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A Review on Tool Pin Geometry of Friction Stir Welding

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Abstract

Friction stir welding (FSW) is an innovative solid joining operation that has recently been intensively adopted in welding various similar and dissimilar metallic materials, including aluminum, steel, titanium alloys, and others. The success of FSW relies on a set of parameters like rotational speed, travel speed, axial force, tool geometry, etc. The role of tool geometry (involving both pin and shoulder design) is highly important in producing sound and high-strength weld joints. Therefore, this research aims to review the latest published works regarding the performance of different tool geometries. The discussion of the findings of the cited works revealed that each tool pin design has shown different behavior due to the various stirring efficiencies of the materials being welded. All in all, the square threaded pin had the best geometry in terms of its mechanical properties compared to other pin designs. The threaded cylinders and threaded taper are most commonly utilized and offer good joints, while the maximum joint efficiency was achieved by the square pin profile and it reached 94% in some investigations.

Keywords: *Tool Pin geometry; Friction Stir Welding FSW; FSW parameters*

1. Introduction

Friction stir welding (FSW) has become a relatively new welding method that was developed by Wayne Thomas in 1991 at the Welding Institute (TWI) of the United Kingdom as a solid-state welding technique[1-4]. This innovation is a huge success for joining materials with low melting temperatures and aluminum alloys [5-7].

Recently, FSW is a versatile joining process capable of welding a wide range of metallic alloys. Some of the metallic alloys commonly welded using FSW include: Aluminum, magnesium, steel, titanium, and so on. Each alloy has its own set of properties, and FSW parameters need to be carefully adjusted to suit the material being welded. The process parameters, tool design, and optimization methods may vary depending on the alloy being joined to achieve high-quality welds with desirable mechanical properties. Ongoing research continues to expand the range of alloys weldable through FSW and improve the quality of joints in different materials. Figure 1 shows the diagram of the FSW process. The shipping, aerospace, automotive, rail, and construction industries are among the industries that use FSW. These days, FSW is being progressively introduced to the at sea structure and energy sectors. [8-10], FSW is also highly advantageous in terms of economic and environmental considerations [11-13].

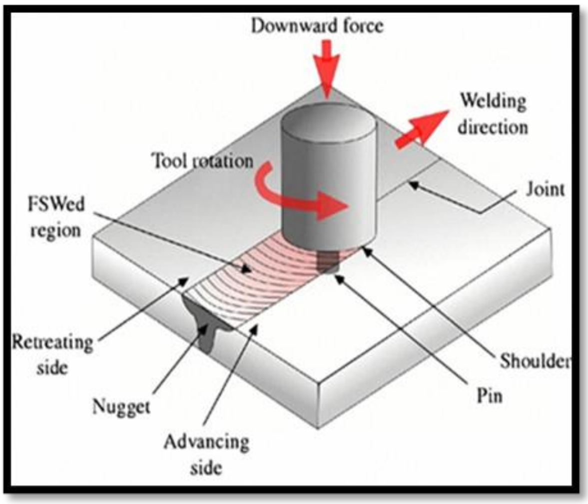

Fig. 1. Basic principle of the FSW process [14].

In FSW, primary and secondary parameters are the two groups of factors that affect the quality of the weld joint. The traverse speed, rotational speed, and tool geometry are the main parameters. In the meantime, the pin profile, welding tool material, workpiece thickness, and workpiece material are the secondary parameters [15-16].

The performance of the FSW process is assessed and judged based on various parameters that determine the quality of the weld and the efficiency of the process. Some key parameters that are used to evaluate the performance of FSW include [17]:

1.Weld Quality Evaluation: Assessing weld effectiveness involves scrutinizing for defects like voids, cracks, and incomplete fusion, alongside ensuring adequate joint strength.

2.Mechanical Properties: Key characteristics include toughness, ductility, fatigue resistance, and tensile strength, pivotal for assessing the weld's performance.

3.Microstructural Analysis: Evaluating alterations in the microstructure across the base material, heat-affected zone (HAZ), and weld area is crucial for understanding material behavior post-welding.

4.Efficiency Metrics: Process efficiency encompasses factors like repeatability, energy consumption, tool longevity, and welding speed, impacting the overall effectiveness of Friction Stir Welding (FSW).

5.Process Variables: Optimizing parameters such as tool geometry, axial force, rotational speed, and feed rate directly influences weld quality and consistency.

6.Heat-Affected Zone Characteristics: Understanding HAZ features, including shape, composition, thermal distortion, and metallurgical changes, aids in comprehending the weld's surrounding environment.

Ongoing research and development endeavors aim to enhance FSW performance by evaluating and refining the process for diverse materials and applications using these indices and parameters. By broadening its utilization across a wider spectrum of materials and industrial needs, and by improving both weld quality and process efficiency, the aim is to elevate the effectiveness of the FSW process [18].

2. The Importance of Tool Geometry and its Role in Succeeding the FSW Weld Joints

The shape of the tool affects the weld joint's uniformity, plastic flow, heat generation, and power consumption. The majority of the heat is produced by the shoulder, which also keeps the plasticized material from escaping the workpiece. The material flow is influenced by both the tool pin profile and the shoulder. A number of new features have been added to tool design in recent years [19-20]. The threads on the pin assist in ensuring that plastically deformed material flows around the pin as the tool advances along the joint line, it subsequently stirs and recombines the plasticized material to the side of the tool where the material cools to form a solid-state weld. At the end of the welding pass, the tool is retracted from the plate and leaves a hole at the end of the weld [21].

In recent years, several new classifications of features have been introduced. The primary classification of the currently used FSW tool geometries, such as a threaded cylinder, a threaded cylinder with flattened sides Flared triflate,Mx triflate, Askew, and Re-stir as shown in Figure 2. enabled the successful welding of parts of higher t hickness by increasing the penetration depth.

Tool	Cylindrical	Whorl™	MX triflute™	Flared triflute™	A-skew™	Re-stir™
Schematics						
Tool pin shape	Cylindrical with threads	Tapered with threads	Threaded, tapered with three flutes	Tri-flute with flute ends flared out	Inclined cylindrical with threads	Tapered with threads
Ratio of pin volume to cylindrical pin volume	1	0.4	0.3	0.3	1	0.4
Swept volume to pin volume ratio	1.1	1.8	2.6	2.6	depends on pin angle	1.8
Rotary reversal	No	No	No	No	No	Yes
Application	Butt welding; fails in lap welding	Butt welding with lower welding torque	Butt welding with further lower welding torque	Lap welding with lower thinning of upper plate	Lap welding with lower thinning of upper plate	When minimum asymmetry in weld property is desired

Fig. 2. Tool Geometry for Friction Stir Welding [22].

3. Time line of the Development of the Geometry of the Pin's tool

FSW was invented and patented by Wayne Thomas at The Welding Institute in 1991[23]. The tools used in FSW, including the geometry of the pin, have undergone several developments and improvements over time. The evolution of pin tool geometry started in the early stages of (1991). The initial development of FSW involved basic cylindrical or threaded pin geometries. Basic shapes served as the primary tools initially; however, to enhance process comprehension, researchers experimented with varying pin lengths, diameters, and materials.

In the late 1990s, researchers began exploring more intricate pin geometries to maximize material flow and mechanical properties. Different pin shapes, including tapered and threaded designs, were scrutinized to enhance weld quality and efficacy[24].

By the early 2000s, tool geometry optimization was achieved through advanced computer simulations and modeling techniques. Further enhancements were made to pin tool designs, focusing on aspects like flute geometry, shoulder diameter, pin offset, and probe materials to elevate welding performance. These efforts aimed to improve material flow, minimize defects, reinforce joints, and enhance process efficiency. Ongoing research and innovation in FSW continue to refine and optimize pin tool geometries across various industries, as illustrated in the subsequent investigations [25].

4. Investigation on FSW Pin Shapes

The researchers looked at different welding pin geometric shapes used in friction stir welding processes in this review.

Galvão et al., 2013 [26] investigated the effects of several FSW variables on the formation of intermetallic compounds (IMCs), during friction stir welding of AA5186 to mild steel. The tool rotation speed was 355 rpm, welding speed was 14-28 mm/min, 0.8 mm plunge depth ,5° tilt angle and the threaded pin tool was used in Figure 3. They concluded that the low welding speeds of 14 mm/min were the tunnel defect first appeared, and that the making of thick IMCs was what led to the joints at low welding speeds having unusually low tensile strengths. The IMCs dropped and the joint's tensile strength increased as welding speed increased. From experimental work, they discovered that utilizing four pins (conical threaded, cylindricalconical threaded, stepped conical thread and neutral flared triflate) with a diameter of 4 and 3 millimetres did not stop the tunnel fault, but that using a standard threaded M3tool pin did, and a bell-shaped nugget formed in its place. They proved that the joint's tensile strength increased to 90% achieved by cylindricalconical threaded. As a result of insufficient bonding between the aluminum and the steel, the joint's strength decreased with faster welding speeds and shorter tool plunges.

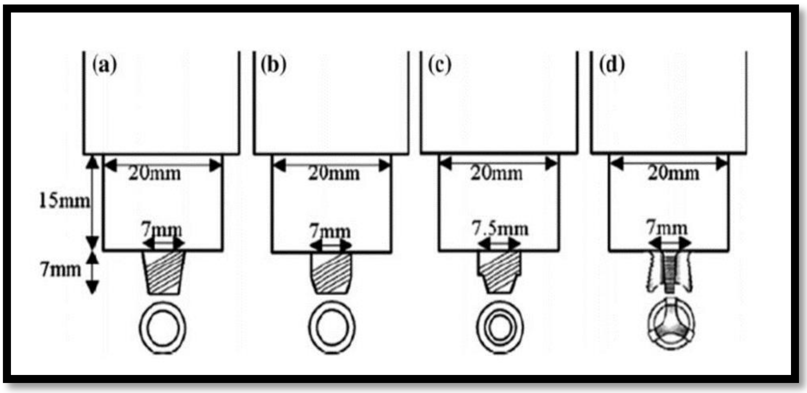

Fig. 3. Pin profiles Geometries. (a) Conical threaded. (b) CylindricalConical threaded. (c) Stepped conical thread (d) Neutral flared triflate [26].

Marzbanrad et al., 2014 [27]studied the effects of pin shape on the mechanical and microstructural flow of material, thermal distribution, and strain fields during the FSW of AA5083. Two separate tools with square and cylinder pin shapes were used to create the joints. As depicted in Figure 4. To investigate how tool pin profiles affect material flow, and temperature, and strain distribution, a numerical model is created using 3D FEM––thermo-mechanically coupled rigid-viscoelastic and strain distributions. In the experimental work, a tensile test was performed. The outcomes found that square pin shapes offered finer grain structures and higher ultimate strengths than cylinder ones. These results can be explained by the square pin profile's higher deviation, large stirring zone, and greater weld zone temperature.

Fig. 4. Square and cylindrical pin shapes [27].

Doos, Qasim M. and Makki, 2014 [28] investigate the impact of FSW T–joints on the mechanical characteristics of AA 5456 plates with 4 mm thickness. The base material was cut into dimensions of 180×70×30 mm^3 for stringers. This research looked at the impact of welding parameters such as rotating speed, transverse speed, plunging depth, and die radii of the gripping clamp on the efficiency of welding and the strength of welded parts. In the experimental work, the three rotational speeds (640, 960, and 1200) rpm and three welding speeds (60, 90, and 110) mm/min and three values for the tool tilt angle (2, 3, and 4) mm were used to achieve the best level of the welding condition that improves the weld quality. Two tool geometries were used for FSW T-joints. The first tool had a square pin profile in two parts, the first part with (5×5×4) mm dimensions starting from the shoulder face with a 22 mm shoulder diameter and the second part with (3×3×1) mm dimensions from the end of the first part. The second tool had a conical pin profile with the basic dimensions (5mm base diameter, 3mm minor diameter, and 5mm length) and a 22 mm shoulder diameter. From the results of this work, the greatest welding efficiency for the aluminum alloy (Al 5456) utilizing the FSW T-joint is 82.05%. **Mustafa, Kadhym and Yahya, 2015** [29] studied the influence of FSW T–joints for Al 6061 T6 Al alloy on mechanical and metallurgical characterization investigated by nine different tool shapes, that are fabricated by Taguchi orthogonal array (OA) with no varying of process parameters (welding speed, rotation speed, die radii, tilt angle, and plunging depth) Figure 5. Four variable geometrical factors (diameter of shoulder: 14.1, 17.1, and 24.1), pin angle (0, 5, and 10), diameter of pin (1.7, 2.2, and 2.7), and shape of pin (smooth, right, and left) with three stages for each factor were utilized. The design of experiments (DOE) was preceded by an L9 (orthogonal) array with 9 experiments. The best parameters were shoulder diameter = 17.1 mm, pin diameter = 2.2 mm, pin angle = 10°, the shape of the pin = Right, UTSSkins actual mean = 168.00 MPa for the welded parts.

The best parameters are the same which give higher UTS and UBF.

Fig. 5. Manufactured tools [29].

Dawood *et al.*, 2015 [30] studied three various pin shapes namely; conical threaded,triangular , and square, as shown in Figure 6. These pin shapes affect on the mechanical characteristics and microstructures of AA6061 joints. The outcomes show that triangular pin shapes produce the best metallurgical and mechanical weld characteristics. Additionally, when utilizing a square tool pin shape, friction stir welding has the lowest micro-hardness and tensile strength. According to this, a more concentrated heat- affected zone (HAZ) and an ideal amount of softening are produced by tool pin profiles and shoulder diameters that are lower. The fracture surface analysis demonstrates that during welding with various tool pin profiles, the joints undergo different types of failure. The specimens produced with triangular pins break during the tensile test with a malleable fracture, according to the fracture surface, while the joints formed with various pin shapes show brittle fracture modes (T1 and T3).

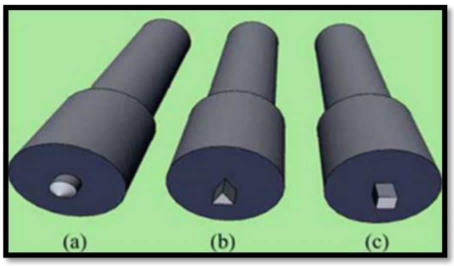

Fig. 6. (a) Threaded tapered cylindrical pin shapeT1, (b) Triangular pin shapeT2, (c) Square pin shape T3 [30].

Ilangovan et.al., 2015 [31] examined how various AA6061-AA5086 joints' mechanical properties were modified by the pin profile (cylindrical, threaded, and tapered pin). In the investigation, cylindrical pin profiles with threads and taper produced joints without defects and with comparable tensile properties. However, the result of this work shows that the threaded cylindrical is preferred due to the superior joints used in their research, as shown in Figure 7.

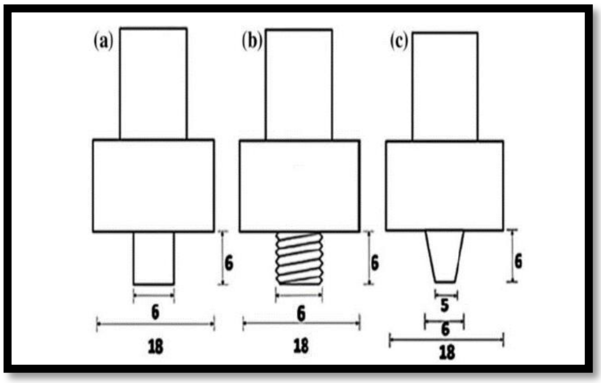

Fig. 7. (a) Cylindrical pin. b) Threaded pin. c) Tapered pin[31].

Al-kubaisy, 2016[32] made an investigation to find the best FSW variables, the Taguchi technique was utilized to identify essential variables for the dissimilar AA2024-T3 and AA7075-T73 of 3 mm thick plates respectively. Using a variety of travel speeds (20, 45, and 69 mm/min), a variety of rotation speeds (898, 1200, and 1710 pm), three various pin shapes (cylindrical, threaded cylindrical, and cone), and a 2° tool tilt angle, FSW was successfully performed. The optimum parameter values were found using the S/N ratio analysis result, and they were 898 revolutions per minute for rotation, 45 millimeters per minute for travel speed, and a threaded cylindrical pin profile with a 76% joint efficiency. Tensile strength statistics indicate that travel speed, which contributed 66.05% more than the other process variables, was the most important variable.

Sabari *et al.*, 2016 [33] investigated the performance of different pin profiles on the FSW joint strength of AAS5-T87-produced underwater cooling media. Figure 8 shows the shapes of threaded taper cylindrical (STC), taper cylindrical (TAC), threaded cylindrical (THC), and taper threaded cylindrical (TTC). The analysis was based on the characteristics of the rotated part and the resulting yield strength of every FSW junctions. From this observation, they found the joint with a taper-threaded pin-profiled tool and underwater cooling media demonstrated excellent tensile qualities, with joint effectiveness of 76% and tensile strength of 345 MPa

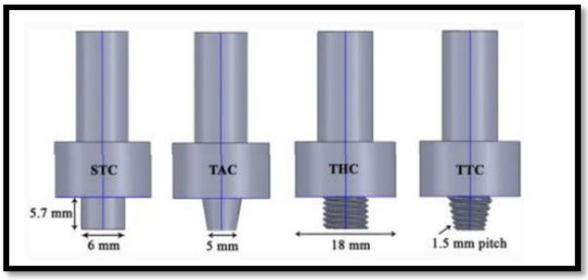

Fig. 8. STC, TAC, THC and TTC pin profiles[33].

Kumar, 2017 [34] attempted to weld the AA7075 T651 and AA6061 T6 using the FSW process. The rotational speed (750 rpm - 1250 rpm) and traverse range (90 mm/min - 110 mm/min) were considered as the studied process parameters. Pin profiles were created using 5 tools, including the threaded cylindrical (TC), triangular (TP), conical (CP), square (SP), and hexagonal (HP) profiles in Figure 9. In this work, the results of the experiment showed that the square tool pin profile and the hexagonal pin profile produced good, clean welds when used at tool revolving speeds of 1250 rpm and 110 mm/min, respectively. The proper choice of tool pin profile, rotational speed, travel, and different necessary parameters will give better consequences.

Fig. 9. Five pin shapes [34].

Sharma *et al.*, 2018[35] examined the impact of various pin profiles on the microstructure, material flow, and microhardness of the various joints during the FSW of commercially pure copper in a butt configuration and AA5754 Al alloy. The pin profiles of taper, cylindrical, taper cam, taper cam, and square shape depicted in Figure 10 are used to perform the joining. The welding speed is 40 millimeters/minute, and the rotational speed is 900 rpm. Out of all the joint profiles, the square pin profile provides the best microhardness and joining.

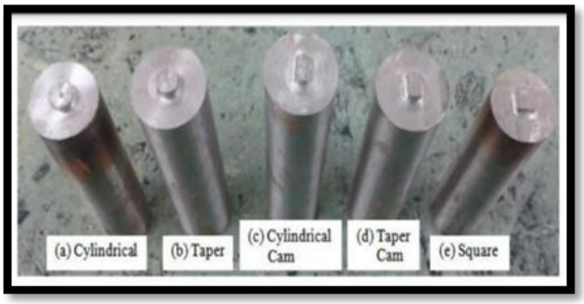

Fig. 10. FSW tool pin profiles[35].

Udaiyakumar *et al.*, 2018 [36] made an investigation on different pin shapes (straight cylinder, straight square, and tapered hexagon) and FSW mechanical qualities on variant Al alloys to evaluate how well they worked. Three pin shapes and two alloy compositions, AA6061 and AA7075, were welded to examine the weld-joint behavior. Microhardness tests were utilized to measure mechanical properties. In this work, the process parameters of each specimen were analyzed and correlated to highlight the qualities and characteristics. The result indicates that the straight square was chosen for microhardness.

Goel *et al.*, 2018 [37] studied the AA6063-T6 butt joint produced by FSW. 5 distinct kinds of pin shapes (cylindrical (CY), tapered cylindrical (TCY), square (SQ), triangular (TR), and hexagonal (HEX)) were fabricated as shown in Figure 11. The results showed that the highest tensile strength (162 MPa) using TCY was demonstrated, while the lowest tensile strength (115.6 MPa) was verified using a triangular shape.

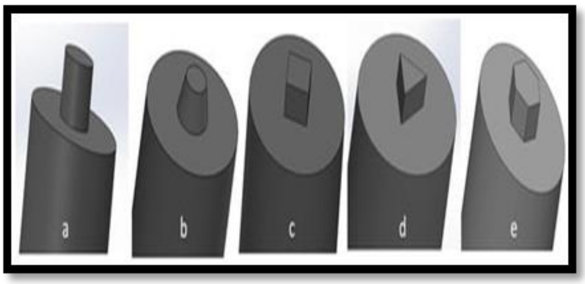

Fig. 11. FSW tools pin profiles (a) cylindrical; (b) tapered cylindrical; (c) triangular; (d) square and (e) hexagonal[37].

Amin, Hanna and Mohamed, 2018 [38] examined the impact of pin shapes on the mechanical characteristics of welding joints for AA6061-T6. To determine the best bobbin pin design, Pin shapes and their effects on the mechanical properties of AA6061-T6 welding joints that have a 6.25 mm thickness were investigated using FSW. Five different pin shapes were used to create the welding joints: straight cylindrical with three flat surfaces, straight cylindrical with four flat surfaces, straight cylindrical with threaded surfaces, and straight cylindrical with threaded surfaces with three flat surfaces, figure 12. In the experimental work, tensile and bending tests were performed to determine the ideal bobbin tool design that had excellent mechanical qualities. Based on tensile strength, the tool of straight cylindrical with 4 flats, an 8 mm pin, and shoulders with a 24 mm diameter given a higher strength (192 MPa), elongation (6.2%), BF (5.6 KN), and efficiency (65.3%).

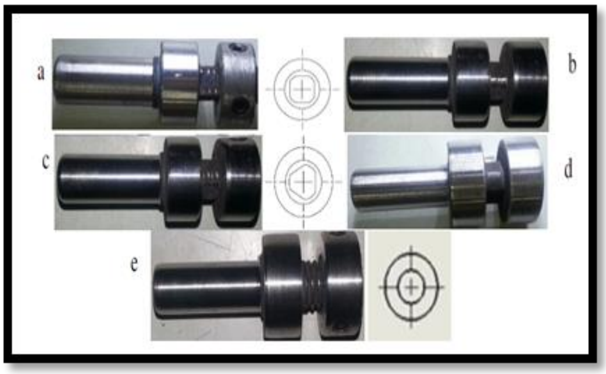

Fig. 12. Straight cylindrical with 4 flat surfaces that are threaded, straight cylindrical with 3 flat surfaces that are threaded, and straight cylindrical pins with 3 flat surfaces that are threaded[38].

Maboud *et al*, 2018 [39] Applied response surface methodology (RSM) to study the mechanical properties of friction stir processing of AA1050 by utilizing four factors (rotational speed 500, 1000, 1500, 2000, 2500), feed rate (58, 87,116, 145, and 174), number of passes (1, 2, 3, 4, and 5), and tool shape (conical,triangle, square, pentagon, and hexagonal) Figure 13. The ANOVA technique was used to identify the important process variables influencing the respondents' responses. According to these findings, the friction stir processing of 1050 aluminum alloy with three FSP passes, a square tool shape, the rotational speed was 1500 reovlutions per minute, and a welding speed was 116 millmeters per minute had a maximum efficiency of 72.9%.

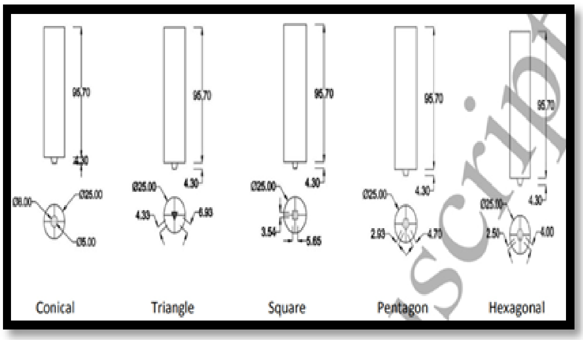

Fig. 13. FSW tool pin profiles[40].

Shammari, 2019 [41] Investigated the mechanical properties of FSW butt joints made from AA2024-T3 and AA6061-T6. The following parameters were chosen for this project: three-pin profiles (cylindrical, cylindrical thread, and triangular) showed in Figure.14, rotation speed (550,950,1500 rpm), travel speed (40,60,80 mm/min), and tilt angle (1,2,3) degrees. They used the ANOVA technique and the signal-to-noise ratio to identify the most important factor influencing the mechanical parameters of the weldment. The result of this work shows that the pin geometry has been found to have the smallest impact, whereas tilt angle has the biggest impact of all the parameters. The travel speed is the most influencial factor in the bending test, and the pin geometry still has the smallest impact.

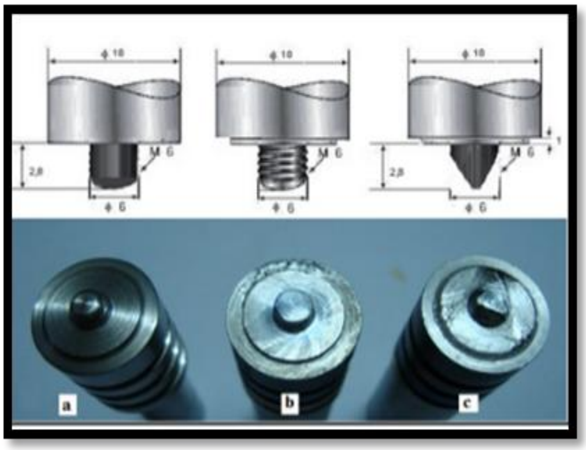

Fig. 14. pin shapes geometry: a) Cylindrical pin, b) Cylindrical Threaded pin, c) Triangle pin [41].

Su, Xue and Wu, 2020 [42] investigated the FSW's performance for three tool pins with three flats. The tool pin T0 is a conical pin, and the tool pins T30, T60, T90, and T120 have three flat areas with varying opening angles of 30°, 60°, 90°, and

120°, respectively. The measurements of the different tools are the same: figure 15 shows that the pin length is 5.75 mm, the pin diameter on top and bottom is 6.00 mm and 4.00 mm, respectively, and the shoulder diameter is 15.0 mm. For a thorough understanding of the coupled thermomechanical phenomena around the tool pin with three flats during FSW, a three-dimensional CFD model is utilized. A quantitative analysis is conducted to determine the impact of the pin flat proportion on the welding loads, material flow behavior, and thermal response. The findings show that the volume of the plastic deformation zone, maximum material flow velocity, temperature distribution, and heat generation rate all continuously increase as the proportion of flat features on the pin side increases. Furthermore, it is discovered that the tool torque is not significantly affected by the tool pin profile (less than 4.7%), and that T90 provides the highest tool torque values.

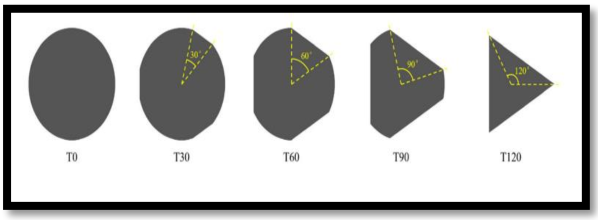

Fig. 15. Three tool pins with three flats[42].

Shiva Chander *et al.*, 2020 [43] examined the AA6351 FSW weld joint's mechanical characteristics using five pin profiles (straight cylindrical, threaded cylindrical, taper cylindrical, square, and triangular) as Figure 16 reveals. In accordance with tensile strength the triangle tool pin gave a mechanically sound and metallurgically free, disorder-free weld.

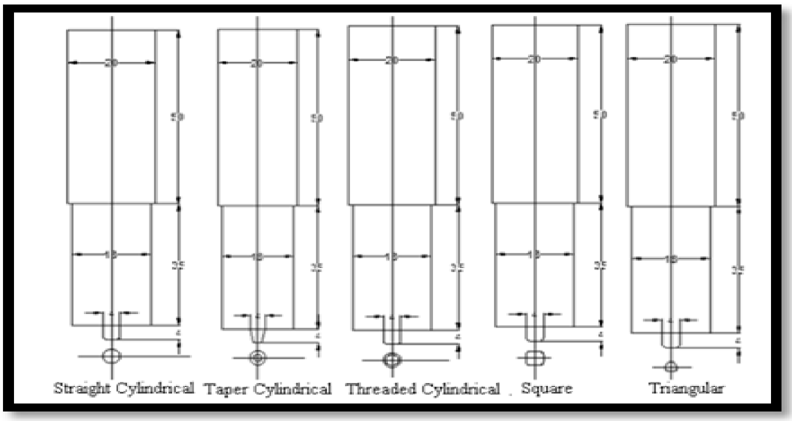

Fig. 16. Straight cylindrical, threaded cylindrical, taper cylindrical, square pin geometries [43].

Mustafa and Daham, 2021 [44] conducted an investigation on the friction stir welding of T-joints made of AA6061-T6. by using the Taguchi technique based on the L9 orthogonal array to investigate the effects of four process factors. These variables are: (transverse speed, type of nanopowders, rotational speed, and groove depth). The simultaneous creation of metal matrix nanocomposites (MMNCs) and welding T-joint sections are combined. Based on tensile tests conducted in the direction of the skin and stringers as well as a joint hardness test, optimum factors and their percentage contribution are determined using the(ANOVA) technique and signal-to-noise ratio approaches. At the optimum conditions of 1550rpm rotational speed, the skin-welded part's best ultimate tensile stress (UTS skin) equal to (177MPa) was obtained. Travel speed of 15 mm/min, Al_2O_3 powder, and a groove depth of 1 mm. All nine studies' metal matrix nanocomposite SEM micrographs showed that the nanoparticles varied widely in the nugget zone as a result of one pass. The maximal hardness value of 80HV is obtained in the nugget zone at rotating speeds of 960rpm, transverse speeds of 15mm/min, type of powder TiO_2, and groove depths of 1.5mm. The groove's depth is the most important parameter in this experiment, The depth of the groove is the most important variable, according to the analysis of variance. Nano-powder particles in the region of FSW improve the UTS and hardness, but the powder clusters in this area will reduce the enhancement of these qualities. The cylindrical pin profile with 1.5mm grove depth is practical and gives higher stirring of nanopowder in the nugget zone due to improving the hardness and tensile strength .

Jayaprakash *et al.*, 2021[45] Welded AA5083 and AA7068 by FSW using three pin profiles including triangle-shaped, tapered cylindrical, and straight cylindrical tools. As shown in Figure 17. The investigation's process factors include force of (3, 4, 5, and 6) KN, rotational speed of (800, 1000, 1200, 1400) rpm, traverse speed of (30, 40, 50, 60) mm/min, and thickness of plates (5, 6, 7, 8) mm. The result of this work shows that the welding zone's improved hardness value and ultimate tensile strength are evidence that the tool profile was effectively put to use. At 267 MPa, the maximum UTS was reached. The highest UTS measured with a triangular tool was 286 MPa. A straight cylindrical tool was used to achieve the highest UTS of 275 MPa.

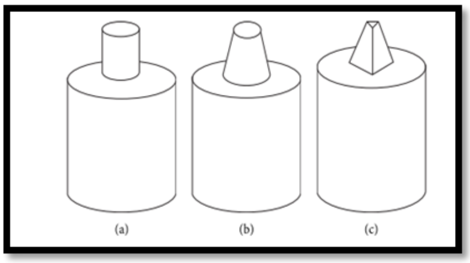

Fig. 17. FSW tool. (a) Cylindrical, (b) Taper, (c) Triangular tool [45].

Battina *et al.*, 2021 [46] studied the mechanical characteristics of welded joints by utilizing five pin profiles namely taper square (TS), straight pentagonal (SP), straight square (SS), straight cylindrical (SC), and straight hexagonal (SH). According to the test results, the straight square tool pin profile had a tensile elongation of 6.7% and a higher UTS of 253 MPa. Compared to other pin profiles, higher micro-hardness and joint efficiency were reported. For a straight square tool pin profile, Figure 18, additional flow ability indications with fine grain structure were studied. The increase in micro-hardness was caused by the presence of a compound and the development of fine-grain structures. A joint without any flaws was created by the square pin profiles.

Fig. 18. various tool pin profiles [46].

Gopi and Mohan, 2021 [47] Studied two geometrical tool parameters to properly define the pin profiles (Triangle TR, Square SQ, Pentagon PN,Hexagon HX,Heptagon HP) Figure.19, five friction stir welding (FSW) processes were selected which are (spindle speed (700,900,1100,1300 and 1500), weld speed (0.8,1.6, 2.4, 3.2and 4.0), and shoulder penetration 0.00,0.04 ,0.08, 0.12 and 0.16), and shoulder profile (-10°, -5°, 0°, 5°and 10°). The Taguchi experimental design approach was used for optimization, and FSW tests were carried out in a typical milling machine. For different plate thicknesses, the parameters were tuned to maximize the tensile strength. The corresponding welding pulses are determined by the number of tool pin polygon edges. The results show that 105–110 pulses/s is the ideal rate for producing a high-quality and defect-free weld.

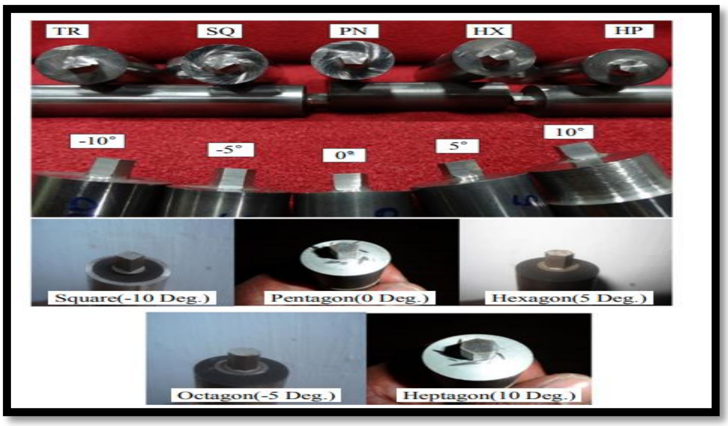

Fig. 19.Various tool pin profiles[47].

Ahmed *et al.*, 2021[48] studied AA1050-H14 comparable lap joints by using the Bobbin Tool-FSW method with a thickness of 10mm. by using three distinct pin geometries (cylindrical, square, and triangular), Figure 20, as well as a concave shoulder profile. Travel speeds of 200, 400, 600, 800, and 1000 millimeters/minute were used in addition to rotation speed of 600 revolutions per minute. The results demonstrated that pin shape and travel speed are regarded as the most crucial controlling parameters in BT-FSW thick lap joints. The temperature generated during the BT-FSW process was measured and studied at the joints' centre line. In comparison to the cylindrical (Cy) and triangular (Tr) pin geometries, the square (Sq) pin produces the greatest BT-FSW stir zone temperature, while the Tr pin produces the lowest stir zone temperature at all applied travel speeds between 200 and 1000 mm/min. Additionally, the temperature at the lap joints dropped as welding speed increased, and the highest temperature of 380 °C was reached with Sq pin at the slowest travel speed of 200 mm/min. By about 20 °C, the temperature on the advancing side (AS) was greater than on the retreating side (RS). At all the different welding speeds examined, defect-free welds were created utilizing a bobbin tool with Cy and Sq pin geometries. When employing the Sq pin, BT-FSW at a travel speed of 200 mm/min results in the maximum tensile shear qualities. The tool pin geometry and welding speed both had a substantial impact on the hardness profiles, although utilizing a triangular pin and increasing the welding speed significantly reduced the width of the softened region.

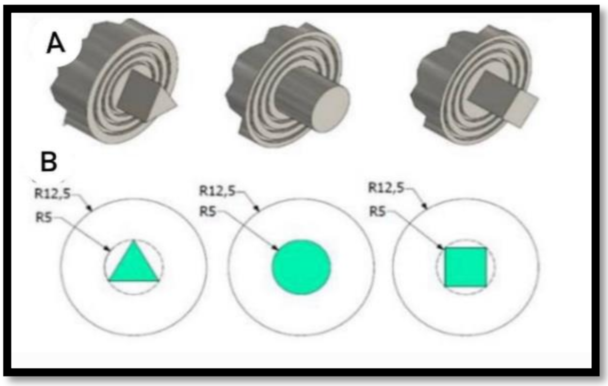

Fig. 20. (A) 3D pin shapes, and (B) dimension of BT pins [48].

Raj *et al.*, 2021 [49] made an investigation by using AA2024-T365 and AA5083-H111 as their base materials, and heat-treated H13 steel for the tool material. Using three different pin profiles namely: (Stepped, triangular, and square), with pin diameter of 5 mm, and a height of 4. 7 mm. The welding variables are the tool rotational speed of 900, 1120, and 1400 revolutions per minute and the travel speed of 16, 40, and 80 millimeters per minute. The plate cuts into AA5086 (100*95*6 mm) and (100*70*6 mm). The optimum variables were (a rotational speed of 1000 revolutions per minute, a traverse speed of 20 millimeters per minute, and tilting angle of 2^{o}). The maximum impact strength of joints was achieved when using a triangular pin profile.

Ahmed *et al.*, 2022 [50] Optimized the FSW parameters of the AA5451 alloy by using Taguchi experimental design. The process variables have significant effects on the welded joint with the FSW method i.e., feed rate (16, 18, and 20 millimeters per minute), rotational speed (1000,1200 and1400 revolutions per minute), and pin profile (taper,threaded and cylindrical) of the tool, Figure 21. When the welding conditions were used, which included a rotation speed of 1400 revolutions per minute, a welding speed of 18 millimeters per minute, and a tool pin with threads, the maximum value of TS, or 160.57 MPa was achieved. Using an optimal setup of 1200 rotating speed and a welding speed of 18 millimeters per minute with pin profile containing threads, 81 HV the highest hardness was obtained.

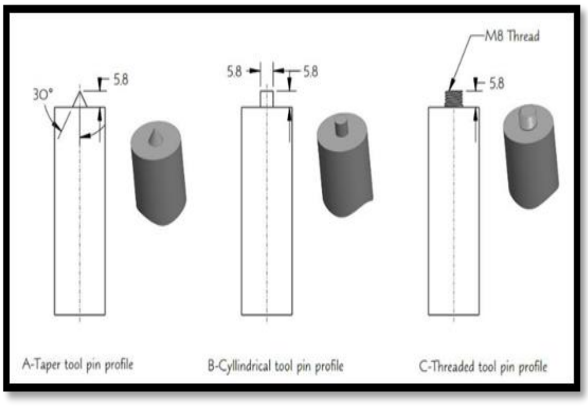

Fig. 21. Tool profiles in the FSW process [50].

Table 1,
presented in detail, illustrates the shapes and their variables, contributing to a better understanding of welding operations.
Summary of the findings for some FSW-selected literatures with different tool geometries.

No.	Authors name	Year	Tool geometry	Work piece material	Weld joint	FSW joint efficiency	Merits	Drawbacks	Remark
1	Galvão et al.,	2013	Conical threaded nut Threaded in a cylindrical-conical shape. Conical thread with steps. An unflappable homage.	Al5186	Butt joint	90%	Tensile strength increased to 90% of the strength of base alloy	Insufficient bonding between the aluminum and the steel	The flat shoulder produces defective welds.
2	Marzbanrad et al.,	2014	Square and cylindrical pin shapes	AA5083	Butt joint	65%	Square pin profile's higher deviation, large stirring zone, and greater weld zone temperature	Failure location of the tensile test specimens was at the retreating side of the SZ.	The peak temperature of the square pin was favorable for the solid diffusion and plasticized mixing.
3	Doos, Qasim M. and Makki,	2014	Square pin, conical pin	AA 5456	T–joint	82.05 %	improves the weld quality	The tunnel defect was raised from the top to the bottom of the weld	Welding parameters with the least heat input resulted in minimum hardness.
4	Mustafa, Kadhum and Yahya	2015	Nine varied tool shapes	AA 6061 T6	T–joint	67%	Improves the weld quality	The excessive heat of the process leads to low mechanical strength	The best parameters when shoulder diameter = 17.1 mm, pin diameter = 2.2 mm, pin angle = 10°, shape of pin = Right
5	Dawood et al.	2015	Tapered threaded cylindrical,triangular , and square	AA6061	Butt joint	54%	Triangular pin shapes produce the best metallurgical and mechanical weld characteristics	A square tool pin shape has the lowest micro-hardness and tensile strength.	Ductile fracture appears in T1, T3
6	Ilangovan, et al.,	2015	Cylindrical pin,Threaded pin and Tapered pin	AA 6061 – AA 5086	Butt joint	65%	Threads and taper-produced connections without defects	The straight cylindrical pin profile tool yielded cross-sectional macro-level defects in the stir zone	Improved tensile strength
7	Al-kubaisy,	2016	Cylindrical, threaded cylindrical, and cone	AA2024-T3 and AA7075-T73	Butt joint	76%	The tensile strength increases with increasing the welding speed	The coarsening reduced the hardness in HAZ	Traverse speed was the most important variable
8	Sabari *et al.*,	2016	Threaded taper cylindrical, taper cylindrical, threaded cylindrical, taper threaded Cylindrical	AA2519-T87	Butt joint	76%	Taper threaded pin gives excellent tensile qualities	The TMAZ showed minimum hardness	Defect-free weld
9	Kumar,	2017	Threaded cylindrical,triangular , conical, square, and hexagonal	AA7075 T651 and AA6061 T6	Butt joint	56%	Square tool pin profile and the hexagonal pin profile produced	The macrostructure of specimen 4 has a defect	Good quality welding

							good, clean welds when used at tool revolving speeds		
10	Sharma et al., 2018	2018	Cylindrical, taper, cylindrical cam, taper cam and square	AA5754	Butt joint	68%	The square pin produce good joining	defect-free joining in square pin profile	Square pin profile showed good welding and hardness
11	Udaiyakumar et al.,	2018	Straight cylinder, straight square and tapered hexagon	AA6061 and AA7075	Butt joint	71%	Straight cylinder tool pin profile an added advantage over other profiles	Some samples of square and taper hexagon tool pin profiles have sharp edge	The straight square is chosen for micro-hardness
12	Goel et al.,	2018	Cylindrical, tapered cylindrical, square , triangular , and hexagonal	AA 6063-T6	Butt joint	59%	The highest tensile strength (162 MPa) using tapered cylindrical was demonstrated	The lowest tensile strength (115.6 MPa) was verified using a triangular shape.	Hooking, kissing and zigzag line defects were observed in the weld zone
13	Amin, Hanna and Mohamed,	2018	Straight cylindrical with 4 flat surfaces that are threaded, straight cylindrical with 3 flat surfaces that are threaded, and straight cylindrical pins with 3 flat surfaces that are threaded	AA6061-T6	Bobbin joints	65.4%	free-defect weld joint	The substrate thickness and the space between the tool shoulders must match	The tool of straight cylindrical with four flats, an 8 mm probe and a 24 mm shoulder diameter giving better tensile strength
14	Martin et al.,	2018	Conical**,** triangle, square, pentagon and hexagonal	AA1050	Butt joint	72.9%	The square pin profile provides good joining and micro-hardness	Cylindrical cam profiles result in defect-free joining	Defect free
15	Shammari,	2019	Cylindrical, cylindrical thread, and triangular	AA2024 T3 AA6061 T6	Butt joint	65%	Tilt angle has the biggest impact of all the parameters	The pin geometry still has the smallest impact.	Optimum welding parameters gave good quality and no defects
16	Su, Xue and Wu,	2020	Conical tool pin	AA2024	Butt joint	74%	The maximum value of tool torque is achieved by using T90	Less than 4.7% is the impact of the pin shape on the tool torque.	Free weld defect
17	Shiva Chander et al.,	2020	Straight cylindrical, threaded cylindrical, taper cylindrical, square, and triangular	AA6351	Butt joint	66%	that square and threaded device pin profiles give highest tensile strength		Improved the weld quality
18	Mustafa and Daham,	2021	Nine pin profiles	6061- T6 with nanocomposites material	T-joint	64%	The most important factor is the depth of the groove	The fact that the use of a 0.5 mm groove's depth is not practical	Nano-powders additives improve mechanical properties and hardness
19	Jayaprakash *et al.*,	2021	Triangle-shaped, tapered cylindrical, and straight cylindrical	AA5083 and AA7068	Butt joint	85%	Cylindrical taper tool produces maximum hardness	The triangular tool provided the minimum hardness	Improved hardness value and ultimate tensile strength

20	Battina et al., 2021	2021	Taper square,straight pentagonal,straight square, straight cylindrical, and straight hexagonal	AA6061-T6 and AA2017-T6	Butt joint	67%	A straight square tool pin profile has higher Micro-hardness and joint efficiency	The joint made with the SC pin profiled tool has a lower UTS	A joint without any flaws was created by the square pin profile's pulsing activity
21	Gopi and Mohan,	2021	Triangle TR, Square SQ, Pentagon PN ,Hexagon HX ,Heptagon HP	AA6082-T6	Butt joint	94%	The tensile strength improved	Reduction in weld strength caused by the formation of coarse grain	105–110 pulses/s is the ideal rate for producing a high-quality and defect-free weld.
22	Ahmed et al.,	2021	Cylindrical, square, and triangular	AA1050-H14	Lap joints	89%	Defect-free welds were created utilizing a bobbin tool with Cy and Sq pin geometries	The hardness values of the stir zone are lower than those of the BM	Defect-free
23	Raj et al.,	2021	Stepped, triangular, and square	AA2024-T365 and AA5083-H111	Butt joint	72%	triangular pin tool has the maximum strength	The stepped pin tool has the minimum strength	Output values increase with a lower feed rate
24	Ahmed et al.,	2022	Taper,Threaded and Cylindrical	AA5451	Butt joint	80.5%	Thread pin shape produced the highest tensile strength	tool rotation speed has the least effect on hardness	Free defect weld

5. Discussion

From the literature survey, it is obvious that samples that are welded with a square pin shape have superior mechanical characteristics (YS, UTS, TE, and microhardness) than samples that are welded with other pin profiles. This improvement is attributed to a finer recrystallized grain structure and fewer defects. Notably, void defects significantly impact tensile characteristics and substantially reduce tensile strength. Consequently, the triangular pin profile demonstrates a lower UTS value of 54%. The enhanced characteristics of the square pin are due to the higher dynamic-to-static volume ratio at its corners, thereby creating more driving force.

The materials' velocity and heat production during the FSW tool's stirring procedure cause the movement of materials in the FSW joining process. Material flow predominantly concentrates in the RS, where all FSW samples have significantly greater stirring procedures. The material motion in the RS was greater than in the AS, which can be explained by this occurrence. Additionally, it is observed that the maximum temperature remains below the tool. This is explained by the material on the workpiece's upper surface proceeding parallel to the tool's shoulder, resulting in a higher shear rate and increased heat generation. These findings align with previous research [48].

Reaching the maximum temperature during the welding process requires more time when utilizing the triangle pin tool. As a result, insufficient dynamic recrystallization caused by heat loss in the stirred zone results in joints with reduced strength and weak joint efficiency. In contrast, the pulsating action of sharp flats and related frictional heating causes the square pin profile to produce higher-temperature and plasticized material. The creation of heat decreases with increasing tool mechanical action. The symmetrical internal heat distribution at a higher pin angle augments mechanical action, decreasing the viscosity of the material and enhancing the stirring behavior, or material flow around the pin. A larger stir zone forms in the joint area as a result of the enhanced stirring procedure caused by the increased plastic flow near the tool.

6. Limitations and Challenges of the FSW Method

Despite the big efforts that have been made by the research centers and investigators to develop and improve FSW performance, it still faces some challenges and involves some limitations that need to overcome, and requires effective solutions to enhance the productivity and performance of the process. Some demerits and challenges are listed below.

1. Cost. The initial cost of FSW equipment and tooling is high, which may deter smaller manufacturers from adopting the technology.
2 Skilled Labor. FSW requires skilled operators to set up and operate the equipment, and a shortage of skilled personnel can be a limitation.
3 Material Limitations. FSW is most effective on certain materials, like aluminum and some alloys. It may not be suitable for all materials, limiting its applications.
4. Size Constraints. FSW machines are often limited in terms of the size of the components they can weld, which can be a limitation in larger manufacturing processes [51].
5. Exit hole. It is generally desired to eliminate the exit hole at the end of conventional friction stir welds, and to remove the exit hole one should cut it from the end of welding [52].

7. Conclusion

Recent research indicates that FSW pin profiles significantly influence material flow and mechanical properties. The friction stir welding method has effectively joined both similar and dissimilar aluminum plates especially in the circumferential welds. It has been observed that the mechanical properties and joint strength are substantially affected by the configurations of various pin profiles. Notably, the square tool pin profile demonstrates superior mechanical properties in FSW joints compared to other profiles such as conical, pedal, cylindrical with threads, triangular, and pentagonal tools. Through an examination of square, cylindrical, triangular, tapered, threaded, and hexagonal tool pins for welding aluminum plates, the square pin shape proves to be the most efficient, exhibiting a 94% tool performance. Conversely, the triangular pin profile displays a lower UTS value of 54%, likely due to the presence of a significant defect.

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الدراسات السابقة لهندسة دبوس الأداة في لحام الاحتكاك الحركي

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المستخلص

لحام مزج الاحتكاك (FSW) هو طريقة للحام في الحالة الصلبة اذ يتم تكوين اللحام تحت درجة انصهار المعدن القاعدي. المواد ذات نقطة انصهار عالية وكذلك المواد اللينة تلقت مؤخراً اهتماماً في انشطة بحث (FSW) ، تم إجراء العديد من الدراسات على المعادن القابلة للانصهار بشكل عالي مثل الفولاذ والتيتانيوم وغيرها. جودة اللحام تتأثر بعوامل متعددة مختلفة ومن اجل الحصول على افضل جودة للحام، اجرت العديد من الدراسات تحقيقات حول سرعات الانتقال والدوران كمعلمات عملية رئيسية، عامل اخر حاسم يؤثر في جودة اللحام هو هندسة الأداة. هدف هذا البحث هو تقييم تطور ملامح مختلفة للدبوس وكيف تؤثر في البنية المجهرية والخصائص الميكانيكية للحام. أظهرت الملامح المربعة للدبوس انها تنتج وصلات قوية، وفقاً للأبحاث التي تم نشرها. بحسب ابحاث اخرى، تشير إلى ان الاسطوانات الملولبة او التفاوت الملولب يقدمان اتصالات متفوقة. الاستنتاج الذي يتفق عليه جميع الابحاث هو ان الهياكل الملولبة هي الاكثر فعالية على اداء الاداة.