Review Article

Influence of Tool Pin Profile on Microstructure and Mechanical Properties in Friction Stir Welding of Alloy Plates: A Comprehensive Review

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Abstract.

The green welding technique known as friction stir welding (FSW) is widely used in a variety of industries, including aerospace, automotive, shipbuilding, railroad, electronics, energy, and defense, to combine comparable and different materials, including metals and non-metals. By keeping the material solid and operating at low heat inputs, this technique avoids thermal distortions, lowers residual stresses, and creates joints free of defects. Joint strength is largely determined by important process variables, including work-piece material, plunge depth, tool geometry, tool tilt angle, traverse speed, and tool rotating speed. The impact of various tool pin profiles on the mechanical characteristics and microstructure of friction stir welded alloy plates is studies in this review. The results show that differences in pin profiles have a major effect on material flow, heat generation, and joint quality in general. It has been demonstrated that optimized tool pin profiles increase weld strength and uniformity while lowering flaws. This study offers substantial advantages for a range of industrial applications by delivering insightful information on how to choose the best tool designs to improve welding performance.

Keywords: Friction stir welding, tool pin profile, joint strength, microstructure, mechanical properties

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1. Introduction

Friction Stir Welding (FSW) has emerged as an innovative and sustainable solid-state joining technology with widespread applications across industries such as aerospace, automotive, shipbuilding, railway, electronics, energy, and defense. Developed and patented in 1991 by The Welding Institute (TWI), Cambridge, England, this method employs a rotating non-consumable tool to join materials without requiring filler materials or generating harmful emissions. The process operates at relatively low heat inputs, maintaining the workpieces in the solid state, thus minimizing thermal distortions, reducing residual stresses, and achieving high-quality welds with enhanced mechanical properties. FSW is characterized by distinct stages, including plunging, dwelling, welding, and retracting. During these stages, the tool interacts with the workpiece to generate frictional heat, plasticizing the material, and facilitating its flow and mixing. The interface of the welded joint experiences varying heat zones, including the nugget zone (NZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ), resulting in a refined grain structure that contributes to superior weld integrity. The design of the tool, particularly the pin profile, is pivotal in influencing the heat generation, material flow, and overall welding performance. Different tool pin profiles, such as cylindrical, threaded, tapered, triangular, square, pentagonal, hexagonal, and hybrid designs, offer varying advantages. For instance, cylindrical pins provide homogeneous material flow and are simple to manufacture, while threaded pins enhance material stirring and bonding. Advanced profiles, such as triangular or hexagonal designs, improve heat distribution and material consolidation, ensuring defect-free welds with superior mechanical properties. Hybrid pin profiles, combining features of different shapes, further optimize joint quality and strength for critical applications.

This study investigates the influence of various tool pin profiles on the microstructure and mechanical properties of FSW joints. By exploring the effects of these designs on material flow, heat generation, and defect reduction, this research aims to provide valuable insights for optimizing tool design. The findings have significant implications for improving weld performance, particularly in joining lightweight alloys like aluminum and magnesium, which are vital for modern engineering applications. This work contributes to advancing FSW technology, enabling industries to achieve higher efficiency and reliability in their joining processes.

2. Literature Review

Numerous researchers have extensively studied the influence of tool pin profiles on the microstructure and mechanical properties of welded plates, particularly for similar and dissimilar metals, as well as aluminum alloy composites. These investigations highlight the critical role of tool pin geometry in optimizing weld quality and performance. The effects of various tool pin profiles, as explored by different researchers, are summarized in the table below:

Material / Parameter	Tool Pin Profile Types	Outcome	References
Material: AA7075-T6 plates has a grain size of 32.736 μm.	Tool: square and hexagon grain size of both square (4.43 μm) and hexagon (5.79 μm) pin profiles	Exhibiting better elastic modulus, elongation, and strength using square tool pin.	[1]
Material: AA 6082-T6 with a 2 mm thickness, rainforced sample, made with fine ceramic Al_2O_3 nanoparticles	Tool: Hexagonal (tungusten carbide material)	well-distributed alumina nano-particles in the stir zone, leading to grain refinement at 3rd pass.	[2]
Material: Two 2mm-Thicked Al 6061 Sheets Process parameter: rotating speeds of 80mm/min and 1600 RPM	Tool: square-shaped pin	The weld exhibited the highest fracture toughness measured using DIC, with regression equations via response surface methodology linking input and output variables.	[3]
Material:AISI 304 stainless steel plate Process parameter: TRS 1050 rpm, welding speed: 24 mm/min	Tool: nine cylindrical different tool pin diameters used in this investigation	At a 2.8 mm tool pin diameter, the maximum tensile strength reached 504 MPa, with a welding efficiency of 99%.	[3]
Material:6061 aluminum sheet 1000 rpm and advancing speeds of 14, 20, and 28 mm/min	Tool: Square, hexagonal, and triangular cross sections, as well as prisms and frustum, were created.	The specimens that were fabricated using frustum pins and square cross-section had the best mechanical characteristics.	[4]
Material:Al 6082	Tool: square pin & hexagonal pin	The square pin design enabled a consistently stable force, while the hexagonal pin design exhibited a decreasing force behavior relative to welding length or time.	[5]
Material:A 2024-T351 aluminium alloy	Tool: square pin profile with edge length of 3.6 mm and 2.65 mm pin	Resulted the better mechanical flow in addition to improved hardness, grain, and tensile strength	[6]
Material:2024 aluminum alloy is an Al-Cu-Mg series hard aluminum alloy	Tool: WNZ under three different tool pins AS and RS at different positions (tool A, B and C) was 12~18 μm, 8~14 μm, 7~12 μm	The conical cam thread tool welded joints performed better than other methods.	[7]
Material: Ti6Al4V T-joints	Tool: WNZ under three different tool pins AS and RS at different positions (tool A, B and C) was 12~18 μm, 8~14 μm, 7~12 μm	The quality of the weld and the attained mechanical strength.	[8]
Material: 2050-T34 Al-Cu-Li alloy plates	Tool: tapered threaded tool.	The combined effectiveness stands at 87.9%, with a tensile strength of 343.5 MPa achieved at the maximum speed of 1600 rpm for TRS.	[9]
Material: Al-6061 T6 aluminum alloy.	Tool: Circular, square and triangular	Comparing the square tool pin profile to other profiles, observations show that it provides higher hardness and tensile strength.	[10]

These studies emphasize that tool pin profiles significantly influence heat generation, material flow, plastic deformation, and ultimately the microstructural and mechanical properties of friction stir welded joints. Optimized tool pin geometries not only enhance weld strength and uniformity but also enable defect-free joints, making them indispensable for critical industrial applications.

3. Effect of tool pin profile on microstructure of the weld

The microstructure of a weld in Friction Stir Welding (FSW) is significantly influenced by the tool pin profile, which plays a crucial role in determining plastic deformation, heat distribution, material flow, and ultimately the mechanical properties and quality of the joint. The geometry of the tool pin directly affects how the material is stirred, mixed, and consolidated in the solid-state welding process, making it a critical factor in achieving high-quality welds. Plastic deformation induced by the tool pin profile governs grain refinement and recrystallization, which are essential for improving the microstructural characteristics of the weld. The profile also determines heat distribution, which impacts thermal gradients and the formation of distinct zones in the weld, such as the nugget zone (NZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ). Furthermore, the pin profile influences material flow by directing and mixing the plasticized material, ensuring homogeneity and minimizing defects such as voids or inclusions. These effects collectively determine the mechanical properties of the weld, including tensile strength, hardness, and fatigue resistance.

Kesharwani et al. [1] investigated the effects of square (SQ) and hexagon (HX) tool pin profiles on the stir zone (SZ) microstructure in friction stir welded AA7075-T6 joints. The SQ pin profile produced defect-free joints with consistent material mixing and superior quality. Using a single-pass FSW technique, they achieved flawless welds with optimal structural integrity. Ahmadi et al. [3] reported that square pin profiles yielded maximum fracture toughness at a welding speed of 80 mm/min and a rotational speed of 1600 RPM, as measured by digital image correlation (DIC). Regression analysis further revealed clear correlations between welding parameters and mechanical properties. Singh et al. [4] observed that the stir zone of joints exhibited varying bandwidths, with the most uniform and efficient weld (99%) achieved using a cylindrical tool pin with a 2.8 mm diameter. Their findings emphasized the importance of balancing heat generation and material flow during the welding process. These studies highlight how tool pin geometry directly affects material flow, heat distribution, and overall weld quality, offering essential insights for optimizing friction stir welding processes. Nia et al. [5] determined the average grain size of the base metal to be 24.9 μm using the line intercept method, as depicted in Fig. 1(a) The microstructure of the 6061 aluminum alloy is illustrated in Fig.1 (b).

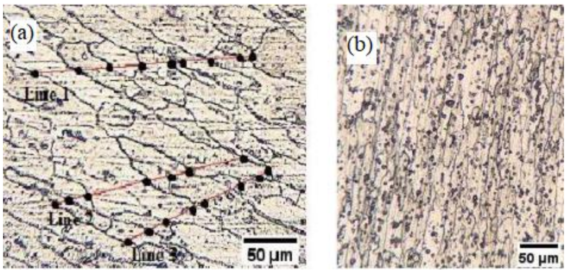

Figure 1. Microstructure of friction stir welded samples at stir zone [5]

Choudhary et al. [7] examined the effect of grain size on joint strength and mechanical properties, finding that a square pin profile with a 0.2 mm eccentricity resulted in 92.6% grain fineness and 87% weld efficiency. For 0.1 and 0.2 mm eccentricities, the dynamic area increased by 8.1% and 16.4%, respectively, improving material flow. Eccentric square tool pins enhanced material mixing and plastic deformation, leading to better microstructural properties, especially at higher rotational speeds, which intensified plasticization. Sun et al. [8] achieved flawless joints, evident from the onion ring pattern in cross-section, using a conical cam thread stirring head. The weld nugget zone (WNZ) had a grain size between 7–12 μm. The intersection of the heat-affected zone (HAZ) and thermo-mechanically affected zone (TMAZ) showed the lowest hardness, with the advancing side (AS) material (2024-T6 Al alloy) appearing lighter in color compared to the retreating side (RS) material (6061 Al alloy). The tool pin caused a vortex motion in the AS, leading to metal redistribution that affected the weld joint. Ambrosio et al. [9] focused on Ti6Al4V T-joints and achieved complete penetration, ensuring joint integrity with β transus across the nugget zone. The joints demonstrated robustness, with less than 20% of the base material fracturing, but failures were linked to thinning and kissing bond flaws at the joint corners, emphasizing the need for careful tool wear management. Kumar et al. [10] observed that increasing tool rotational speed (TRS) reduced the grain size in the nugget zone (NZ) from 17.11 μm to 11.80 μm. The joint strength increased with smaller grain sizes and more grain boundaries. The fine equiaxed grain structure in the NZ resulted from dynamic recrystallization during FSW. Grain size was influenced by TRS, with lower rotational speeds showing a more heterogeneous distribution of elements like aluminum (Al), magnesium (Mg), and copper (Cu). Kiran and Nadikudi [12] found that a straight square geometry pin tool produced a more uniform distribution across the weld nugget, as shown in the microstructural analysis. Swetha and Chinmaya Padhy [13] successfully joined AA-2014 T4 and AA-6061 T6 alloys via FSW without tool breakage or degradation, resulting in a stir zone with uniform grain size. Darsono et al. [14] reported voids and elongated cavities in the TPT welding tests, but no fusion defects were found, indicating that the straight thread pin tool (STPT) yielded superior results. Nejad et al. [19] found that the tapered pin resulted in the finest grains, and tensile fractures regularly occurred at the base metal/stir zone (SZ) interface.

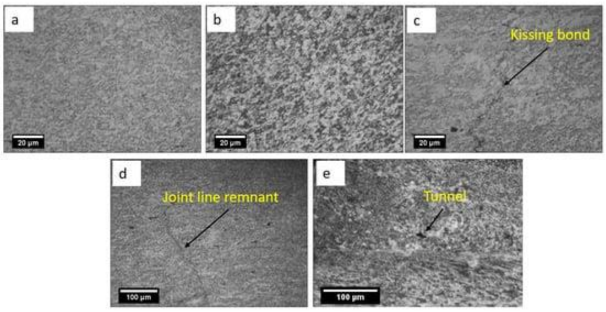

Fig.2. Nugget joint structure using different tool pin profile (**a**) cylindrical pin; (**b**) tapered cylindrical pin; (**c**) square pin; (**d**) hexagonal pin; (**e**) triangular pin.[19]

4. Effect of Tool Pin Profile on Mechanical Properties

The effectiveness of friction stir welding (FSW) is significantly influenced by the selection of the tool pin profile, which impacts the mechanical properties of the weld. Mohammed et al. [2] found that the square-shaped (SQ) pin profile resulted in higher hardness and modulus compared to the hexagonal (HX) pin profile, with the joint achieving a maximum yield strength of 154.9 MPa and ultimate tensile strength (UTS) of 227.61 MPa. Nia et al. [5] reported the base metal's yield stress, ultimate strength, and elongation as 268.8 MPa, 298.3 MPa, and 52%, respectively. Mugada and Adepu [6] observed that hexagonal pins (TCC HEX) produced welds with higher mechanical properties, achieving a tensile strength of 187 MPa and average hardness of 79 HV at the stir zone. Choudhary et al. [7] noted that eccentric square pins enhanced tensile strength, hardness, and grain refinement by 56%, 46%, and 9.6%, respectively, for AA2024. Sun et al. [8] achieved a maximum tensile strength of 364.27 MPa (86.73% of the base metal) using a conical cam thread pin, with tensile strengths consistently above 80% of the base metal. Ambrosio et al. [9] demonstrated robust mechanical strength in Ti6Al4V alloy joints, with ultimate tensile strength (UTS) and yield stress (Y) reaching 96% and 87% of the base material, respectively, though elongation at break was limited to 15%. Kumar et al. [10] found that increasing tool rotational speed (TRS) to 1600 rpm improved tensile strength by 37.2%, while lower TRS resulted in reduced strength. Niranjan et al. [11] showed that square tool pins significantly improved tensile strength and microhardness, with optimal parameters identified through the Taguchi method. Kiran and Nadikudi [12] compared square geometry tools with hexagonal and taper-threaded tools, finding that square tools produced the best tensile properties due to their pulsing action. Swetha and Chinmaya Padhy [13] confirmed that square pin tools achieved the highest tensile strength, followed by tapered pins, especially at fast welding speeds (150 mm/min) and high rotational speeds (1200 rpm). Miloud et al. [15] observed that cylindrical profiled tools provided superior weld quality, with the cylindrical tool yielding 14.94% efficiency compared to the conical tool's 7.94%. Ahmed et al. [16] noted that FSW speed increase from 100 to 500 mm/min improved both tensile strength and yield stress, although hardness was lower in the weld zone. Nejad et al. [19] found that tapered pins provided the best mechanical properties, particularly under optimal processing conditions. Finally, Goel et al. [20] reported that tapered cylindrical tools resulted in a tensile strength of 162 MPa, surpassing the triangle tool joints, and noted higher impact strength in tapered cylindrical joints. Kumar et al. [21] joined 2050-T84 Al-Li alloy using various tool pin profiles and found that the hybrid tool pin profile resulted in higher tensile strength compared to the other profiles as shown in Fig.3.

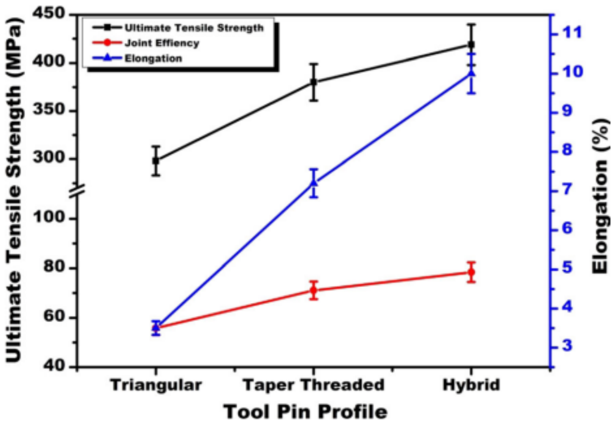

Fig. 3 Different tool pin profile used join Al-Li alloys 2050-T84

5. Conclusions:

This study highlights the significant impact of tool pin profiles on the microstructure and mechanical properties of friction stir welded joints. The findings demonstrate that the choice of pin profile affects key factors such as heat generation, material flow, and joint strength. Optimized tool pin profiles help minimize defects, enhance weld quality, and improve the overall performance of the welded joints. This research emphasizes the importance of selecting suitable tool designs based on specific welding parameters to achieve superior results. By refining tool pin profiles, it is possible to enhance the mechanical properties of welded joints, offering long-term advantages for various applications.

Source of Support: Nil
Conflict of interest: Nil
Acknowledgement: None

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How to cite this article: Kesharwani G S, Kumar S. Influence of Tool Pin Profile on Microstructure and Mechanical Properties in Friction Stir Welding of Alloy Plates: A Comprehensive Review. Subharti J of Interdisciplinary Research, Apr. 2026; Vol. 8: Issue 1, 15-9