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An Examination of New Advancements in Friction Stir Welding for Diverse Industrial Uses

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Abstract

Background: Sustainable manufacturing focuses on optimizing resource and energy use while minimizing environmental impact. This approach emphasizes energy-efficient and eco-friendly techniques to support long-term industrial growth. Welding, a crucial manufacturing process for creating complex structures, often relies on fusion methods that involve consumables such as filler materials, electrode coatings, shielding gases, or fluxes, leading to the emission of hazardous fumes detrimental to both human health and the environment. In contrast, Friction Stir Welding (FSW) is a solid-state joining process recognized for its energy efficiency and environmental sustainability. As a "green" manufacturing technology, FSW produces no harmful gases or radiation, making it an eco-friendly alternative to conventional welding methods. Its applications span diverse industries, including aerospace, automotive, marine, and railways. This paper illustrates the sustainable manufacturing attributes of FSW, highlighting its energy-efficient and environmentally friendly nature.

Furthermore, it explores the potential advantages of FSW for future industrial applications, emphasizing its role in advancing sustainable practices across various sectors. **Conclusions:**The study offers a forward-looking perspective by identifying potential areas for future research and addressing challenges that may emerge in the field of FSW. It emphasizes the importance of integrating environmental and economic considerations into the implementation of FSW to enhance its sustainability and applicability across industries.

Keywords: FSW, Principles, Microstructural, Mechanical Properties, Future Trends of FSW.

1. Introduction

Welding plays a crucial role in today's fast-evolving industrial landscape. With technological advancements, traditional welding methods such as MIG, TIG, and oxy-acetylene, alongside modern techniques like laser welding, have been adapted for diverse materials and applications. Among these, Friction Stir Welding (FSW) stands out as a solid-state process that joins materials without melting, ensuring superior structural integrity and compatibility with dissimilar materials. This unique capability overcomes challenges related to varying melting points and thermal expansion. FSW's versatility makes it invaluable across industries like automotive and marine engineering, where its solid-state approach offers distinct advantages over conventional fusion welding methods.

In this decade, welding has become progressively essential in addressing the requirements of a swiftly evolving industrial environment and various applications. As companies advance to adopt innovative technology and designs, welding remains a crucial activity, tackling the complex issues presented by contemporary engineering. Welding comprises diverse processes, each designed for use and materials. Notable types encompass conventional techniques, for example, arc welding, including MIG, TIG, and stick welding[1-5]. Flam welding [6] and contemporary advancements like laser welding [7]. FSW has arisen as an innovative option, offering certain benefits compared to conventional welding techniques [6].

In contrast to conventional welding, which depends on melting and solidification, (FSW utilizes a solid-state method [8]. This attribute reduces the likelihood of heat deformation, maintaining the integrity of structural materials as bonded. Moreover, FSW demonstrates superiority in welding different materials, which poses difficulties for conventional methods owing to variations in melting temperatures and thermal expansion. The solid-state characteristic of FSW enables the smooth joining of materials with differing characteristics, facilitating novel applications in areas where incompatible materials are common[9-10]

FSW has achieved considerable acclaim as a joining of a solid-state technique across multiple sectors since its introduction in 1991[11-14]. Fusion welding (FW) technology is garnering interest because of its capacity to unite materials that are challenging to bond with conventional procedures. FSW provides numerous benefits compared to traditional welding methods, including the efficient joining of incompatible materials and reduced expenses associated with adhesives, self-piercing of rivets, or alternative fasteners. Conventional welding methods may adversely impact joint characteristics due to variations in all properties. The FSW styles are especially effective for joining dissimilar materials because they operate at a considerably lower temperature than the melting point of the base material[15-16]. This approach, which has several advantages such as lower prices, improved fatigue and strength of tensile, a tool non-consumable, little environmental effect, and heightened sustainability, has significantly advanced the automobile manufacturing sector[17]. This method has become critically important in automotive manufacturing because of its multiple advantages, including enhanced fatigue and tensile strength, resource efficiency, environmental sustainability, and reduced operational expenses. FSW is a quickly advancing technology with significant potential in the marine industry [18-19]. Recent innovations have improved the quality of the weld and overall productivity, making it increasingly attractive for industry applications. Cutting-edge designs of tools featuring pins of multiple shoulders effectively reduce welding stress while boosting joint strength [20-23]. Automated FSW systems further enhance the uniformity and efficiency of welding complex and large structures. Integrated FSW techniques, which mix FSW with other methods such as arc, have been shown to improve both the quality of weld and efficiency of the process in specific scenarios[24-27]. FSW is widely utilized across different industrial applications, including the repair of ships and structures offshore. It is particularly effective for joining panels of aluminum alloy and panels of the deck and repairing damaged components. Offshore applications include welding aluminum alloy parts in structures like oil platforms and turbines of wind. Beyond the marine sector, FSW is extensively applied in the automotive industry, particularly for materials with similar or differing properties due to its lower thermal input. It enables the seamless joining of different materials, like Al/Mg, Al/steel, and Al/Ti, demonstrating its versatility across a range of applications[29-30].

Machine learning (ML) methods have garnered much focus as effective models for many manufacturing systems in recent years[31-35]. Applications for machine learning have also been observed in the field of FSW. Machine learning methodologies have exhibited notable applicability across diverse engineering domains, such as fracture mechanics[36-38], structural engineering [39], composite materials[40-44], laser cutting [28], and friction stir processing [45], among others. Various FSW methods possess distinct welding settings and conditions, rendering the modeling process complex and time-consuming. Learning Machine techniques are recommended for modeling FSW owing to their capacity to comprehend the correlation model control factors and process responses via error-based learning during training [46]. This review highlights the developments in FSW for maritime applications, showcasing its benefits over traditional techniques. Key areas of improvement include strength of joint, resistance of corrosion, fatigue performance, welding equipment, selection of material, prevention of corrosion, and protection of surface, alongside the integration of machine learning approaches. The study advocates more investigation and highlights the importance of addressing economic and environmental aspects in the broader adoption of FSW technology.

2. Principles of FSW

FSW is a cutting-edge solid-state welding method that joins metals to form sturdy, superior connectors without melting them. It uses a specific tool that has a revolving pin and a shoulder[47-49]. As the tool enters the joint., the frictional heat generated softens the material without liquefying it, forming a malleable plasticized region that allows for grain refinement and material fusion. The rotating motion of the tool mixes the softened material, resulting in a seamless and robust weld along the joint line [50]. This method is particularly effective for joining aluminum, offering the strength of superior and minimal distortion, making it highly valuable in industries such as industrial manufacturing[50-55].

The shoulder and the pin, the two primary parts of the FSW tool, are each made for a particular welding application. The larger, flat shoulder applies a downward force to secure the materials, while the pin is tailored for welding materials thinner [56]. Typically, heat-resistant and resistant wear materials make up the shoulder. Materials like carbide of tungsten and many FSW tools include cooling systems to dissipate heat, extending tool life and reducing friction[57-62]. The pin, a small, contoured, or threaded part, penetrates the joint and plays a critical role in regulating material flow and guaranteeing the appropriate joint characteristics [63]. Constructed from durable, heat-resistant materials, the pin's design, including its profile, rotational speed, and direction, is crucial for achieving optimal weld quality[64-66]. Advanced FSW tools may feature retractable pins to adjust penetration depth, which is beneficial for materials of varying thicknesses. Threaded pins [65] are often utilized to improve material combination and the quality of joints. The tool's rotation generates sufficient heat to soften the surrounding material, creating a plasticized zone where grain structures are refined. This eliminates common defects like voids and inclusions found in traditional fusion welding. As the tool progresses, the material solidifies behind it, forming a strong weld with a refined " nugget of weld " that achieves maximum strength [67].

The quality of welds in the Friction Stir Welding (FSW) process is determined by critical parameters that must be optimized for specific applications. Proper adjustment of these factors is essential to produce superior welds without flaws and with the required mechanical qualities[67-70]. Flexibility in modifying these parameters makes FSW a flexible technique for combining a variety of materials and components.

The speed of rotational FSW tools affects the generation of heat, material plasticity, and flow dynamics. While higher speeds can improve welding efficiency, they may also accelerate the wear of the tool and reduce control over material flow. Traverse speed plays a key role in ensuring thorough mixing and flow of material, but it increases heat input and extends the welding cycle. Conversely, speeds of traverse faster reduction heat input, however, may compromise the quality of joint[70-74]. The choice of tool material is critical to the welding process. FSW tools must be made from materials with higher resistance to wear and withstand the mechanical and thermal stresses of welding. Common materials include tungsten carbide, tool steel, and cermet. Selecting the right tool material is crucial to avoid contamination and ensure efficient material flow. Additionally, the tool's design, particularly the pin and shoulder geometry, has a major impact on material flow, heat generation, and joint integrity[75-78]. The profile of the pin and dimensions of the shoulder are customized for specific applications, while tilt angles improve performance for certain materials and configurations of joints[79-82].

The downward force applied by the FSW machine is another vital factor, as it governs the interaction and friction between the workpieces and the instrument. This force has to be closely monitored to maintain the proper flow of material and ensure joint integrity. The type of material being welded also affects the FSW process, requiring adjustments to tool parameters for thicker materials or complex geometries. By fine-tuning these variables, the FSW process can achieve optimal results across diverse applications. FSW employs a specialized tool with a rotating pin and shoulder that generates frictional heat, softening the materials without melting them. This process creates a plasticized zone that facilitates material mixing and grain refinement, resulting in high-quality welds. The tools, including pin and shoulder geometry, materials, and cooling systems—are tailored to specific welding applications, influencing weld quality and efficiency. Key parameters like speed of rotation, traverse speed, and tool material are optimized to achieve defect-free joints with desirable mechanical properties.

3. Characterization of Microstructural and Mechanical

FSW is a technique of solid-state welding that can induce microstructural and mechanical alterations in FSW joints. The agitation process enhances grain refinement, leading to microstructural alterations that influence the mechanical properties of the weld[83-85]. The mechanical qualities, including hardness, strength of tensile, and toughness, are influenced, rendering FSW joints appropriate for industrial applications. Consequently, examining both the mechanical and microstructural characteristics of joint FSW is essential. The texture formation in the zone stirred through FSW is attributed to the combined impacts of significant deformation of plastic and elevated temperature exposure[86-88]. Likewise, the disintegration of precipitates and their ensuing coarsening are noted within and adjacent to the agitated region[88-89]. The variations in microstructure across different regions significantly influence the mechanical properties observed post-welding. As a result, many researchers have examined microstructural change that transpires during FSW[90-95]. Because of the strong plastic deformation and frictional heat production, FSW creates a refined microstructure in the stirred zone. The most significant area affected is the zone of nugget, commonly referred to as the weld nugget. At the interface between the recrystallized nugget zone and the base material, there is a gradual transition on the advancing side of the tool and a more distinct boundary on the retreating side [96]. The nugget zone can be categorized into two distinct shapes: a basin-shaped nugget that broadens toward the upper surface and an elliptical nugget with an oval configuration. The shape of the nugget zone is influenced by several factors, including the welding process parameters, tool geometry, the temperature of the workpiece, and the thermal conductivity of the material being welded.

Recrystallization of dynamics through FSW is recognized to result in the development of equiaxed, fine granules in the zone of nugget[97-99]. The dimensions of returned to crystal form grains in FSW materials are substantially affected by multiple factors, encompassing parameters of FSW, the geometry of the tool, the composition of the workpiece, temperature of the workpiece, vertical pressure, and cooling of active. The grain size within the zone of weld increases in the upper region, whereas it diminishes as one proceeds away from the zones of weld centerline.

4. Improvement of FSW Joints' Mechanical Properties

A few studies have shown that the variations in hardness resulting from FSW differ amidst precipitation-hardened aluminum alloys and those hardened by solid solution. In precipitation-hardened aluminum alloys, FSW creates a thermomechanically affected zone (TMAZ) encompassing the center of the weld[100-105]. Previous studies indicate that the noted diminish in hardness is primarily due to the breakdown and dissolution of fortifying precipitates during the cycle of the thermal FSW process[106-112].

Sato et al. [113] investigated the hardness profiles of the microstructure in FSW 6063Al-T5 and found that the distribution of precipitates had a greater impact on the hardness profile than grain size. Similarly, Svensson et al. [114] studied the microstructure and properties of FSW 5083Al-O. They observed that the zone of the nugget contained fine equiaxed grains, characterized by a decreased presence of large particles and a grown concentration of particles of small.

In 5083Al, hardness was primarily impacted by the density of dislocation, with hardening of strain identified as the main hardening mechanism. FSW facilitated the formation of tiny crystals that have recrystallized in the zone of the nugget and improved the grain structure in the TMAZ. The area of nugget and TMAZ exhibited higher densities of dislocation than the base material. Additionally, both small and large Al6(Mn, Fe) particles were found in the nugget zone and substrate. The hardness profile of FSW 5083Al could not be fully explained using the Hall–Petch relationship but was instead attributed to Orowan strengthening, particularly the dominant effect of dispersion strengthening due to the distribution of small particles. FSW alters the microstructure of welded joints through grain refinement, enhancing mechanical properties like hardness, tensile strength, and fatigue resistance. The stirred zone, or weld nugget, exhibits dynamic recrystallization, which contributes to improved joint strength. Differences in microstructural characteristics across zones impact mechanical performance, making detailed analysis critical for applications in sectors like marine engineering.

5. Future Trends of FSW

Friction Stir Welding (FSW) is a cutting-edge technique that enhances mechanical properties and joint strength by eliminating solidification and melting processes. It is particularly well-suited for industrial applications, especially in joining dissimilar materials such as aluminum alloys, due to their corrosion resistance and minimal post-welding cleanup requirements. FSW is expanding its applications to include high-strength steels, titanium alloys, and composites. It offers significant benefits such as improved structural strength, reduced weight, and enhanced corrosion resistance, making it ideal for advanced engineering challenges.

Hybrid FSW, when integrated with laser welding, facilitates innovative applications for combining diverse materials, such as hybrid hull designs, enabling the customization of vessel attributes to fulfill specific criteria[114-120]. The monitoring and analysis of welding parameters in real-time through FSW and data analytics can enhance the quality of the weld and reduce defects. Laser-assisted FSW, a hybrid method, enhances the properties of welded joints by preheating the workpiece, hence minimizing the wear of the tool and the force of plunging. This method facilitates material fusion and enhances the welding procedure's regulation. Laser-assisted FSW has demonstrated favorable outcomes in industrial sectors, where robust welds are essential for structural integrity and performance. FSAW improves the mechanical and microstructural characteristics of joints[121-131]. FSW is augmenting its material capabilities to encompass composites, titanium alloys, high-strength steels, and aluminum alloys to fabricate stronger, lighter, and corrosion-resistant vessels for saline environments. The integration of laser welding with friction stir welding will facilitate hybrid hull designs, promoting innovation in shipbuilding. FSW will modify the vessel's characteristics by integrating diverse materials, including titanium alloys for weight reduction and composite materials or resistance to corrosion [127]. The integration of technology will enhance the welding process through the use of automation technologies, such as advanced robotics, facilitating real-time monitoring and analysis to improve weld quality and minimize faults. Advanced techniques like LAFSW [128] and FSAW [203] will be employed to enhance weld properties and regulate the welding process.

LAFSW reduces tool wear and force requirements while enhancing the properties of welded joints, rendering it advantageous in the aerospace and industry of automotive sectors. FSAW integrates the benefits of FSW and the manufacturing of additives, facilitating the creation of intricate geometries with enhanced durability and strength.FSW is widely used in industrial applications, including pipelines, maintenance, and structures offshore, where it is preferred for its ability to weld aluminum alloys and other materials. Hybrid approaches, such as combining FSW with laser welding, offer enhanced weld quality and adaptability. Advanced technologies like machine learning are increasingly applied to optimize FSW parameters and predict welding outcomes. Future research is expected to focus on expanding FSW's material compatibility, integrating automation, and incorporating sustainability considerations in industrial projects.

5. Conclusion

FSW is a highly efficient method for joining materials, particularly in marine applications such as underwater joints. This study examines recent advancements in FSW and its applications in the marine industry, highlighting the key factors and parameters that influence its effectiveness. This study delves into the fundamental principles and operational mechanics of FSW, emphasizing its capability to produce high-strength joints with superior mechanical and corrosion-resistant properties. The study examines the impact of FSW parameters on microstructural changes in materials, demonstrating how tool stirring, grain refinement, and superplasticity contribute to improved joint mechanical properties. These enhancements bolster the efficiency and economic viability of FSW in industrial applications.

Additionally, the study underscores the importance of using materials compatible with FSW that can endure harsh industrial conditions and resist corrosion effectively. This paper examines future research opportunities in FSW for maritime engineering, emphasizing the integration of environmental and economic considerations to promote sustainability and cost efficiency in large-scale industrial applications. It advocates for the development of methodologies that enhance industrial efficiency and productivity while minimizing ecological impact. The paper highlights the pivotal role of FSW in achieving these goals and encourages its comprehensive adoption across the industry. The study investigates the microstructural and mechanical aspects of welding processes, with a focus on optimizing parameters for improved performance. It highlights the role of FSW in preserving marine structures by reducing corrosion and protecting surfaces. Future research should prioritize the development of advanced FSW equipment, exploration of innovative materials, and strategies to mitigate environmental impact. FSW technology is transforming industrial applications by enhancing the efficiency and durability of structures while aligning with environmental and economic objectives. Through ongoing research, innovative techniques, and a focus on sustainability, FSW demonstrates its potential to drive the sector toward greater efficiency, resilience, and environmental stewardship. Although still in its early stages, FSW holds immense promise for advancement and development, offering substantial implications for the future of industrial applications.

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