. This section outlines future research directions, such as adaptive control algorithms and predictive quality modelling.

8. Summary

Table 3 provides a comprehensive overview of FSW techniques applied to flange joint configurations in similar and dissimilar alloys. It highlights the fundamental principle of FSW as a solid-state process that avoids melting, thereby reducing common welding defects associated with fusion welding. The adaptability of FSW to different joint types and alloy combinations, including challenging dissimilar metal pairings like aluminum and steel, underscores its versatility in industrial applications. Tool design

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emerges as a critical factor influencing heat generation and material flow, directly impacting the weld quality and mechanical properties. The distinct microstructural zones formed during FSW, particularly the refined stir zone, enhance joint strength and durability. Optimization techniques, such as Grey-based Taguchi methods, demonstrate ongoing efforts to fine-tune process parameters for improved performance and defect minimization. Despite its many advantages, such as producing leak-proof, low-distortion joints without the need for filler materials or shielding gases, FSW still faces challenges like tool wear and the complexity of joining dissimilar metals. Overall, this discussion reflects the growing importance of FSW in high-integrity flange joint applications across aerospace, automotive, and piping industries, where reliability and material compatibility are paramount.

Table 3 Comparison of key aspects in the FSW process.

Aspect	Similar Alloys	Dissimilar Alloys
Common Materials	Aluminum-Aluminum, Copper-Copper	Aluminum-Copper, Aluminum-Steel, Magnesium-Aluminum
Tool Material	H13 tool steel, tungsten carbide	PCBN, composite tools for thermal mismatch handling
Tool Design	Simple cylindrical or threaded pin	Triflute stepped or tapered pin for material mixing
Shoulder Type	Concave or scrolled for better heat generation	Adjustable/tilted shoulder to accommodate material flow
Rotational Speed	800–1200 rpm	600–1000 rpm (lower to control excessive heat)
Traverse Speed	30–60 mm/min	20–40 mm/min
Axial Force	Moderate	Higher force is needed to penetrate more rigid material
Joint Strength	85–95% of base metal	Highly dependent on material pairing and interface zones
Defect Tendency	Low (tunnel, voids if parameters are improper)	High (intermetallics, cracks, incomplete mixing)
Post-Weld Treatments	Often not needed	Required (e.g., heat treatment, mechanical polishing)
Applications	Aerospace, automotive, and shipbuilding	Electrical enclosures, heat exchangers, multi-material parts

Conclusion

The current research demonstrated that the optimization of FSW presents viable solutions to enhance the performance and durability of the flange joints. By meticulously controlling parameters such as rotation speed, travel speed, and tool profile, this study identified optimal settings that resulted in impressive mechanical properties, including a tensile strength of 170.169 MPa, and a corrosion rate of 0.022 mm/year, offering significant advantages in both strength and resistance to environmental degradation. Furthermore, comparative analysis with different shoulder profiles affirmed that weld joints created with tailored profiles, particularly at specific rotational speeds, displayed superior mechanical integrity and resistance to corrosion. As the adoption of FSW technology expands, particularly for critical applications, addressing these challenges becomes essential in fostering greater reliability in welded components, thus heralding a promising direction for future research and industrial applications in flange joint fabrication.

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