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INFLUENCE OF PIN PROFILE GEOMETRY ON THERMAL **EFFICIENCY AND MATERIAL FLOW IN FRICTION STIR WELDING: A COMPREHENSIVE REVIEW**

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ABSTRACT

This review explores the impact of different pin profiles on thermal efficiency and material flow in Friction Stir Welding (FSW). Pin profile selection is critical in FSW, as it directly affects heat generation, material flow, and weld quality. Each profile-cylindrical, threaded, tapered, square, triangular, fluted, whorl, and bobbin-creates unique heat and flow characteristics that influence weld structure and performance. Cylindrical pins offer moderate heat generation for softer materials, while threaded and square profiles enhance material mixing through increased friction, improving weld strength but requiring careful thermal management. Tapered and fluted profiles support even heat distribution, beneficial for thicker or dissimilar material welds. Whorl and bobbin profiles improve thermal uniformity, particularly in thicker joints, enabling more consistent weld quality. This paper highlights the thermal efficiencies of these profiles and the critical balance between heat input and material flow. Selecting an appropriate profile optimizes thermal management and minimizes defects, making FSW a versatile technique for various alloys and complex joint configurations. This review provides insights into how different pin geometries can be tailored to achieve efficient, high-quality welds across applications, while addressing future research directions in pin design to expand FSW's applicability and efficiency.

Keywords: Friction Stir Welding, Pin Profile Geometry, Thermal Efficiency, Material Flow, Weld Quality

1. INTRODUCTION

Friction Stir Welding (FSW) is an innovative solid-state joining process that has gained significant traction across multiple industries, particularly in aerospace, automotive, shipbuilding, and railways, due to its ability to join materials without melting. Developed in the 1990s, FSW offers advantages over traditional fusion welding methods, including improved mechanical properties, reduced porosity, minimal distortion, and the ability to weld difficult-to-join materials, such as aluminum alloys and high-strength steels. This technique is especially valuable for applications that demand high structural integrity and resistance to defects in welded joints. During FSW, a specially designed rotating tool, featuring a shoulder and a pin, plunges into the materials to be joined and traverses along the joint line. The friction between the rotating tool and the workpiece generates localized heat, softening the material around the pin without reaching the melting point. This softened material then flows around the pin, forging a solid joint upon cooling. A critical factor influencing the heat generation, material flow, and quality of the weld is the profile of the tool pin. Different pin profiles, such as cylindrical, conical, and threaded designs, play an instrumental role in the thermal distribution within the welded material, affecting joint strength, microstructure, and overall weld quality.

Thermal analysis of FSW is essential to understand the heat distribution patterns, peak temperatures, and cooling rates in the welded region, as these thermal factors directly impact microstructural transformations and mechanical properties of the weld. Accurate thermal analysis helps in optimizing the process parameters, such as tool rotation speed, traverse speed, and axial force, to achieve desirable weld characteristics and to prevent defects like tunnel formation or incomplete fusion. Furthermore, the choice of pin profile influences the heat generation rate and temperature distribution, which can be tailored to meet the specific requirements of various materials and applications.

This review paper focuses on the thermal analysis of friction stir welding using tools with different pin profiles. It provides an overview of the role of tool pin geometry in the thermal behavior of FSW, examines the effects of various pin profiles on heat generation and distribution, and highlights recent advancements in computational and experimental techniques for thermal analysis in FSW. By synthesizing findings from recent studies, this paper aims to offer insights into how different pin profiles influence weld quality and process efficiency, paving the way for further optimization of FSW in industrial applications.

J. V. Christy et al. [1] explore the challenges of fusion welding aluminum alloys, citing issues such as porosity and solidification cracks. They review alternative FSW techniques like underwater (UFSW) and vibrational (VFSW) friction stir welding to address these issues, emphasizing VFSW's potential for energy efficiency and versatility. The review also urges more research on friction stir welding of aluminum matrix composites (Al-MMCs) C. Zhang et al. [2] analyzed dissimilar AA2024-T351 to AA7075-T651 joints made by friction stir welding under high heat input, focusing on the effects of post-weld heat treatment (PWHT) on the microstructure and mechanical properties. The study found that abnormal grain growth (AGG) occurred in the nugget zone (NZ) after PWHT, compared to the fine equiaxed grains



in the as-welded joint. The AA2024 side exhibited more significant grain growth than AA7075. Despite the presence of stable shear textures, the joint performance did not improve post-PWHT due to weak penetration at the interface, causing fractures to occur in the NZ P. Kah et al. [3] address the challenges faced by the transportation industry, focusing on energy-efficient and ecologically sustainable solutions. Aluminum alloys play a key role in meeting these demands due to their lightweight properties. While advancements in aluminum welding techniques have mitigated many welding issues, some defects persist. The study reviews defect formation in friction stir welding, laser beam welding, and arc welding of aluminum alloys. It examines the relationship between friction stir welding parameters and weld defects, and discusses issues like porosity and hot cracking in laser welding. Metallurgical factors influencing microstructure and defect prevention in arc welding are also presented. K. R. Ramkumar et al. [4] investigated the fabrication of AA7075/TiC metal matrix composites (MMCs) with varying TiC content (0, 2.5, 5, and 7.5 wt.%) via stir casting. The composites were characterized using X-ray diffraction and electron microscopy. Mechanical properties, such as flexural strength and hardness, as well as tribological properties like wear resistance and friction coefficient, were analyzed. Results showed that TiC dispersion enhanced mechanical and surface properties compared to monolithic AA7075 due to particulate strengthening. X-ray diffraction confirmed successful composite formation with no inter-metallic phases, highlighting the positive influence of TiC on the ductile AA7075 matrix C. Zhang et al. [5] studied the effect of rotational speed on the microstructure, mechanical properties, and corrosion behavior of dissimilar friction stir welded AA2024/7075 joints. Results showed that rotational speed significantly influenced the local microstructure, forming fine equiaxed grains in the nugget zone (NZ) with grain size decreasing from the shoulder to the bottom zone. Different shear textures developed in the NZ, varying with speed.

The optimal tensile strength (411.4 MPa) was achieved at 950 rpm with 87.6% welding efficiency relative to AA2024. The welded zone exhibited higher corrosion current density, with the best corrosion resistance observed at 950 rpm due to optimal precipitate characteristics Y. C. Chen et al. [6] examined the precipitate evolution in friction stir welded 2219-T6 aluminum alloys using transmission electron microscopy. In the weld nugget zone (WNZ) and thermo-mechanically affected zone (TMAZ), some metastable precipitates overaged to equilibrium phases, while others dissolved into the aluminum solid solution. In the heat-affected zone (HAZ), the precipitates coarsened, indicating significant microstructural changes due to the thermal and mechanical effects of the welding process S. Raja et al. [7] reviewed the emerging field of nanomaterial-reinforced friction stir welding (FSW), which enhances joint properties by creating composite joints with improved surface characteristics such as hardness, strength, corrosion resistance, wear resistance, and fatigue life. The review discusses the need for nanoparticle reinforcement in FSW, types of nanoparticles used, their properties, and behavior.

It also analyzes the microstructural changes in reinforced joints and explores how these changes affect various properties. Additionally, the review covers methods for nanoparticle deposition in FSW and concludes with prospects for future development in this area J. Li et al. [8] studied the friction stir welding (FSW) of 7A04-T6 aluminum alloys, achieving the highest tensile strength at a welding speed of 120 mm/min and a rotation speed of 1000 r/min, reaching 77.93% of the base material's strength. The nugget zone (NZ) had fine grains with a boundary misorientation angle of 15°, which hindered micro-crack propagation and enhanced joint toughness. The S-N curve showed a decrease in fatigue strength with increasing fatigue life. A fatigue limit of 141 MPa was determined, with fractures occurring in the heat-affected zone (HAZ). A subsequent laser local heat treatment (LLHT) further refined the microstructure, improving mechanical properties A. Heiderazadeh et al. [9] explore the unique capabilities of friction stir welding (FSW) and friction stir processing (FSP) in tailoring microstructure and performance through large strains, high temperatures, and high strain rates. While much focus has been on FSW parameters affecting weld quality, this study emphasizes understanding microstructural evolution during FSW/P. It examines mechanisms of grain structure development, phase transformations, and precipitation across various materials, with particular attention to managing intermetallic compounds in dissimilar metal joints. Additionally, the study highlights FSP's role in local microstructure refinement and metal matrix composite formation.

The review concludes by identifying knowledge gaps and future research directions R. Kesharwani et al. [10] investigated the microstructure, mechanical properties, and texture evolution of AA6061-T6 metal matrix composites (MMCs) reinforced with silicon carbide (SiC) and zinc (Zn) particles via friction stir welding (FSW). The stirred zone (SZ) showed ultra-fine grain refinements of 4.79 μ m for SiC and 4.18 μ m for Zn, compared to the base metal's 44.97 μ m. This refinement led to dynamic recrystallization with homogeneous particle distribution. The SiC-reinforced composites exhibited recrystallization textures such as P {011} <112> and cube {001} <101>, while Zn-reinforced composites showed textures like copper {112} <111> and Goss {110}. Microhardness was 110 ± 4 HV0.2 for SiC and 120 ± 5 HV0.2 for Zn, with tensile strengths of 224 MPa and 236 MPa, respectively.



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2. TYPES OF PIN PROFILE

In Friction Stir Welding (FSW), the design of the tool pin profile is crucial for achieving desired weld characteristics, as it directly influences heat generation, material flow, and overall weld quality. Various pin profiles are commonly used, each tailored to specific welding requirements. The cylindrical pin is one of the simplest designs, providing balanced heat generation and material flow, particularly effective for softer materials like aluminum alloys. However, it may lack sufficient stirring action for harder materials. Threaded pins, in contrast, are designed with threads along their surface, creating a "screw-like" effect that enhances material mixing and promotes better joint strength. This profile, suitable for materials requiring additional stirring action, improves weld consistency but may contribute to excessive heat and tool wear in certain applications.

The tapered pin, which narrows from the base to the tip, is designed to optimize material flow and heat distribution. Its conical shape reduces welding forces, making it useful for various thicknesses and enhancing thermal stability. For materials requiring intense mixing, square or triangular pins introduce additional turbulence in the weld zone, improving mechanical properties and joint integrity. These profiles, however, demand careful thermal management due to higher friction and wear. Additionally, fluted pins (e.g., triflute) incorporate grooves along their surface to promote vertical material flow and reduce the heat needed to produce sound welds. This design is particularly useful in dissimilar material welding, where heat management is essential to accommodate varying melting points.

Whorl or spiral pins feature helical designs that facilitate both horizontal and vertical flow, ensuring consistent heat distribution along the weld path and reducing welding force requirements. Similarly, bobbin (double-shoulder) pins employ a double-shoulder design to apply uniform heat and pressure across both sides of the weld, minimizing distortion and enhancing the quality of thick welds. For even stronger interlocking and grain stability, hexagonal pins are sometimes employed, although they require advanced friction management due to their high heat generation.

In some cases, polygonal and custom-shaped pins are used for specific applications that demand unique stirring patterns to achieve specialized weld characteristics. Examples include pentagonal or star-shaped pins, which create a highly tailored material flow suitable for challenging applications. Conical threaded pins combine the benefits of tapered and threaded designs, providing enhanced flow and heat generation, which is beneficial for high-strength alloys and complex material joints. Finally, concave and convex pins are occasionally used for specific thermal distribution needs, particularly in thicker materials, as they offer control over heat concentration and flow direction. Selecting the optimal pin profile is thus critical in FSW, as each profile offers distinct advantages and limitations that can be matched to the material, joint configuration, and mechanical requirements of the welded structure.

3. EFFECT OF PIN PROFILE

The effect of pin profiles on material flow is a fundamental aspect of Friction Stir Welding (FSW), directly influencing weld quality, microstructure, and mechanical properties. Each pin profile introduces unique material movement patterns within the weld zone, enhancing or limiting the efficiency of the stirring process. For instance, cylindrical pins provide a relatively uniform material flow, making them effective for creating smooth, consistent welds in softer materials, but may lack the aggressive stirring action needed for higher-strength alloys. Threaded pins, on the other hand, introduce a "screw-like" effect that actively pulls material down along the length of the pin, improving mixing within the weld zone. This action is particularly beneficial for welds requiring greater material interlocking and homogeneity, though it can lead to elevated heat input that may need careful management.

Tapered pins, with their conical shape, promote a gradual, controlled flow of material from the tool shoulder down to the root of the weld. This design reduces the welding force required and allows for a smoother transition of material flow, which can help minimize defects and ensure even distribution of temperature. More complex profiles, such as square and triangular pins, create turbulence and intense mixing within the weld zone, which is particularly advantageous for joining dissimilar materials or for high-strength alloys where a robust joint structure is essential. These profiles enhance bonding by creating localized zones of high plastic deformation but can also lead to excessive tool wear due to the increased friction and heat generated.

Advanced designs, such as fluted or triflute pins, further enhance material flow by channeling material vertically along the pin through grooves or flutes, reducing resistance and creating a more uniform mixing action. This feature is especially useful in dissimilar material welding, where differential heat management is required. Whorl and spiral pins, with their helical structures, provide both horizontal and vertical stirring effects, ensuring thorough mixing across all areas of the weld and contributing to more consistent mechanical properties across the joint. The bobbin pin profile, with shoulders on both ends, exerts equal force and heat distribution on the top and bottom surfaces of the weld, allowing for effective joining of thick materials without backing plates.



Each pin profile thus plays a critical role in directing material flow, determining the extent of plastic deformation, and influencing the overall thermal cycle experienced by the weld. The selection of an appropriate pin profile is essential to achieving a defect-free weld with optimal mechanical properties, tailored to the specific requirements of the material and joint configuration.

4. THERMAL EFFICIENCY OF PIN PROFILE

The thermal efficiency of pin profiles in Friction Stir Welding (FSW) is a key factor in determining the quality and characteristics of the weld. The pin profile not only affects material flow but also influences the amount of heat generated and how that heat is distributed throughout the weld zone. Each profile shape induces varying levels of friction, plastic deformation, and energy dissipation, which all contribute to the thermal profile and efficiency of the welding process.

Cylindrical pins generally provide moderate thermal efficiency, producing consistent but relatively low heat, which can be advantageous for welding softer materials like aluminum alloys.

This profile minimizes excessive heat, helping to prevent overheating and preserving microstructural properties. However, it may lack the thermal intensity needed for harder materials, where higher energy input is often necessary. Threaded pins, due to their helical structure, generate additional friction and consequently higher heat. The threads increase surface contact with the material, enhancing thermal efficiency and promoting deeper penetration, but this can also lead to excessive localized heating, which requires careful monitoring to avoid overheating or excessive tool wear.

Tapered pins enhance thermal efficiency by concentrating heat at the wider shoulder end and gradually reducing it along the tapered profile. This allows for a controlled thermal gradient, which is useful for thicker materials or joints that need a more uniform heat profile without excessive buildup.

Tapered designs also help in managing heat dissipation along the weld length, contributing to a stable and efficient welding process. Square and triangular pins are known for generating high heat due to their angular edges, which increase friction and promote intense stirring action. This high thermal efficiency is beneficial for tougher materials but can lead to thermal stress and potential distortion in softer materials, necessitating precise control over process parameters.

Fluted or triflute pins contribute to efficient heat generation by reducing resistance during material flow, which can allow for a lower welding force and controlled thermal buildup. The flutes act as channels for distributing heat evenly across the weld zone, increasing thermal efficiency while preventing localized overheating. Whorl and spiral pins generate uniform heat along the weld line due to their helical structure, which enhances both thermal and mechanical efficiency. These profiles are ideal for applications where even heat distribution is critical, especially in dissimilar material welding. Lastly, bobbin (double-shoulder) pins create balanced thermal efficiency on both sides of the weld, making them particularly effective for thick materials, as the dual shoulders help to regulate heat distribution and minimize heat loss.

In summary, the thermal efficiency of a pin profile depends on the specific shape, which controls heat generation, dissipation, and distribution. Selecting the appropriate profile allows for optimization of the thermal input, ensuring consistent weld quality, minimizing defects, and achieving a stable thermal cycle tailored to the material and joint requirements.

5. CONCLUSION

In conclusion, the pin profile in Friction Stir Welding (FSW) plays a vital role in determining both the thermal efficiency and material flow, significantly impacting weld quality and performance. Each profile—whether cylindrical, threaded, tapered, or complex shapes like square, triangular, or fluted—offers unique characteristics that influence the heat generation, distribution, and overall energy input in the weld zone. Profiles like cylindrical pins provide moderate thermal input suitable for softer materials, while threaded and square profiles increase friction and mixing, enhancing thermal efficiency but requiring careful control to prevent overheating.

Advanced profiles, such as tapered, whorl, and bobbin designs, help achieve more uniform thermal distribution, making them ideal for thick or dissimilar material welds.

Choosing the right pin profile optimizes thermal management, ensuring effective plastic deformation and consistent mechanical properties in the weld. The profile should be selected based on the specific material properties, joint configuration, and desired weld characteristics.

Ultimately, understanding the effect of pin profiles on thermal efficiency is essential for achieving defect-free, highquality welds in various industrial applications. Future research may continue to explore novel pin designs, optimizing FSW for an even broader range of materials and thicknesses, and further improving efficiency and weld integrity.



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