

EFFECTS OF TOOL PIN PROFILE IN FRICTION STIR WELDING: A REVIEW ON MICROSTRUCTURAL EVOLUTION AND MECHANICAL PERFORMANCE OF ALLOY JOINTS

GURU SEWAK KESHARWANI, SANJEEV KUMAR*

Swami Vivekanand Subharti University, Department of Mechanical Engineering, 250003 Meerut, Uttar Pradesh, India

* corresponding author: placid.san@gmail.com

ABSTRACT. Friction stir welding (FSW) is an eco-friendly, sustainable, solid-state process that is increasingly being used to join metallic, non-metallic, polymer, and composite materials to create high-quality welds with minimal flaws. The tool pins' profiles govern material flow, heat generation, and weld integrity. The literature shows that threaded, taper threaded, triangular, and hybrid pins enhance mixing, grain refinement, hardness, and tensile strength, while cylindrical or smooth pins often cause defects. Microstructural investigations confirm that complex pin geometries promote finer grains and higher strength and hardness. A fracture analysis of welded samples reveals that shift in failure location from the nugget to the thermo-mechanically affected zone (TMAZ) depends on the geometry of the tool pin. Despite these advances, only a few studies have examined different materials, and standardised evaluation of tool geometries is lacking. Using computational and machine learning methods for predictive modelling, expanding applicability to lightweight alloys in aerospace and automotive manufacturing, and developing hybrid and adaptive pin profiles are the upcoming research priorities.

KEYWORDS: Friction stir welding, tool pin profiles, microstructure, tensile strength, hardness.

1. INTRODUCTION

Friction Stir Welding (FSW) is an eco-friendly solid-state welding method (fumeless, sparkless, reducing material loss, and cost-effective over time) developed by TWI in 1991. It uses mechanical deformation and frictional heat to create high-quality welds in lightweight materials. FSW facilitates the joining of similar and dissimilar materials by producing high-efficiency, defect-free welds with improved strength. Its adaptability to various materials, including aluminium, magnesium, steel, polymers, and composites, provides excellent fatigue resistance and low treatment requirements, which are highly important in industries such as aerospace, automotive, shipbuilding, railways, and communications [1]. A non-consumable rotating tool, consisting of a shoulder and a pin, is used to plasticise and mix the material along the joint line without melting [2]. The frictional heat from the shoulder and the stirring action of the pin generates intense plastic deformations, resulting in the formation of distinct microstructural zones: the stir zone (SZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ). The SZ, or nugget zone, typically exhibits fine equiaxed grains due to dynamic recrystallisation, whereas the TMAZ shows plastically deformed structures, and the HAZ undergoes thermal effects that can weaken local properties [3, 4]. The tool design, particularly the pin profile, is a critical factor that influences material flow, heat generation, and microstructural refinement.

The various tool pin profiles used for joining the materials are shown in Figure 1, and listed in Table 1. Figure 1a shows the triangular pin profile. The three edges, generate localised shear zones and facilitate turbulent material flow during friction stir welding, resulting in enhanced grain refinement and improved hardness. However, this design typically increases torque requirements and tool wear. Figure 1b shows the square pin profile. The four edges ensure balanced stirring and efficient oxide disruption, leading to symmetric nugget zones, however, with slightly elevated torque demand compared to cylindrical profiles. Figure 1c shows the pentagonal pin profile. The five edges further improve thermal distribution and mixing uniformity, promoting superior metallurgical bonding, however, the increased complexity poses the risk of localised excessive torque and wear. Figure 1d shows the hexagonal pin profile. The six edges maximise shear and contact area, thus improving the overall consolidation of the material and joint quality. However, this comes at the cost of higher frictional forces and a potential tool degradation if the parameters are not optimised. Figure 1e shows the cylindrical pin profile. It is characterised by a uniform cross-section that enables stable material flow and reduced torque, making it suitable for basic joining processes. However, it commonly suffers from insufficient mixing and a higher likelihood of root defects. Figure 1f shows the taper threaded pin profile. Its combination of a tapered shape and helical threads improves vertical material movement and defect suppression, resulting

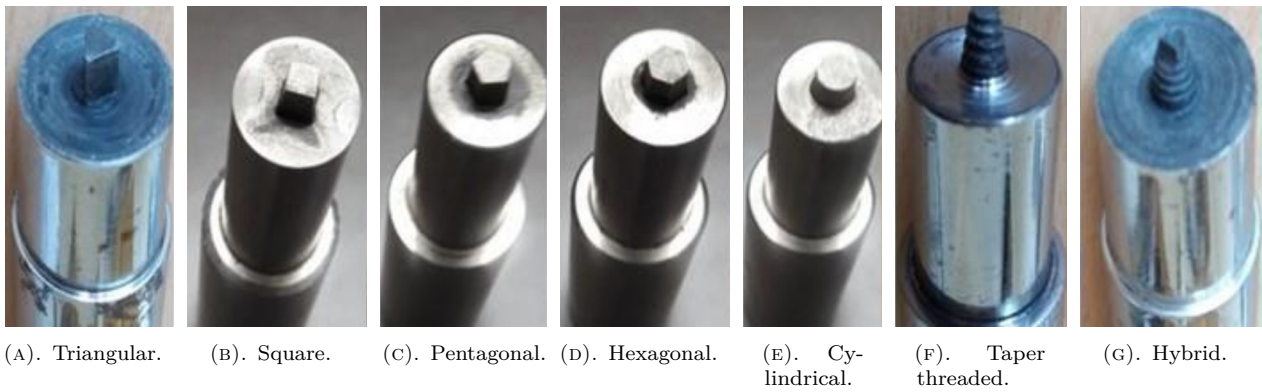


FIGURE 1. FSW tools with different pin profiles [5].

Tool pin profile	Advantages	Limitations
Cylindrical	Simple design; uniform material flow; lower torque requirement; long tool life	Poor transverse mixing; higher chance of root defects; risk of incomplete consolidation
Threaded cylindrical	Axial pumping action improves vertical mixing; reduces voids; larger processed zone	Generates excessive heat; higher tool wear; increased power consumption
Tapered cylindrical/Conical	Gradual diameter change enhances forging and consolidation; reduces tunnel defects	Sensitive to plunge depth; risk of overheating at high rotational speeds
Triangular (polygonal)	High shear at edges; improves stirring and dynamic recrystallization; refined grains; better hardness	Higher torque demand; corner stagnation possible; reduced tool life
Square (polygonal)	Strong stirring; improved oxide disruption; balanced flow pattern	Increased torque and tool wear; risk of surface flash if parameters not optimized
Pentagonal/hexagonal	Multiple edges enhance mixing and thermal distribution; improved metallurgical bonding	Greater torque requirement; complex flow may cause local defects if not optimized
Hybrid (combined features)	Integrates benefits of polygonal, threaded, or tapered pins; effective for dissimilar joints	Manufacturing complexity; higher cost; requires careful optimization to justify use

TABLE 1. Comparative analysis of different tool pin profiles [6–8].

in strong consolidation, particularly in thick workpieces. However, it also generates excessive heat and accelerates the tool wear [2]. Finally, Figure 1g shows the hybrid pin profile. Its design incorporates features from polygonal, tapered, and threaded profiles to precisely adjust material flow and heat generation for challenging or dissimilar joints, providing superior adaptability at the cost of increased manufacturing complexity and the need for precise process optimization. It provides staged stirring and consolidation, making the profile especially effective for complex or dissimilar material joints.

Aluminium alloys are usually the most responsive to pin design when it comes to different types of materials. Threaded and hybrid profiles give the optimum balance of joint strength and defect reduction. However, steel requires pin profiles that can produce more heat and pressure, such as polygonal or tapered designs, in order to achieve sufficient plasticisation. For polymers and composites, the reduced tolerance to ro-

tational heat makes smoother and lower-shear profiles, particularly tapered or cylindrical geometries, more suited for preventing deterioration and to guarantee adequate mixing. The comparison, with respect to different materials, is shown in Table 2.

There is still much to study about the exact effect of tool pin profile on mechanical performance and microstructural evolution. Without offering a systematic assessment of the ways in which various geometries impact heat generation, material flow, and the creation of weld zones (SZ, TMAZ, and HAZ), the majority of previous research has concentrated on general tool design. In addition, there hasn't been a thorough examination of the relationship between changes in pin profiles and important joint performance indicators, such as hardness and tensile strength. The pin profile is a crucial factor in determining weld integrity, however, recent studies only highlight tool design in general. By compiling and critically evaluating the existing research on the effects of the pin

Tool pin profile	Key effects			General trends (Across materials)
	Aluminium alloys	Steels	Polymers/composites	
Cylindrical	Ensures uniform flow and low torque; long tool life, but limited mixing near the root zone	Low heat generation insufficient for full plasticization; high forces needed	Maintains structural integrity with minimal thermal degradation; mixing often incomplete	Favorable for low-viscosity materials due to steady flow, but mixing limitations persist
Threaded cylindrical	Enhances vertical flow and reduces voids; high-quality joints in Al 6xxx/7xxx series	Improves plastic flow through pumping action but increases tool wear due to hardness	Promotes better layer fusion; mitigates voids in thermoplastics	A good balance of stirring and consolidation; wear and excess heat are key limitations
Tapered cylindrical/conical	Gradual taper aids defect-free joints; ideal for variable thickness plates	Provides strong consolidation if properly cooled; sensitive to plunge depth	Useful for gradient materials; may overheat soft matrices	Forging pressure distribution improves with taper; overheating control is crucial
Triangular (polygonal)	Strong shear enhances grain refinement and mechanical strength	High shear beneficial but causes elevated torque and wear	Excessive shear can degrade polymers; effective only in reinforced composites	High-shear polygonal pins optimize microstructure but at cost of torque and wear
Square (polygonal)	Balanced material flow; good oxide breakup; improved nugget structure	Results in fine grains; greater torque needed; surface flashes possible	Improves polymer homogenization but risks edge tearing	Robust stirring geometry widely applicable; torque management vital
Pentagonal/hexagonal	Excellent thermal balance and mixing; effective for multi-pass welding	Capable of defect-free welds under controlled speed conditions	Harder to stabilize flow in soft matrices; risk of overmixing	Geometry enhances consolidation; requires process optimization
Hybrid (combined features)	Ideal for dissimilar alloys (e.g., Al-Cu); improved bonding and mechanical strength	Enables joining of steels to light alloys; higher fabrication complexity	Useful for hybrid composite-metal joints; enhances compatibility	Customizable and effective across types but costly and parameter-sensitive

TABLE 2. Comparison of tool pin profiles across material categories [9–11].

profile, this study fills the knowledge gap and offers a framework for optimising tool design for better microstructural control and improved weld quality in alloy joints. However, it lacks integration with modelling, computational fluid dynamics (CFD) AI, and ML, leaving microstructure-performance predictions for diverse alloys underexplored.

2. EFFECT OF TOOL PIN PROFILE ON DIFFERENT MATERIALS

Pin profiles have distinct effects on the quality and strength of the weld in different materials. In dissimilar material welding, improving microstructure, lowering flaws, and obtaining higher joint performance depend on pin design optimisation. Numerous studies have shown the importance of pin profiles in attaining optimal weld quality. The Tables 3–6 below provide an overview of these results, emphasizing the impacts that different researchers have documented.

Mohammed and Birru [4] investigated friction stir

processing of AA 6082-T6 using a hexagonal tool at rotational speeds of 710 rpm and 900 rpm, with 2 and 3 passes at a constant traverse speed of 40 mm min⁻¹, and reported well-distributed alumina nanoparticles with refined grain structure at the third pass.

3. EFFECT OF TOOL PIN PROFILE ON MICROSTRUCTURE

The different tool pin profiles affect the resulting microstructure of FSW (indicated in Table 7) due to their impact on heat generation, material flow, and dynamic recrystallization. Grain size, distribution, and defect formation are all affected by variations in pin shape, which ultimately determines the mechanical properties. Optimising pin profiles improves joint quality, making it possible to adjust microstructural and performance features for various applications. In order to create more uniform and flawless microstructures, threaded pins are usually reported to enhance material flow and mixing by creating additional shear

Material	Tool pin profile	Parameters	Outcome	Ref.
AA 6082-T6	Plane cylindrical, tapered cylindrical, threaded cylindrical, and square pin profiles	Tool rotational speed of 710 rpm and traverse speed of 132 mm min ⁻¹	Square pin produced minimal tunnel defects and superior strength; tapered cylindrical pin achieved highest hardness; threaded pin caused defects and lowest hardness	[11]
AA 7039	Cylindrical, conical, triangular and square, each with three different diameters (5 mm, 6 mm and 7 mm)		Square pin (6 mm) produced optimal welds with finer grains, better mixing, and superior strength compared to other profiles and diameters	[12]
AA6082 and AA5052	Tapered cylindrical, pentagonal, and hexagonal	Tool rotational speed levels: 840, 1 045, 1 300 rpm, Traverse (welding) speed levels: 25, 45, 65 mm min ⁻¹	Pentagonal tool pin achieved highest strength (101.45 MPa, 74 % joint efficiency) as compare to other tool, refined welds, and optimized wear performance with minimal prediction error (<3 %)	[13]
AA7075-T6	Cylindrical, square and conical tool-pin	Constant tool rotation speed of 800 rev min ⁻¹ and a travel speed of 50 mm min ⁻¹	Square pin produced finest grains, highest microhardness, and best efficiency (60.5 %); cylindrical lowest efficiency, while conical revealed highest ductility	[14]
AA5754	Cylindrical pin, novel dual-pin, and tapered square pin	Constant 1 200 rpm rotational speed and 150 mm min ⁻¹ traverse speed	Cylindrical pin ensured highest strength and ductility, while dual-pin and tapered square caused defects, poor grain uniformity, and reduced formability	[15]
AA2219-T87 Al alloy	Square, triangular, and conical tool pins		Square pin produced optimal material flow, finer grains, and lower pit density, delivering superior mechanical strength and corrosion resistance over triangular and conical pins	[16]
AA6061 and AZ91D	Threaded circular, triangular, and square		Square pin produced defect-free welds, finest grains (4.59 μm), and highest strength (144.32 MPa), outperforming threaded circular and triangular profiles	[17]

TABLE 3. Effect of tool pin profile on joint quality for Al alloy.

pressure through the threading. These profiles give aluminium alloys well-refined grain structures, which improve their tensile qualities. However, a microstructural analysis also shows that, if welding settings are not optimum, threaded cylindrical pins may be vulnerable to tunnel flaws, which compromise joint integrity. Simpler cylindrical and hexagonal pins agitate less vigorously, resulting in coarser grains and less uniform microstructures. Due to the reduced material flow and less heat input around the pin, these pins may occasionally exhibit greater failure rates. Mechanical performance may be lowered by the resulting microstructure, which often has bigger grain sizes and less advantageous refinement. Threaded and tapered pins improve bonding and mixing at the weld interface in polymers and polymer composites, resulting in stronger joints with finer microstructural zones. For example, cone or threaded tapered pin profiles

increase joint quality at the microstructural level by enabling enough polymer flow without creating flaws. Although they may increase tool wear, square pins regularly encourage finer, more granular microstructures in aluminium alloys. Threaded pins improve grain refinement and material flow, however, they can cause tunnel flaws in the absence of parameter control. Simple cylindrical or hexagonal pins typically result in coarser grains and more potential for defects.

Tapered and threaded pins enhance the joint strength and microstructural bonding in polymer welding. A hybrid tool pin profile uses multiple geometric shapes to optimise heat generation, material flow, and microstructural refinement in the weld zone. The hybrid profile facilitates defect-free welds with enhanced mechanical properties by enabling more uniform stirring, increased plastic deformation, and enhanced consolidation of joint surfaces. When compared to

Material	Tool pin profile	Parameters	Outcome	Ref.
AZ91C and AZ31B alloys	Cylindrically tapered, threaded cylindrical tapered pin	Tool rotation speed (1000 rpm), traverse speed (2 mm s^{-1}), axial force (5kN) and tilt angle (0.50)	Threaded tapered pin with zero offset produced defect-free joint, 186 MPa strength	[18]
AZ31	Taper threaded, taper cylindrical and straight cylindrical	Rotational speeds such as 900 rpm, 1120 rpm and 1400 rpm, traverse speed of 25, 40, 75 mm min^{-1}	Taper thread tool pin profile revealed higher mechanical properties at TRS of 1120 rpm and TTS of 40 mm min^{-1} to other tools	[19]
AZ91	Triangular, square, hexagonal, inward conical and outward conical		Hexagonal pin ensured uniform flow and best coalescence; outward conical improved strain, grain refinement, and strength, while inward conical caused tunnel defects and poor properties	[20]
AA7075 and magnesium AZ31B alloys	Cylindrical and taper	Range of tool rotational speed from 600 and 700 rpm, welding speed of 20 and 25 mm min^{-1}	Taper tool at 600 rpm, 20 mm min^{-1} achieved maximum UTS (110 MPa); however, cylindrical tool at 700 rpm, 20 mm min^{-1} showed highest impact energy (18 J)	[21]
AZ91D and AA2024	Square, triangular		Square pin produced defect-free joints with highest UTS (153.27 MPa), while triangular pin showed lowest strength (124.81 MPa) due to dense IMCs	[22]

TABLE 4. Effect of tool pin profile on joint quality for Mg alloy.

Material	Tool pin profile	Parameters	Outcome	Ref.
AISI 304 and AISI 316	Cylindrical tungsten alloy tool	Range of tool rotational speed from 600 to 900 rpm, with a constant welding speed of 40 mm min^{-1}	Defect-free AISI 304-316 joints at 800 rpm showed superior yield strength, hardness, and ductile fracture, with adequate corrosion resistance in severe environments	[23]
AISI 431 martensitic stainless steel (MSS) and AISI 1018 low carbon steel			Optimized RFW (FRNP/FRNT 7.14 MPa s^{-1} , FRGP/FRGT 7.14 MPa s^{-1} , RTSP 26.66 rps) achieved MSS/LCS joints with 650 MPa tensile strength and 515 HV hardness	[24]

TABLE 5. Effect of tool pin profile on joint quality for steel.

traditional profiles, studies indicate that they can improve strength by up to 26%, reduce tunnel flaws, and manage grain size more effectively in both similar and dissimilar alloy materials [33].

Kesharwani et al. [36] joined AA7075-T6 plates using square and hexagon pin profiles, showing that square profiles yielded high-quality joints with refined grains ($4.43 \mu\text{m}$) and effective dynamic recrystallisation. Yang et al. [39] investigated the effect of cylindrical, square, and triangular tool pins on the microstructure and mechanical properties of friction stir

welding of dissimilar Al/Mg alloy joints. Cylindrical, bowl-shaped, and stepped-type joint structures were observed using these tools. The square tool and triangular tool provided smooth joints, as shown in Figure 2.

Singh et al. [40] used a square pin profile tool, and EBSD analysis revealed the presence of fine, equiaxed, recrystallised grains in the stirred zone, resulting from dynamic recrystallisation and heating, with a high fraction of HAGB, enhancing joint mechanical properties. Mastanaiah et al. [33] used

Material	Tool pin profile	Parameters	Outcome	Ref.
Poly(methyl methacrylate)	Frustum, cubic and triangle tool pin profiles		Frustum pin produced defect-free PMMA welds with maximum tensile strength (59 MPa LS, 43 MPa TS) and highest impact energy, outperforming cubic and triangular pins	[25]
Polyethylene (HDPE)	Frustum, cubic, and triangular	Rotational speed of 1 200 rpm and traverse speed of 25 mm min ⁻¹	Frustum pin yielded defect-free HDPE welds with balanced heat (91 °C) and stable flow, while cubic and triangular pins caused excess heat, over-stirring, and voids	[26]
Nylon 6	Threaded tool pin profile	Rotational speed of 1 000 rpm and welding feed 10 mm min ⁻¹	Counter-clockwise tool rotation in Nylon 6 FSW using a left-hand threaded pin produced defect-free joints with superior mechanical properties compared to clockwise rotation	[27]
	Concave, flat and convex		Concave shoulders and threaded/grooved tools in FSSW enhance material flow, heat generation, and weld strength	[28]
PE1000 polyethylene	Zigzag, square, and straight tool path profiles	Spindle speed of 1 400 rpm, a feed rate of 10 mm min ⁻¹	Zigzag tool path produced strongest PE1000 joints with ductile fracture surfaces; ANOVA confirmed tool path profile as most significant parameter for weld quality	[29]
PA66-GF30	Threaded pin tool	Rotational speed 1 000, 1 200, and 1 400 rpm. Speed 20, 30 mm min ⁻¹	Induction-assisted FSW of PA66 with PA66-GF30 strip achieved 91 % joint efficiency; optimal 1 000 rpm and 20 mm min ⁻¹ ensured uniform fiber dispersion and defect-free welds	[30]
API X65 steel and Inconel 625	Polycrystalline boron nitride (pcBN) tool		Optimal orbital FSW of API X65/Inconel 625 requires balanced heat input (1.8–3 kJ mm ⁻¹); low heat causes insufficient plasticization, high heat induces	[31]
Acrylonitrile butadiene styrene and polycarbonate	Tapered, Threaded, and threaded with tapered	Tool rotational speed (800, 1 200, and 1 600 rpm)	Threaded tapered pin at 1 600 rpm achieved maximum UTS (21.61 MPa) and 70.55 % joint efficiency in ABS/PC FSW, with uniform interface and effective material transport	[32]

TABLE 6. Effect of tool pin profile on joint quality for polymer.

a hybrid tool pin and a conventional tool pin profile to join AA2219-T6 plates and observed that the hybrid tool provided better strength than the conventional tool. Moharrami et al. [41] found that threaded triangular tapered tools improved the tribological properties of the as-cast composite due to refined Mg₂Si intermetallics, ultrafine grains, and reduced casting defects. Ahmed et al. [42] observed a significant grain refinement, with 18, 15, and 18 μm grain sizes at 100 mm min⁻¹ and 12.4, 10, and 11 μm at 500 mm min⁻¹, respectively. Tiwan [43] found fine equiaxed grains in SZ resulting from dynamic recrystallisation, while stepped pin welds had coarser microstructures. Sundar et al. [44] successfully joined Al6061-T6 plates at 1 200 rpm and 45 mm min⁻¹ using three FSW conditions. SSFSW showed the highest recrystallisation (77 %) and grain refinement, reducing grain size by 37 % compared to UWFSW and increasing yield strength by 22.8 % compared to CFSW. SSFSW also improved formability with a strong γ-fibre presence and enhanced joint efficiency by 7.2 % in terms of ultimate tensile strength, due to a higher fraction of precipitates and dislocation density. Alkhafaji et al. [45] joined the AA6061-T6 aluminium alloy us-

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Tool pin profile	Grain structure	Stir zone quality	Defect tendency	Notable microstructural features	Ref.
Cylindrical	Moderately refined, elongated	Uniform, moderate mixing	Low	Basic recrystallization, moderate grain refinement	[34]
Threaded	Highly refined, equiaxed	Excellent mixing, fine grain throughout	Very low	Promotes dynamic recrystallization and defect-free stir zones	[35]
Square	Fine grains at edges, variable	Enhanced local shear, edge mixing	Medium	Possible flash formation with irregular grain distribution	[36]
Tapered	Fine grains, strong gradient	Improved material downward flow	Low	Grain size gradient through thickness	[37]
Pentagonal	Very fine, equiaxed grains	Strong stirring action, high heat input	Very low	Highest tensile strength and microhardness, very fine grains	[38]
Hexagonal	Fine, equiaxed grains	Good stirring action, slightly lower heat input than pentagonal	Low to very low	Close to pentagonal, slightly less effective in tensile and hardness	[36]
Hybrid	Ultra-refined, uniform, equiaxed	Superior stirring, highly homogeneous	Very low	Synergistic effect of multiple geometries, best grain refinement	[33]

TABLE 7. Effect of different tool pin profiles on microstructure.

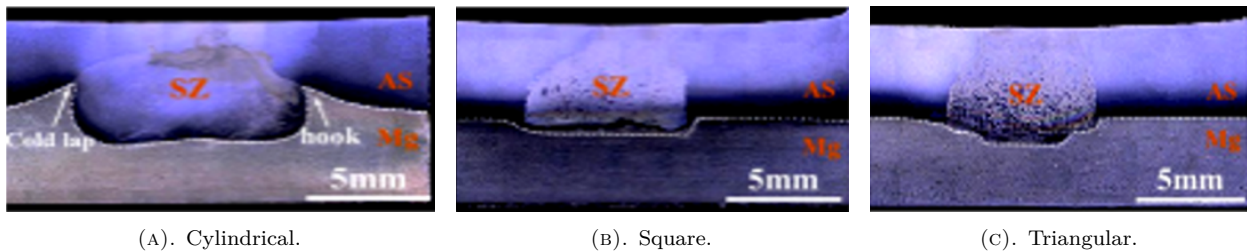


FIGURE 2. Joint macrostructure of welded samples using different tool pins [39].

ing cylindrical and conical pins with different shoulder diameters of 12 mm and 16 mm. Due to increased heat and plastic deformation, the 16 mm shoulder and cylindrical pin achieved finer grains. Mehri et al. [46] successfully joined AA7075-T6 thin sheets by FSW, achieving a homogeneous SZ with fine equiaxed grains. The microstructure showed the finest grains and fewest substructures at a moderate heat input and plastic strain, correlating with the highest mechanical tensile properties due to minimal dislocation obstacles. Sasikala et al. [47] observed that triangular pin profiles produced finer, more uniform grains ($4.7 \mu\text{m}$), leading to refined precipitates, such as Al_2Cu and Al_2MgCu , as confirmed by an EDS analysis. Rana et al. [48] studied the microstructure development of dissimilar AA7075/AA6061 alloys welded via FSW at 20 to 60 mm min^{-1} traverse rates and a constant rotation rate of 708 rpm. The grain size in the nugget zone decreased from $5.82 \mu\text{m}$ at 20 mm min^{-1} to $3.64 \mu\text{m}$ at 60 mm min^{-1} . Elyasi et al. [49] found that the threaded pin tool generated more heat during FSW than the cylindrical pin tool. The threaded pin joint exhibited more agitation, which resulted in increased mechanical interlocking and finer microstructure in the stir zone for copper and AA6068, due to higher

material velocity and strain rate. Kumar et al. [50] observed that the triangular end of the coupled hybrid tool had a minimum average grain size of $11.27 \mu\text{m}$ at NZ, however, it also had the maximum grain size, $17.62 \mu\text{m}$, as shown in Figure 3.

4. EFFECT OF TOOL PIN PROFILE ON MECHANICAL PROPERTIES

The tool pin profile affects material flow, heat generation, and microstructure, all of which have a substantial effect on the mechanical properties of friction stir-welded samples. Variations in pin shape affect grain refinement, tensile strength, hardness, and ductility. Advantages and trade-offs of different tool pin profiles are listed in Table 8.

Knowing this relationship improves joint quality and performance by optimising welding parameters for various technical applications.

4.1. THREADED TOOL PIN PROFILE

Threaded pin profiles enhance material mixing by generating strong vertical and rotational flow. This promotes thorough plastic deformation, uniform particle dispersion, and improved interfacial bonding,

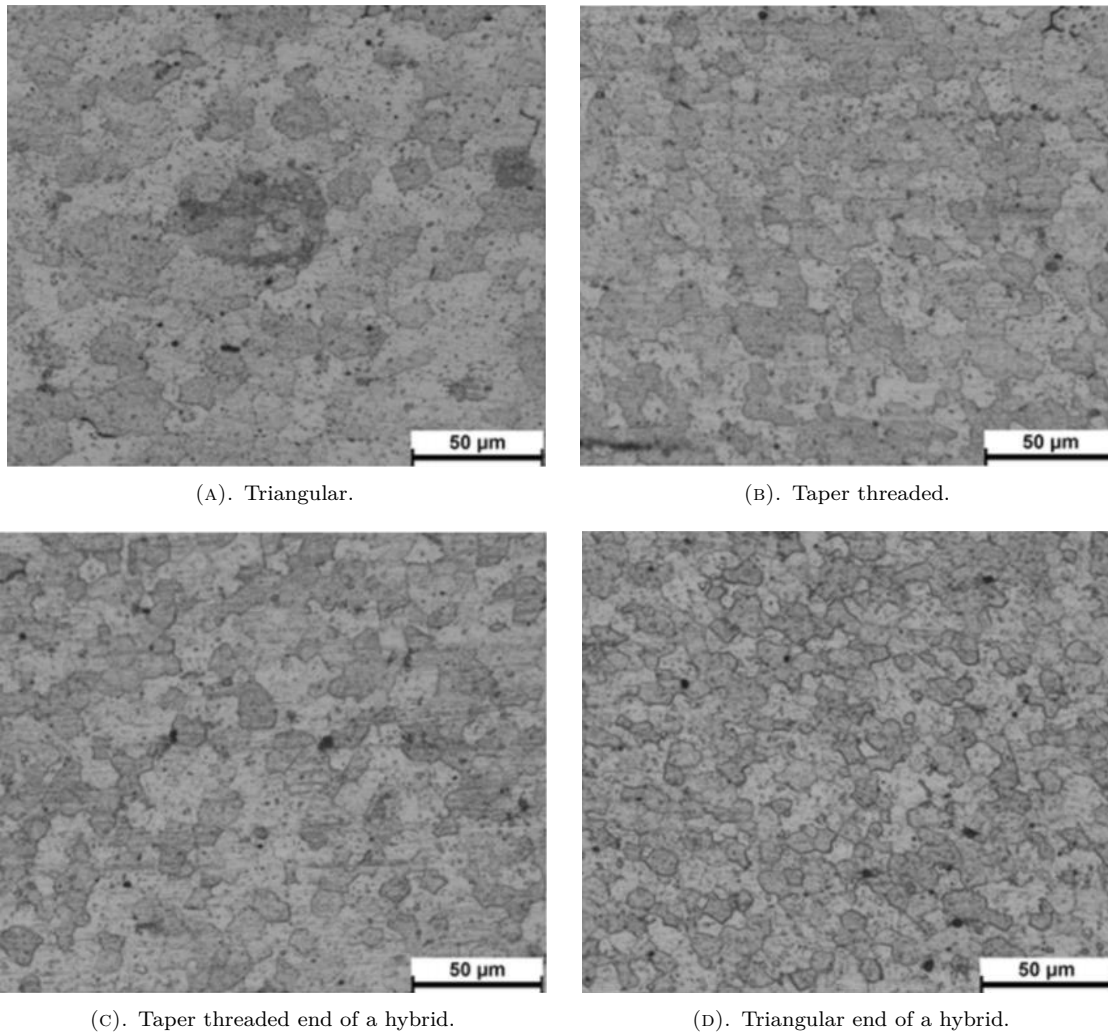


FIGURE 3. Grain size in NZ for different tool pins [5].

Tool pin profile	Advantages	Trade-offs/limitations
Threaded (cylindrical/tapered)	Enhances material flow and mixing; promotes uniform nanoparticle distribution; improves tensile strength and hardness	Higher heat input and torque; risk of excessive grain coarsening; potential for flash defects
Conical/Conical cam thread	Generates effective stirring; improves tensile strength and elongation; smoother flow lines	Less effective at low speeds; can localize heat, causing uneven microstructure
Cylindrical (smooth/grooved)	Simpler design; stable heat input; effective for thin plates; low wear	Lower tensile strength compared to non-cylindrical pins; limited mixing efficiency
Square	Strong stirring action; higher tensile strength and hardness; refined grains	Higher tool wear due to sharp corners; risk of tunnel defects at higher traverse speeds
Triangular	Provides better ductility; improved fracture toughness; suitable for composites	Less surface finish quality; higher stress concentration at corners
Hexagonal	Balanced mixing and heat distribution; lower temperature rise compared to square; good strength-ductility balance	Moderate wear; slightly lower strength than square pins in some alloys
Special/Hybrid (fluted, triflate, stepped, etc.)	Tailored material flow; may optimize both strength and ductility; suitable for complex alloys or composites	Complex manufacturing; unpredictable wear behavior; not widely tested across materials

TABLE 8. Advantages and trade-offs of different tool pin profiles.

resulting in defect-free, homogeneous weld zones with superior strength. Kumar et al. [50] welded 2050-T84 Al-Li alloy plate using a taper-threaded tool at different tool tilt angles (TTAs). They found that a TTA of 2 degrees produces higher hardness and tensile strength. Furthermore, the maximum strength [51] was achieved at a TTS of 3 mm s^{-1} and a TRS of 1400 rpm [52]. Balmiki et al. used a cylindrical threaded tool to combine ABS and PS materials in order to reinforce multi-wall carbon nanotubes. They found that the maximum tensile strength and joint efficiency were achieved at a TTS of 0.5 mm s^{-1} and TRS of 800 rpm [53]. Samal et al. [54] used Al_2O_3 as a filler to join a banana pseudostem fibre-reinforced epoxy hybrid composite and found that the composite with a fibre content of 30% exhibits the best mechanical properties and hardness. Kumar et al. [55] used a taper threaded tool on 2050-T34 material with varying TTS (6, 8, and 10 mm s^{-1}) and TRS (1000, 1900, 2200, and 2500 rpm) at a TTA of 2° and achieved the highest tensile strength at a TRS of 1900 rpm and a TTS of 10 mm s^{-1} . Patil et al. [56] studied the AA6082-O alloy using taper screw thread and triflutes as pin profiles at 1200 rpm and welding speeds of 60 to 85 mm min^{-1} . They achieved a defect-free joint, 27.58% elongation, and 92.30% of the base metal's ultimate tensile strength. Ishfaq et al. [57] observed that threaded pins significantly improved the properties of ME20 magnesium alloy. An optimal spindle speed of 1600 rpm enhanced the weld strength and surface finish. Ugender et al. [19] welded AZ31 magnesium alloy joints at a spindle speed of 1120 rpm a welding speed of 40 mm min^{-1} using a taper threaded tool pin. This produced a higher stir zone hardness. Gupta et al. [58] found that for Al 1120 plates, using a taper threaded pin tool resulted in better tensile and flexural strength, while a cylindrical threaded pin tool achieved higher hardness and impact strength. El-Sayed et al. [59] tested AA5083-O welds at speeds of 50 mm min^{-1} with spindle speed of 400 rpm and 630 rpm using cylindrical threaded and tapered smooth tools. The highest tensile strength and hardness were achieved at 400 rpm with the threaded tool. Liu et al. [60] studied Al/Cu FSW T-lap joints using pre-set wires and progressive pins. Pre-set ER6061 wires reduced defects, enhanced tensile strength by up to 43.8%, controlled IMC growth, and improved corner material flow, yielding stronger, smoother, and more reliable joints. Kumar et al. [61] found that the threaded tool pin achieved 90% joint efficiency for the AA1100 aluminium alloy at a spindle speed of 1800 rpm and a welding speed of 50 mm min^{-1} . The maximum elongation was 8.38% at a spindle speed of 2400 rpm and a welding speed of 45 mm min^{-1} .

4.2. CONICAL CAM THREAD TOOL PIN

Sun et al. [62] investigated the effect of different pin shapes on 4 mm 2024-T6 aluminium alloy; the conical cam thread tool achieved a maximum tensile

strength of 364.27 MPa (86.73% of the base metal), with 14.95% elongation, greater hardness, and plastic fractures in joints. Akbari et al. [63] found that using threaded pins with 0.75 mm and 1 mm with thread pitches significantly improved particle distribution during FSW, achieving uniform reinforcement dispersion, higher strain, and temperatures higher than circular tools. Hoa et al. [64] used numerical modelling of FSW to demonstrate that the asymmetrical conical and triflate tools created a larger deformation area and more powerful stirring action than the axisymmetric conical tool, enhancing the material flow and improving welding performance. Salari et al. [65] found that using a stepped conical threading tool at a spindle speed of 600 rpm yielded the highest tensile characteristics for 5456 aluminium alloy sheets.

4.3. CYLINDRICAL TOOL PIN PROFILE

Cylindrical pins promote smooth, uniform material flow with limited turbulence, resulting in moderate mixing efficiency and reduced heat generation, which sometimes lead to insufficient intermixing compared to profiled pins such as square or threaded designs. Garg et al. [67] welded the AA6061T6 alloy using a cylindrical grooved tool pin with straight flutes (CGF) and reported the maximum flexural load and tensile strength for this profile. Singh et al. [68] used a cylindrical threaded pin with a concave shoulder for the magnesium alloy, demonstrating that the size of the pin and shoulder are more important than the design features. The result was high-quality joints and good heat conductivity. In their study of AA6061 alloy FSW joints, Emamian et al. [69] found that the threaded cylindrical profile produced the best tensile strength with a spindle speed of 1600 rpm and a welding speed of 100 mm min^{-1} . The conical profiles at a spindle speed of 800 rpm and a welding speed of 40 mm min^{-1} performed worse. Janeczek et al. [70] found that the mechanical qualities of a cylindrical tool for AW-3004 aluminium alloy were approximately 37% better than those of a tapered threaded tool. Balamurugan et al. [71] found that a taper cylinder tool produced a maximum weld strength of 165.84 MPa and joint efficiency of 78.37% with 71 HV hardness for FSW of 5052-H32 and 6061-T6 aluminium alloys. Yang et al. [72] found that, for AA6061-T6, the geometry of the shoulder and pin affects heat generation, tool torque, and SZ contour. The cylindrical pin tool achieved a yield strength of 173 MPa, while the triflute threaded tool achieved an elongation of 32.0%. Kumar et al. [73] found that for AA6061-T6, fluted shoulders and grooved pins produced finer grains, with a cylindrical pin tool achieving a yield strength of 173 MPa and a triflute threaded pin achieving an elongation of 32.0%. The fluted shoulders and grooved pins enhanced stirring and heat distribution, the cylindrical pin ensured a uniform flow to increase strength, while the triflute threaded pin improved plastic flow, which enabled greater ductility and elon-

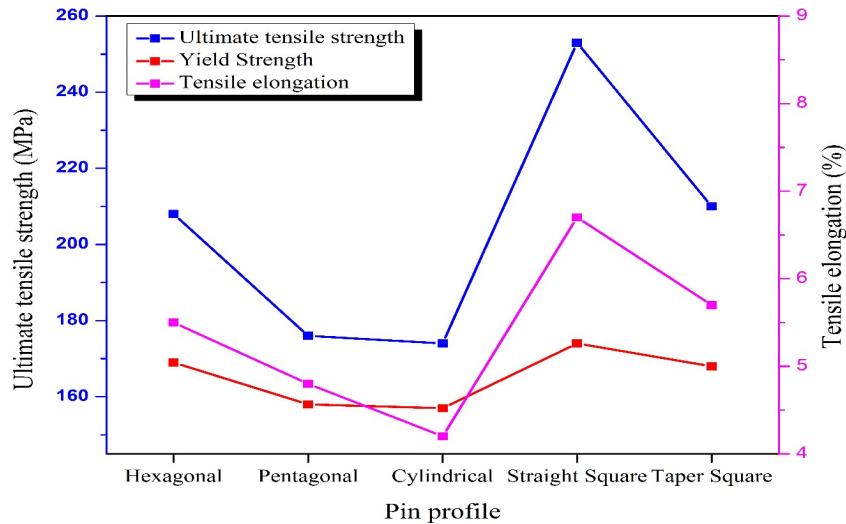


FIGURE 4. Influence of different tool pin profiles on tensile properties of friction stir welding of dissimilar materials AA6061-T6 and AA2017-T6 [66].

gation. Kadian et al. [74] found that, for AA6061, the taper pin produced the finest microstructure and highest mechanical properties at low TRS (630, 800, and 1000 rpm) and TTS (63, 80, and 100 mm min⁻¹) when using cylindrical, screw-threaded cylindrical and taper tools.

4.4. SQUARE TOOL PIN PROFILE

Khodaverdizadeh et al. [75] found that, at 600 rpm and 75 mm min⁻¹, the square pin profile produced better mechanical properties than the threaded cylindrical profile. Marzbanrad et al. [76] observed that, for AA5083, a square pin profile produced higher ultimate strength than a cylindrical profile. This may be because the square pins create a pulsating flow and generate higher heat, thereby improving mixing and grain refinement. Periyasamy et al. [77] found that AA7075-T651 and AA6061 dissimilar joints made with a 3° concave shoulder profile and square pin achieved maximum tensile strength (298 N mm⁻²), hardness (143 HV), and bending angle (49°). Krishna et al. [78] found that using a straight, square tool pin profile to join Al6061 and Al 7075 enhanced the hardness values in the welded and heat-affected zones. Ghangas et al. [79] studied AA 7039 FSW joints made using four pin profiles (cylindrical, conical, triangular, and square) and three pin diameters (5 mm, 6 mm, and 7 mm). The 6 mm square pin profile achieved the best weld quality. The 6 mm square pin produced the optimal amount of heat, creating intense stirring from its corners, ensuring fine grain structure, defect-free consolidation, and superior material flow, resulting in the highest weld quality. Osman et al. [80] found that, for Al6061/Al2O3-TiB2, square and triangular pin profiles achieved better grain refinement, higher hardness, and improved wear resistance. Using a square tool pin with a spindle speed of 1750 rpm and a welding speed of 30 mm min⁻¹ resulted in a tensile strength of 83.5 MPa and a sur-

face roughness of 0.85 μm, outperforming other pins. Mouria et al. [22] found that square tool pin profiles achieved higher tensile properties than triangular pins when joining AZ91D and AA2024 alloys. Battina et al. [66] used a straight, square tool pin profile to join AA6061-T6 and AA2017-T6 alloys, achieving higher tensile strength and elongation. Figure 4 shows a comparison of the tensile strength between notched and smooth specimens in friction-stir-welded joints of the aluminium alloys AA6061-T6 and AA2017-T6. As the graph shows, straight, square tool pin profiles offer superior tensile properties.

4.5. TRIANGULAR TOOL PIN PROFILE

Triangular pin profiles create intense, intermittent stirring with localised high strain rates, enhancing plastic flow but sometimes causing uneven mixing and defects, leading to moderate strength and hardness compared to square pins. Dawood et al. [81] reported that the triangular tool pin profile yielded better mechanical properties and a ductile fracture mode compared to other tool pin profiles. Darmadi et al. [82] investigated that for AA6061 alloys, the triangular tool pin provided superior mechanical properties compared to circular and square pins, and double-side FSW joints exhibited better quality than single-side joints. Chandra & Butola [83] found that FSW of AA7075 with B4C nanoparticles (< 30 nm) at 1200 rpm yielded nanocomposites with microhardness of 195 HV and 46.7% greater wear resistance, demonstrating improved tribological behaviour.

4.6. HEXAGONAL PIN PROFILE

Hexagonal pin profiles generate strong, multidirectional stirring and adequate heat, promoting efficient material mixing, uniform grain refinement, and balanced mechanical properties with reduced defect formation in friction stir welds. Mugada and Adepu [85] reported that welds made with hexagonal pins (TCC)

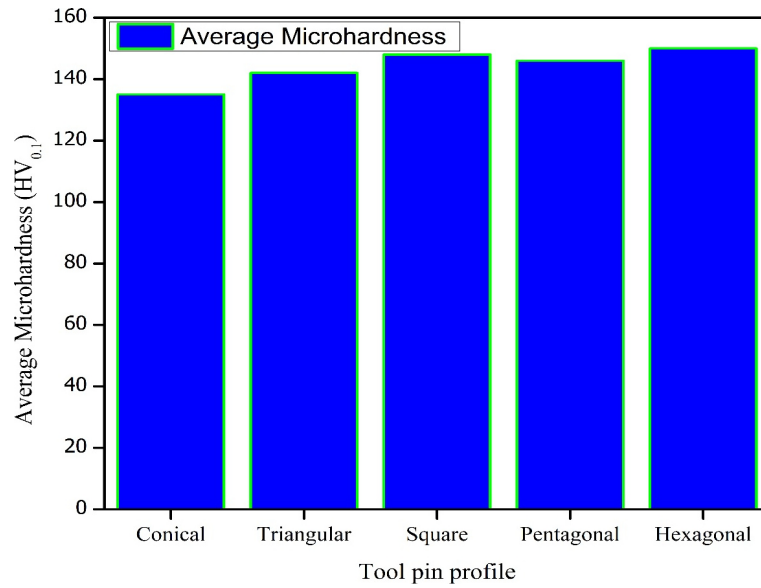


FIGURE 5. Average hardness in the nugget zone of friction-stir-welded AA2014-T6 plates with different tool pins [84].

Observed fracture mode	Likely cause	Tool design guidance
Brittle fracture at the interface	Insufficient plastic flow, low heat input	Increase shoulder diameter or pin volume (tapered/triflute/pentagonal pin) to enhance stirring and heat generation
Fracture through advancing side (AS)	Asymmetric flow, tool offset too high	Adjust tool offset toward retreating side or modify pin threads/flutes to balance flow
Fracture at root (bottom)	Incomplete penetration or poor material mixing	Increase pin length slightly or use a trapezoidal/conical pin with bottom threads to improve root mixing
Mixed fracture across SZ/TMAZ	Nonuniform strain or temperature	Optimize pin taper angle and shoulder concavity to homogenize heat distribution
Ductile fracture within SZ	Balanced heat and plastic flow	Indicates optimized tool design; maintain current configuration

TABLE 9. Fracture mode according to tool design.

HEX achieved superior mechanical properties, including a strength of 187 MPa and an average hardness of 79 HV in the stir zone. These results indicate that the hexagonal pin profile effectively improves the weld's mechanical characteristics. Mohammed & Birru [4] used a hexagonal tungsten carbide tool at a spindle speed of 710 rpm and a welding speed of 40 mm min⁻¹ for three passes. The weld achieved the following properties: yield strength of 154.9 MPa, tensile strength of 227.61 MPa, elongation of 10.5%, grain size of 16.02, and hardness of 74 HV. Palani et al. [86] found optimal settings for defect-free welds of AA8011 and AA6061-T6 with a hexagonal pin profile to be: spindle speed of 1500 rpm, plunge depth of 2.5 mm, and welding speed of 40 mm min⁻¹. This profile provided superior tensile strength and weld joint properties. Gadakh et al. [87] found that the hexagonal pin profile yielded lower temperatures for an analytical model than the square pin profile. Ramanjaneyulu et al. [84] welded AA2014-T6 aluminium alloy plates using tool pins with different

profiles (conical, triangular, square, pentagonal, and hexagonal) at a constant TRS of 1000 rpm, TTS of 600 mm min⁻¹, and tilt angle of 2°. As shown in Figure 5, the hexagonal pin produced superior mechanical properties due to its six corners generating intense stirring, uniform heating, effective material flow, fine grain structure, and defect-free joint consolidation.

5. FRACTURE ANALYSIS

Table 9 shows the results of the fracture analysis of the friction-welded samples, which were produced using various tool pin profiles. The analysis revealed significant differences in the fracture modes and mechanical performance. The tool design and the welding parameters significantly impact the resulting weld properties. Decreasing the weld speed and increasing the tilt angle or rotational speed can reduce brittle fracture, which is usually caused by low heat input. In order to address interfacial separation caused by insufficient forging pressure, either the axial force or the shoulder

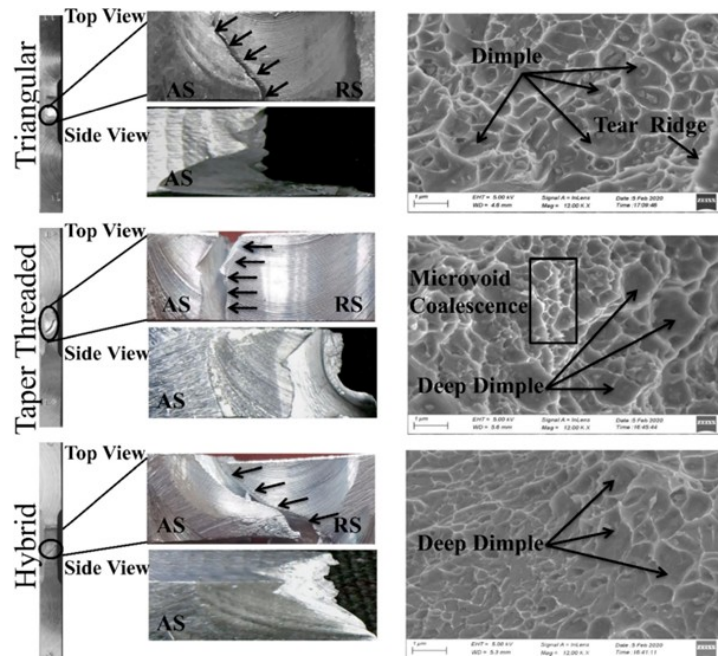


FIGURE 6. Tensile fracture of welded samples using different tool pin profiles [9].

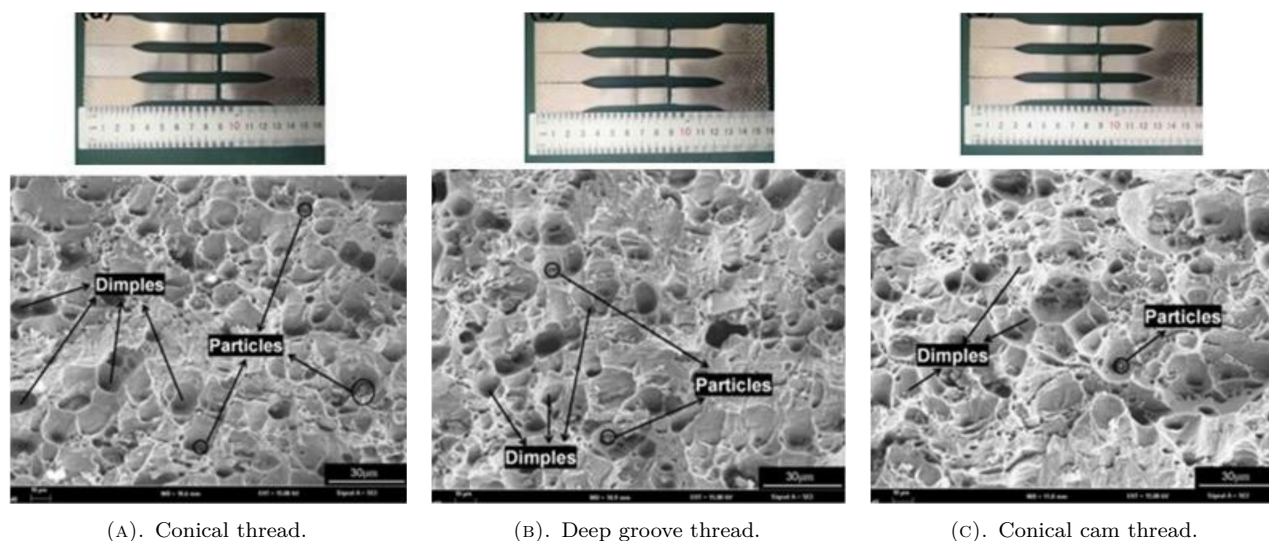
plunge depth should be increased. A minor decrease in traverse speed or an increase in pin length can help to alleviate root defect fracture, which indicates incomplete penetration. Reducing the rotation speed or shoulder diameter and increasing the travel speed can prevent overheating and ductile fracture, which are characterised by excessive heat and grain coarsening. Fracture analysis reveals ductile failure with uniform mixing and tensile strengths approaching 80 % of those of the base aluminium strength in aluminium-copper joints welded with squared pins. By contrast, triangular pin designs tend to produce mixed fracture modes that combine ductile and brittle properties, which correspond to weaker joints that exhibit internal defects, such as dislocations, separations, and particle cracking. The mechanical characteristics and fracture behaviours of cylindrical and tapered pins often fall within the middle range [88]. Better plastic flow and material mixing during welding, which improve mechanical strength and weld integrity, are indicated by ductile fracture modes observed for squared pin shapes. Therefore, tool design should prioritise pin shapes that optimise material processing and steer away from stress concentrators. To maximise heat input and strain distribution, and thus encourage ductile fracture and reduce weld flaws, it is essential that parameters such as traverse and rotational speeds are selected in tandem with the chosen pin profile [89].

The fracture analysis of 2050-T84 Al-Li alloy associated with different tool pin profiles shows different fracture morphologies, as illustrated in Table 9. A semi-ductile fracture is caused by the triangular pin's combination of dimples and tear ridges. Deep dimples and microvoid coalescence on the taper-threaded pin indicate increased ductility. The hybrid pin's deep dimples indicate improved plastic deformation and

joint strength, as shown in Figure 6, and demonstrate the correlation between pin design and fracture behaviour. Smooth surfaces, grey fibre texture, and 45° cracks were observed in tensile fracture specimens that fractured at the TMAZ on the AS, as can be seen in Figure 7. The mechanical properties decreased due to phase precipitation and segregation caused by thermal cycles. The phase distribution was inconsistent due to limited mechanical stirring. Cracking occurred during tensile testing due to weak spots formed by the V-shaped cross-section of the weld. The fracture morphology of joints welded with various tool pins exhibited equiaxed dimples with smooth walls at the TMAZ on the AS, indicative of plastic fracture. Second-phase particles were seen at the bases of the dimples; finer particles created smaller dimples, while larger particles created larger ones. Crack cores developed at particle boundaries due to differences in the bonding strengths of the second-phase particles and matrices, and they grew under stress until they fractured. As shown in Figure 7, the depth of dimples increased with elongation following the fracture, highlighting the gradual plastic deformation and fracture behaviour affected by tool pin designs.

6. CONCLUSION

This review emphasises that tool pin geometry strongly influences the microstructure, and weld quality in FSW. Cylindrical and tapered pins are durable and straightforward, but often cause weak mixing and root defects. Polygonal pins enhance stirring, grain refinement, and strength, though at the cost of higher torque and tool wear. Threaded and taper-threaded pins increase the movement of plasticised materials and decrease flaws, however, they cause overheating



(A). Conical thread.

(B). Deep groove thread.

(C). Conical cam thread.

FIGURE 7. Tensile fracture of welded samples using threaded tool pins with different profiles [43].

and coarsen the grain. Hybrid profiles combine the advantages and are particularly useful for dissimilar or lightweight alloys, though the manufacturing complexity limits their widespread use. Future research may focus on adaptive tool pin designs, predictive modelling, machine learning, and cost-performance evaluations to guide industrial adoption in aerospace, automotive, and multi-material systems.

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