Tool Designing for Friction Stir Welding Variants

Namrata Thakkar and Vishvesh Badheka

Abstract The shoulder and probe are the major components of the rotating tool of Friction Stir Welding (FSW) technology. When it comes to producing a high-quality weld connection, tool design is crucial. The key design elements that substantially impact weldment quality and microstructure are pin length, pin diameter, shoulder diameter, shoulder profile, pin profile and surface features. A friction stir welding tool can be a fixed (conventional tool, conventional bobbin tool, conventional friction stir spot welding tool, pinless tool) or adjustable (floating bobbin tool, adjustable gap/double reacting bobbin tool, refill friction stir spot welding tool) type. Pin profiles such as square, hexagonal, cylindrical, threaded, and tapered affect the grain size and structure, hardness, heat generation and appearance of the weldment. Concave, convex, and flat shoulder profiles affect particle distribution and microstructure. The weld joint quality is determined by the combined effect of the pin and shoulder profile. This paper reviews the effect of various pins and shoulder profiles on friction stir welded joints. Empirical relationship between pin diameter, shoulder diameter and sample thickness as well as most commonly used dimensions for tools have been presented in the paper.

Keywords Friction stir welding (FSW) · Tool design · Bobbin tool · Variants of FSW

1 Introduction

Friction Stir Welding (FSW) has gained popularity as it is an environment-friendly process. FSW is a solid-state welding process performed with the help of a rotating tool. The rotating tool generates frictional heat, that plasticizes the material below its melting point, forming a weldment. It has proven to be a technique capable of welding both thick and thin sheets. The main components of a conventional FSW tool are a shoulder and a pin, whereas a bobbin tool has an additional lower shoulder that

N. Thakkar (✉) · V. Badheka
Pandit Deendayal Energy University, Gandhinagar, Gujarat, India
e-mail: namrata.tmc18@sot.pdpu.ac.in

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eliminates the requirement of a backing plate. Friction Stir Spot Welding (FSSW) can be performed using a conventional tool, a pinless tool or a refill tool. The pinless variant of FSW tool consists of only a shoulder whereas the refill tool consists of a pin and a sleeve. Apart from welding parameters like rotational speed of the tool and plunge depth, tool designing plays an important role in producing a joint with higher mechanical properties. Critical design parameters include Pin Length (PL), Pin Diameter (PD), Shoulder Diameter (SD), pin and shoulder profiles and surface features. The designing of conventional tool, bobbin tool and friction stir spot welding tool has been discussed in this paper.

2 Conventional Friction Stir Welding Tool

A conventional tool is a rotating tool consisting of a pin and a shoulder. The role of the pin is to generate frictional heat and mix the softened molten material, whereas the shoulder is responsible for generating frictional heat on the surface of the workpiece and downward forging action that is required to constrain the heated softened material beneath it [1]. Conventional tool has specially designed pin and shoulder to achieve optimum characteristics for a weld. Pin profile, shoulder profile and dimensions of the tool affect the weld quality (Fig. 1).

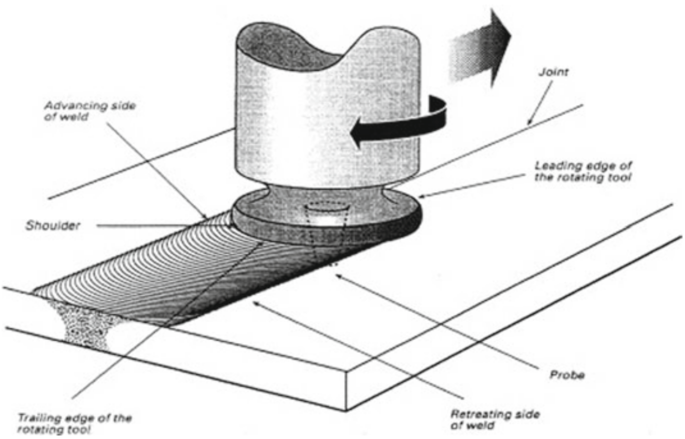

Fig. 1 Conventional friction stir welding process [2]

2.1 Conventional Tool Pin Profiles

The stirring pin profile affects the heat generation, micro-hardness, size of the deformation region, amount of plasticized material that is moved from advancing side to retreating side and the travel speed of the tool. Profiles like cylindrical, cylindrical taper, cylindrical threaded, triangular, square, pentagonal and hexagonal has been experimentally tested to obtain optimum weld quality. Threaded pins generate more heat and are efficient in moving heated material from advancing side to retreating side. Thread feature enhances the plastic material movement and accelerates the flow of plastic material by exerting a downward force [3]. Padmanaban et al. [4] concluded that the joints welded by threaded cylindrical pin are free from defects and exhibit higher tensile strength compared to other pin profiles. Pitch value of the threads determine whether the pin will act as a driller or a stirrer. The pin will act as a driller if the pitch of the threads is very high [2].

Deformation patterns and size of the deformation region depends on the pin profile. Pin profiles like square and hexagon reduce the size of the deformation region [5]. Features like flats on the pin are provided to increase the amount of material carried from advancing side to retreating side. Flat feature also helps in achieving higher temperatures in the weld zone. Pulsating action which is only achieved through providing flat features on the pin, refines the grain structure. Finer grains are obtained with square and hexagonal pin profiles [5–7]. Triangular pin profile has the least area of contact with the molten material which in turn generates least friction compared to square and hexagonal pins. Triangular profile pins sweep least amount of plasticized material due to its lowest static to dynamic volume ratio. Dynamic volume (swept volume) to static volume (pin volume), known as swept ratio quantifies the amount of material plasticized during the process [5, 7]. Less heat generation and amount of material plasticized by a triangular pin may result in lower strength and defects in a weldment. Taper feature provided to the pins help in achieving higher mechanical properties like hardness, elongation and ultimate tensile strength, defect-free joints and finer grain structure [2, 8] (Figs. 2 and 3).

TWI has recently developed the WhorlTM and MX TrifluteTM tools. Frustum shaped probes in both the tools displace less material compared to cylindrical tool having the same root diameter. WhorlTM and MX TrifluteTM reduce the displaced volume by about 60% and about 70% respectively. Cylindrical probes require more effort to traverse through the plasticized material than a frustum shaped probe for

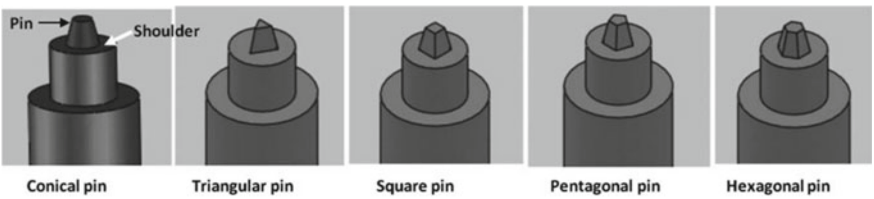

Fig. 2 Pin profiles [5]

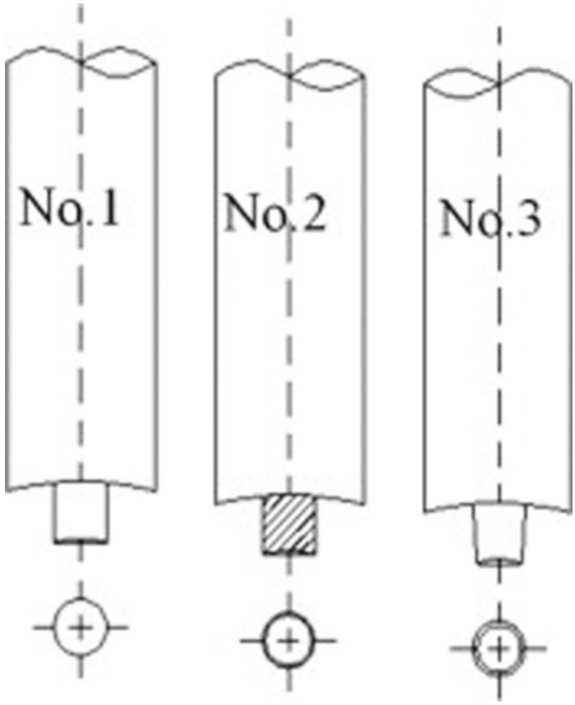

Fig. 3 Simple cylindrical, screw threaded cylindrical, taper cylindrical [8]

a certain minimum probe tip diameter [9]. Re-entrant feature of the WhorlTM tool, helical ridge is responsible for providing a downward augering force, ensuring that the next ridge faces less interference and to enable a more effective material flow. The ridge having a non-uniform pitch, are placed at a distance greater than the thickness of the ridge itself [9]. These specially designed probes having re-entrant features have an increased surface area compared to featureless probes.

Re-entrant features on a triflute probe can be designed according to the material and joint geometry. They can be designed with any combination of left, neutral or right-handed flutes/ridges grooves. The inclined ridges move the fragmented oxides in an upward or a lower direction by deflecting the plasticized material. In order to reduce the volume of triflute tools, an additional helical feature is provided [9, 10]. These novel designs of the tools have very high swept rates compared to conventional cylindrical probes. The dynamic to static volume ratio for MX Triflute™ probe is 2.6:1, 1.8:1 for Whorl™ probe and 1:1 for a cylindrical probe [9] (Fig. 4).

2.2 Conventional Tool Shoulder Profiles

Flat, concave and convex type shoulder profiles are the most commonly used profiles. A flat shoulder, being the simplest design, does not trap plasticized material during

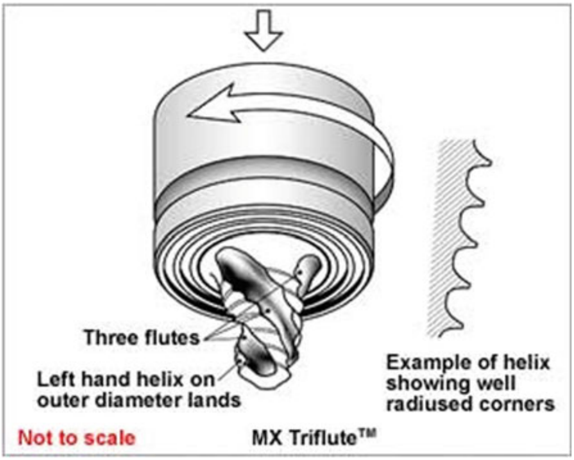

Fig. 4 Trade-marked MX triflute tool [9]

the process, whereas a concave shoulder is highly used due to its material entrapment characteristic. A concave type shoulder has an inclination of about 6°–10° compared to a flat shoulder, which entraps the material and directs its flow towards the pin. Convex shaped shoulder has gained popularity due to its ability to maintain a constant contact with the base metal. Though it is considered that the influence of outer shape of shoulder on the weld quality is minimal, the outer surface of the shoulder can have a conical or cylindrical geometry [1, 11]. Galvão et al. [12] conducted experiments using a conical shaped shoulder and concluded that conical shape of the cavity will act as a reservoir for plasticized material and will direct the material flow towards pin (Fig. 5).

Re-entrant features like grooves, concentric circles, scrolls and ridges are often provided at the end surface of the shoulder to entrap the plasticized material and direct the flow towards the pin. These features prevent the molten material flow towards the periphery of the shoulder. The scroll feature is a spiral shaped channel that move the material from the periphery to the centre of the shoulder [1, 9]. A combination of convex shoulder and scroll feature can provide sound welds due to constant contact and entrapment of material throughout the process [1]. Although, a scroll feature is not suitable for the welding of thin sheets as the feature periodically deposits the material at the rear end of the tool and, increases the thickness of the material [12]. A. Scialpi et al. [13], experimentally proved that a combination of fillet and cavity can be used to improve the weld quality. It was also observed that though shoulder geometry has reduced effect on the micro-hardness and nugget grain structure, features like fillet, cavity and scroll improved the quality of weldment.

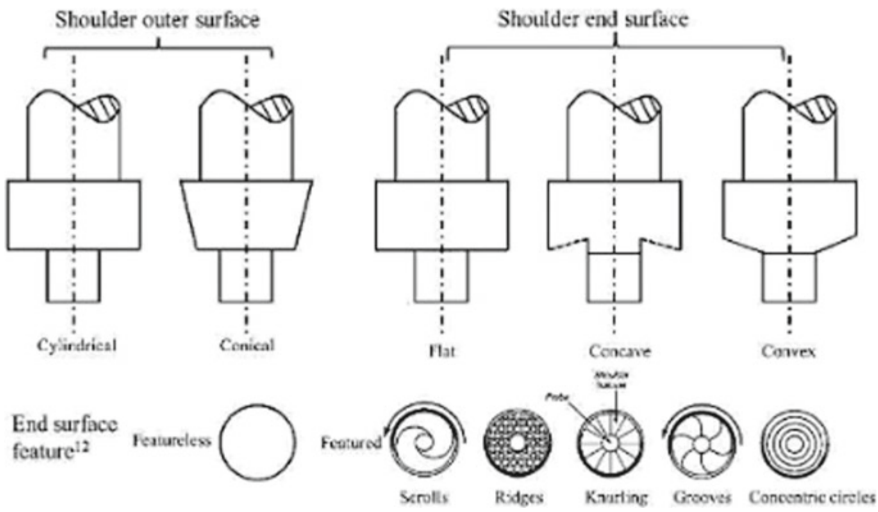

Fig. 5 Primary and secondary shoulder profiles [11]

2.3 Conventional Tool Dimensions

For designing a conventional FSW tool, shoulder and probe diameter are critical design parameters. Zhang et al. [1], deduced empirical relationships for Shoulder Diameter (SD) and Sample Thickness, Probe Diameter (PD) and Sample Thickness and Shoulder Diameter (SD) and Probe Diameter (PD) from the available literature (Fig. 6).

$$SD(mm) = 2.2 * \text{Sample thickness}(mm) + 7.3\,mm \tag{1}$$

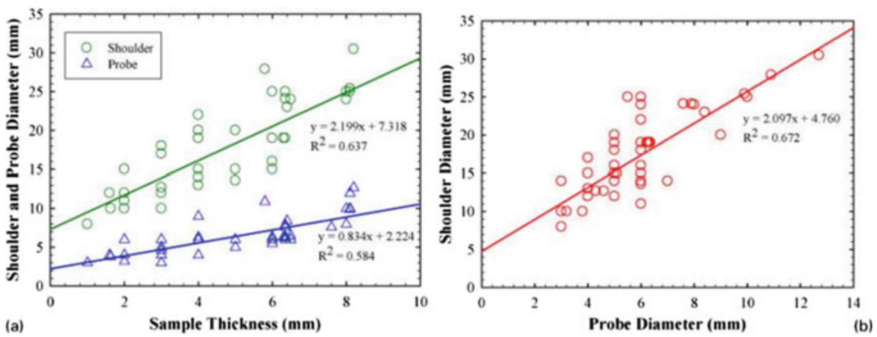

Fig. 6 **a** Shoulder and probe diameter versus sample thickness and **b** shoulder diameter versus probe diameter [1]

$$\text{PD(mm)} = 0.8 * \text{Sample thickness(mm)} + 2.2\,\text{mm} \tag{2}$$

$$\text{SD(mm)} = 2.1 * \text{PD(mm)} + 4.8\,\text{mm} \tag{3}$$

3 Bobbin Tool Friction Stir Welding

Self-reacting friction stir welding, also known as bobbin tool friction stir welding has a specially designed tool having two shoulders and a pin. During the process, both shoulders generate frictional heat. The reactive forces generated during the process, are cancelled out by the two shoulders resulting in a very low axial force [14, 15]. During a bobbin tool friction stir welding process, no backing plate is required, as the lower shoulder supports the base metal. Fixed gap bobbin tool, floating bobbin tool, adaptive or double driven bobbin tool and pinless bobbin tool are major variants of this technique. The gap between the shoulders remains constant throughout the process for a fixed gap bobbin tool. The movement of fixed gap tool about z-axis is restrained [14]. A floating bobbin tool, is designed as a fixed gap bobbin tool and is allowed to float in the axial direction. The novel design of floating bobbin tool adjusts its position according to the base metal in such a way that the axial force reduces drastically [16] (Fig. 7).

An adaptive tool or a double driven bobbin tool, is driven from both the ends, providing an enhanced flow path. Double driven tool is capable of altering the distance between both the shoulders during the process, and is allowed to oscillate in the axial (z-axis) direction. In a double driven tool, the aspect ratio of the probe can be altered [14, 17].

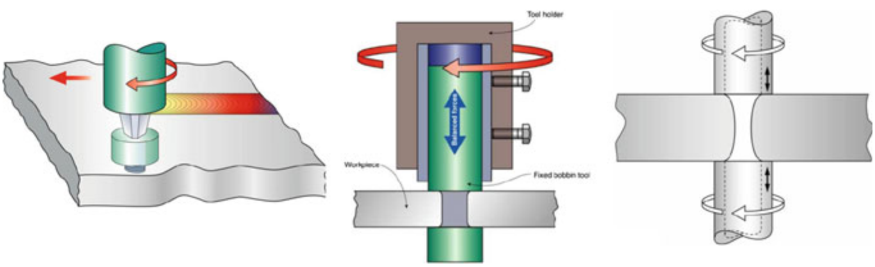

Fig. 7 Fixed gap bobbin tool, floating bobbin tool, adaptive bobbin tool [16, 17]

3.1 Bobbin Tool Pin Profiles

Bobbin Tool Friction Stir Welding (BT-FSW) process has been employed with various pin profiles like cylindrical taper, trigonal, hexagonal, outward conical and inward conical. Out of all these pin profiles, cylindrical tapered pin with flats is a commonly used profile [18]. Mohammad Hosein Mirzaei et al. [19] conducted double shoulder friction stir welding using trigonal, square, hexagonal, inward conical and outward conical pins and concluded that the heat generated by un-edged pins is more than edged pin profiles. Trigonal and outward conical pins result into joints having lower mechanical properties whereas hexagonal and square pin profiles yielded joints having superior mechanical properties like ultimate tensile strength (UTS) and elongation. As the number of edges increase from square to hexagonal profile, the material boxes moved by the pins decrease in size but increase in number. Such a material movement enhances the material coalescence, improving the joint properties [19]. Pin profiles like outward conical and trigonal should be avoided as a trigonal profile results into undesired flow of material and an outward conical profile pin reduces the mechanical properties by excessive heating [19] (Fig. 8).

Re-entrant features like flats, threads, grooves and flutes can be added to the tool pin to enhance the horizontal and vertical movement of plasticized material. Thread feature is responsible for the vertical movement of the molten material and flat feature enhances the horizontal movement [14]. While designing the tool pin, grooves shall be carefully added as they trap the material between them and resist the vertical flow. Excessive heat is generated for the materials trapped between grooves as a groove feature has a tendency to only generate heat and not axial flow [19]. A pin having three to four flat features and having threads will generate a sound weld having high mechanical properties due to combined horizontal and vertical material flow [14, 19, 20]. Wu et al. [21], designed and experimented a novel adjustable-gap bobbin tool on Al-Cu aluminium alloy. The adjustable-gap tool pin, having half-right and half-left feature enhanced material mixing in the vertical direction of the weldment. Specially designed half-right hand and half-left hand thread filled the voids by converging material flow towards the centre (Fig. 9).

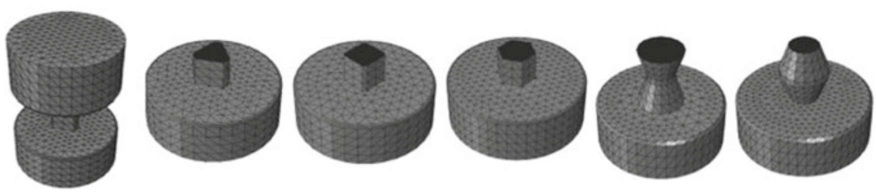

Fig. 8 Various pin profiles of a bobbin tool [19]

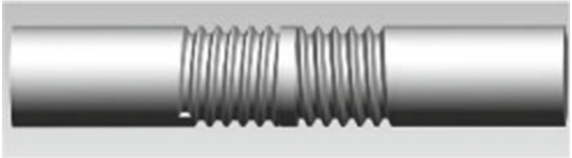

Fig. 9 Novel adjustable-gap bobbin tool pin having right and left-handed threads [21]

3.2 Bobbin Tool Shoulder Profiles

Similar to a conventional friction stir welding tool, the primary features of bobbin tool shoulder include flat, concave and convex [18]. A flat shoulder, in spite of being the simplest design, does not trap plasticized material and produces flash. Concave profile of a shoulder entraps the molten material and feeds it to the pin by acting as a reservoir. A convex shoulder acts in a unique way by remaining in a constant contact with base metal plate of varying thickness [1, 15, 18]. The outer shape of the shoulder can be cylindrical or tapered. Tapered shoulders have successfully welded flash-less joints [16]. Scroll feature is the most used secondary feature on the shoulder as it promotes the flow of plasticized material in a horizontal direction towards pin. Okamoto et al. [20] deduced that scroll feature will enhance the vertical flow and dispersion of oxide film when provided on convex shoulder instead of a flat shoulder (Fig. 10).

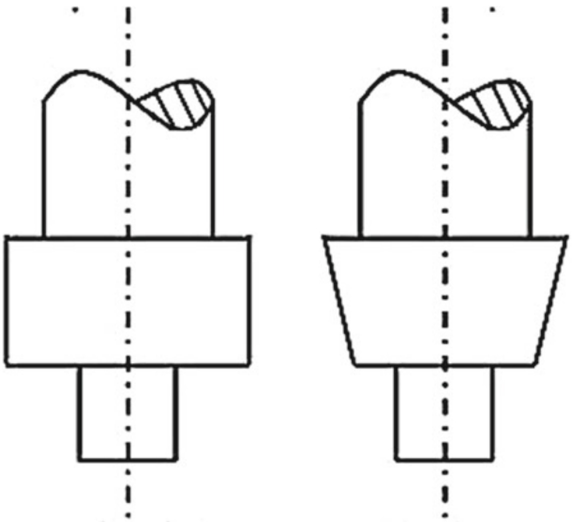

Fig. 10 Cylindrical and tapered shape of shoulders [11]

3.3 Bobbin Tool Dimension and Size

Pin Diameter (PD), Pin Length (PL), Upper Shoulder Diameter (USD), Lower Shoulder Diameter (LSD) and gap between upper and lower shoulder are critical parameters while tool designing. The upper and lower shoulder are generally taken to be of equal diameters [15, 20, 22–33], but it is recommended that the lower shoulder should have a smaller diameter than upper shoulder. Lesser diameter of lower shoulder results into less bending moment and torque on the pin, as well as less generation of frictional heat on the lower surface due to less contact with the plate [34–36]. The lower shoulder will provide insufficient support to the plate from the vibration if a very small value of diameter is chosen. Also, a reduced area of contact may result into premature solidification of weld zone.

Shoulder gap being an important design parameter, enhances material stirring and vertical flow. An optimum compression effect and frictional heat is produced if the shoulder gap is determined [18]. The pinching gap of the shoulders generate dragging force for the material to flow around. An optimal combination of pinching gap at the centre and periphery are required to produce sound welds [20]. In the literature available, no definite method has been suggested for the selection of shoulder and pinching gap and have been designed using a trial and error. Pin length usually kept the same as base metal thickness, can also be taken as 0.9 times the thickness of the base metal [14]. Figure provided below summarizes experiments conducted with bobbin tool and empirical relations have been obtained using least square approximation method [15, 20, 22–33, 37–40] (Fig. 11).

$$\mathrm{USD(mm)} = 1.87 * \mathrm{PT(mm)} + 9\,\mathrm{mm} \tag{4}$$

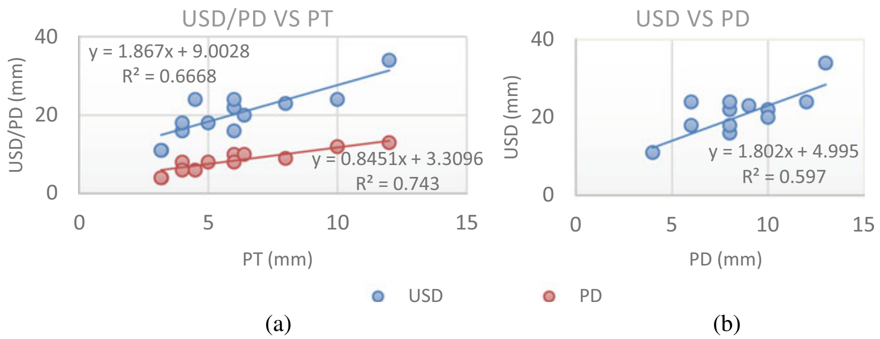

Fig. 11 **a** Upper shoulder diameter/pin diameter versus plate thickness, **b** upper shoulder diameter versu pin diameter

$$PD(mm) = 0.85 * PT(mm) + 3.31\,mm \quad (5)$$

$$USD(mm) = 1.8 * PD(mm) + 5\,mm \quad (6)$$

4 Friction Stir Spot Welding (FSSW)

A friction stir spot welding involves the rotation, plunging and retraction of the tool. The rotational speed of the tool and its plunge depth are predetermined. A conventional FSSW tool has a shoulder-pin setup, where the length of the pin is fixed. A conventional tool has a tendency to move the material in a downward direction, away from the tool shoulder. As the tool pin has a fixed length, a plate having a constant thickness can be welded. The tool is responsible for heating the base metal, inducing material flow, confine the plasticized material and prevent it from overflowing [41]. The drawback of a conventional FSSW tool is that, it can cause thinning of the top sheet due to excessive tool penetration [42]. Due to the presence of pin, a keyhole defect at the end of welding process is observed (Fig. 12).

A pinless tool, as the name suggests, is a tool only having a shoulder. The pinless tool performs welding process by rotation, plunging and retraction from the base material. This tool eliminates the occurrence of keyhole defect at the end of the welding process [43]. Features like scroll and flutes can be provided to enhance the quality of the weld (Fig. 13).

A refill FSSW tool comprises of a sleeve, pin and a clamp. The clamp is responsible for holding the sheets together whereas the sleeve and pin are responsible for spot welding the sheets. Pin plunge and sleeve plunge are the two variants of this process. For a sleeve plunge method, once the clamp has held the sheets together tightly, the sleeve plunges into the sheets till a predetermined depth and simultaneously the pin moves upwards. Once the predetermined depth has been achieved, the sleeve retracts to its original position and the pin moves towards the sheets. In this process, the hole

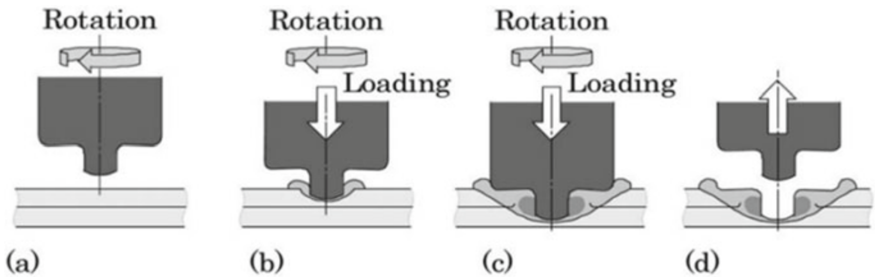

Fig. 12 **a** Rotation of tool, **b** plunging of tool, **c** dwell period, **d** drawing out of tool [41]

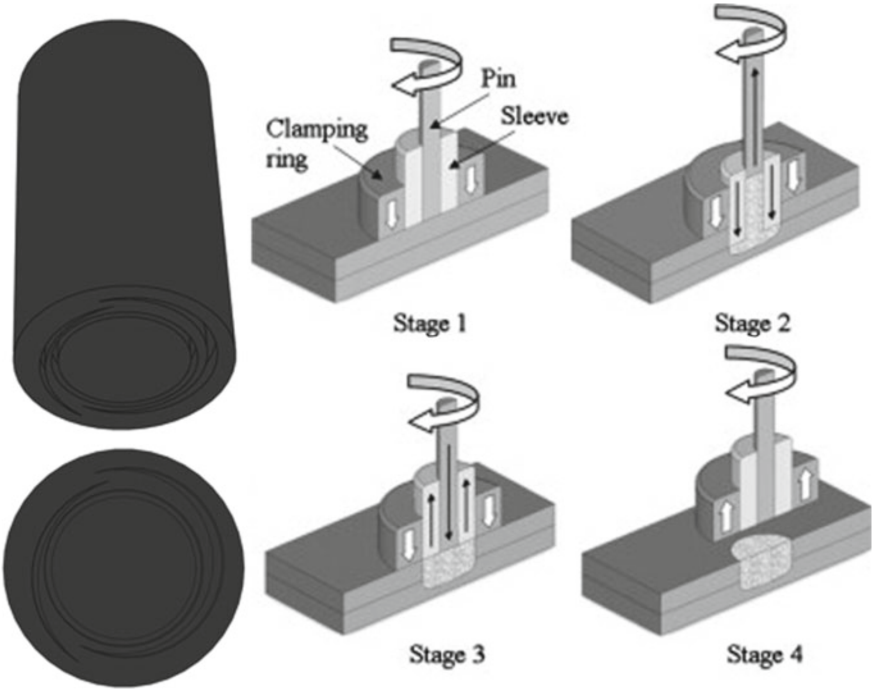

Fig. 13 Pinless FSSW tool with scroll feature, sleeve plunge variant of FSSW [41]

is completely filled with the molten material, eliminating the keyhole defect. For a pin plunge method, the pin is responsible for the penetration in the sheets, whereas the sleeve retracts. A sleeve plunged joint has a larger welded area compared to a pin plunged joint [44].

4.1 Pin Profiles

Pin profiles like triangular, square, hexagonal, spherical, inverse-tapered and other off-centre have been employed for friction stir spot welding process [45–49]. A high forging force is exerted by a cylindrical pin, but is a commonly used pin profile in a conventional FSSW process [48, 49]. It has been experimentally proven that a tapered pin forms a smaller hook compared to a conventional cylindrical pin [49]. A triangular pin generated more heat compared to a cylindrical pin due to the presence of flat features. Joints having higher mechanical strength and larger bonding area formed using triangular pins. Inspite of a triangular pin having above mentioned advantages, it is recommended that, it should not be used to weld steels, as the sharp flat features will worn away after being used for some time [41, 48, 49, 50]. For an

Fig. 14 FSSW tool pin profiles—cylindrical, tapered, inverse tapered, triangular [41]

inverse tapered pin, a hook feature will be extended up to the top surface, resulting a joint has low mechanical properties [45] (Fig. 14).

Secondary features such as threads, flutes and flats increase the area of contact and increase the heat generation. Such features have given improved results for lightweight materials, but for materials like steel, these features get worn out after a few spot welds. Hence, it is recommended that complex secondary features shall not be provided for materials like steel [41, 51]. Although, features like stepped-spiral and coarse thread can be provided on polycrystalline cubic boron nitride (PBCN) tools [52, 53]. A cylindrical pin is the most used pin profile for refill FSW as it is designed to move in axial direction [41].

4.2 Shoulder Profiles

The primary shoulder profiles in a conventional FSSW are the same as conventional FSW and Bobbin Tool FSW. The primary profiles include flat, concave and convex [48, 54]. A concave shoulder, the most commonly used profile produces a weld sound by the formation of a sharp hook. Concave shoulder, which acts as a reservoir for the plasticized material results into a weld joint having higher mechanical properties compared to a flat or convex shaped shoulders [45, 48, 54]. The joint properties exhibited by a convex shoulder is inferior to those exhibited by a flat shoulder, making the flat shoulder an intermediary choice. A convex shoulder welds a joint having lowest mechanical properties due to thinning of the top sheet and insufficient mixing of molten material [48, 49]. Like conventional FSW tool and bobbin tool, secondary features like scroll and concentric circles can be provided at the end surface of concave and convex shoulders (Fig. 15).

Re-entrant features like long and short wiper flutes, scroll flutes and proud wiper are the most important features for a pinless tool to produce a joint of good quality. Welds exhibit higher mechanical properties with use of re-entrant features, due to an enhanced flow of molten material and deeper penetration of the plastic zone [55]. Uematsu et al. [56] experimentally obtained joints having higher tensile-shear strength using a scroll grooved tool compared to a conventional tool having concave shoulder and a probe (Fig. 16).

Fig. 15 Concave, flat and convex shoulder profiles [41]

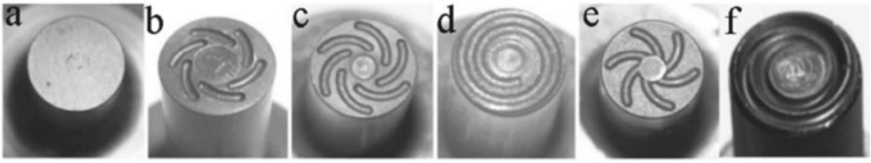

Fig. 16 Re-entrant features for pinless tool [41]

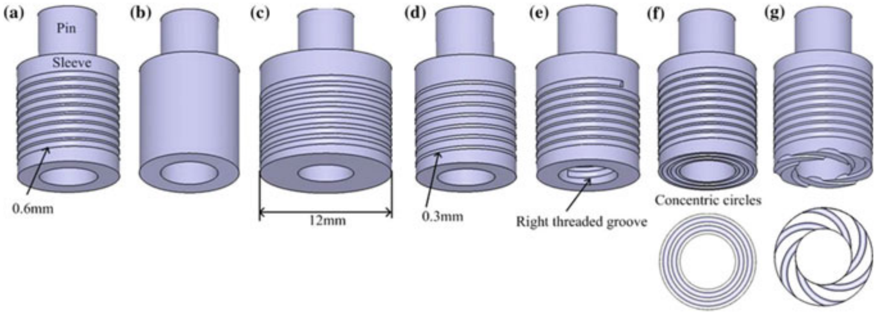

Fig. 17 Secondary features of a refill FSSW sleeve [58]

Shude Ji et al. [57] studied sleeve features like grooves on the wall and concentric circles and grooves at the bottom surface of the sleeve. It was observed that, groove width is negatively proportional to flow velocity. Provision of threaded grooves on sleeve walls alters the behavior of material flow. Experiments proved that scrolled grooves on the bottom surface of sleeve are more efficient than concentric circles (Fig. 17).

4.3 Tool Dimensions

Shoulder Diameter (SD), Pin Diameter (PD), Pin Length (PL) and angle of concave shoulder are critical design parameters that need to be determined in a correct way to obtain a sound weld. Heat generation depends on the pin and shoulder diameter.

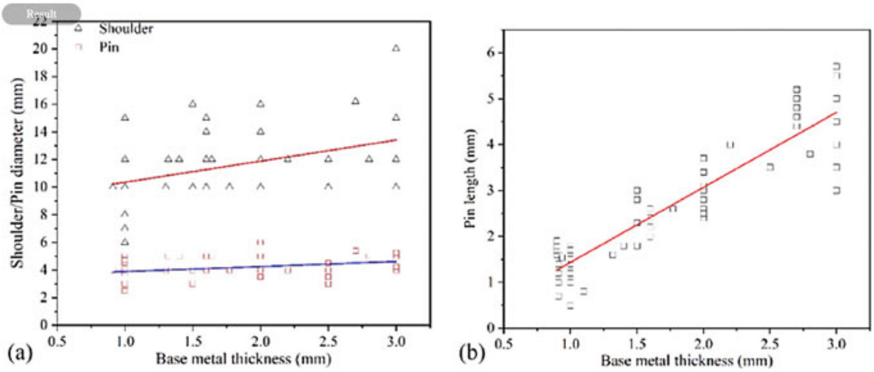

Fig. 18 **a** Shoulder and pin diameter versus base metal thickness **b** pin length versus base metal thickness [41]

Larger diameters result into more frictional heat [1, 58]. Pins having larger diameters have proven to bond larger area, but produces excessive flash [45, 59]. Design of concave shoulder for a conventional FSSW tool must not have an extreme angle. Extreme angles for a concave shoulder result into insufficient axial force, decreasing the weld quality (mechanical strength) of the joint [58]. Zhikang Shen et al. [41] graphically represented the linear increase of pin length with the plate thickness. It was also observed that the shoulder diameter linearly increased with the plate thickness. For a conventional FSSW tool, a pin diameter of 4 mm can be employed, irrespective of the plate thickness [5]. The pin length for thin workpiece has less importance and the tool can be considered to be pinless [42]. From the available literature for pinless tool, it can be observed that a shoulder diameter of 10 mm is the most used diameter [42, 43, 56, 60, 61] (Fig. 18).

External and internal sleeve diameter, pin diameter and groove width on sleeve are important dimensions for designing a refill friction stir welding tool. The outer diameter and groove width influence the material flow velocity whereas threaded grooves on the inner wall affect the bonding ligament thickness [57]. From the literature available, it can be deduced that, a diameter of 9 mm for sleeve and 5–6.4 mm for a pin diameter is commonly employed in a refill friction stir spot welding process [41].

5 Conclusion

In this paper, pin profiles, shoulder profiles and tool dimensions for conventional tool, bobbin tool and friction stir spot welding tools were reviewed.

For a conventional tool, pin profiles like cylindrical, cylindrical tapered, triangular, square, pentagonal and hexagonal have been used for friction stir welding. Similarly, pin profiles like cylindrical, trigonal, hexagonal, inward and outward conical have been used for bobbin tool friction stir welding. In a refill friction stir spot welding tool, cylindrical and triangular pin profiles result into joints having superior mechanical properties. Secondary features like flats, flutes, threads and grooves can be provided to increase the contact area between plate and pin, increase heat generation and to acquire joints with superior qualities. Although, for friction stir spot welding of steels it is recommended that complex secondary features shall not be provided as it decreases the tool life.

Flat, concave and convex profiles are common to conventional, bobbin and friction stir spot welding tools. Re-entrant features like scroll, concentric circles and grooves can be provided on the bottom surface of shoulder to improve the weld quality.

Empirical relationship between Pin Diameter (PD), Shoulder Diameter (SD) and sample thickness have been mentioned for a conventional tool. Similarly, empirical relationship between Upper Shoulder Diameter (USD), Pin Diameter (PD) and Plate thickness (PT) have been established using least square approximation method. From the available literature, it has been concluded that a pin with 4 mm diameter can be used for conventional spot welding process irrespective of the plate thickness. For refill spot welding tool, a sleeve diameter of 9 mm and a pin diameter of 5–6.4 mm can be used. For a pinless spot welding tool, a shoulder diameter of 10 mm can be used to obtain defect-free joints.

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References

1. Zhang YN, Cao X, Larose S, Wanjara P (2012) Review of tools for friction stir welding and processing. Can Metall Q 51(3):250–261. https://doi.org/10.1179/1879139512y.0000000015
2. Boz M, Kurt A (2004) The influence of stirrer geometry on bonding and mechanical properties in friction stir welding process. Mater Des 25(4):343–347. https://doi.org/10.1016/j.matdes.2003.11.005
3. Zhao YH, Lin SB, Wu L, Qu FX (2005) The influence of pin geometry on bonding and mechanical properties in friction stir weld 2014 Al alloy. Mater Lett 59(23):2948–2952. https://doi.org/10.1016/j.matlet.2005.04.048
4. Padmanaban G, Balasubramanian V (2009) Selection of FSW tool pin profile, shoulder diameter and material for joining AZ31B magnesium alloy – An experimental approach. Mater Des 30(7):2647–2656. https://doi.org/10.1016/j.matdes.2008.10.021
5. Ramanjaneyulu K, Madhusudhan Reddy G, Venugopal Rao A, Markandeya R (2013) Structure-property correlation of AA2014 friction stir welds: role of tool pin profile. J Mater Eng Perform 22(8):2224–2240. https://doi.org/10.1007/s11665-013-0512-4
6. Sharma N, Siddiquee AN, Khan ZA, Mohammed MT (2017) Material stirring during FSW of Al–Cu: Effect of pin profile. Mater Manuf Process 33(7):786–794. https://doi.org/10.1080/10426914.2017.1388526
7. Kumar A, Raju LS (2012) Influence of tool pin profiles on friction stir welding of copper. Mater Manuf Process 27(12):1414–1418. https://doi.org/10.1080/10426914.2012.689455

8. Motalleb-nejad P, Saeid T, Heidarzadeh A, Darzi K, Ashjari M (2014) Effect of tool pin profile on microstructure and mechanical properties of friction stir welded AZ31B magnesium alloy. Mater Des 59:221–226. https://doi.org/10.1016/j.matdes.2014.02.068
9. Friction stir welding—tool developments (February 2001) (2001b) TWI. https://www.twi-global.com/technical-knowledge/published-papers/friction-stir-welding-tool-developments-february-2001
10. Thomas W, Johnson K, Wiesner C (2003) Friction stir welding—recent developments in tool and process technologies. Adv Eng Mater 5(7):485–490. https://doi.org/10.1002/adem.200300355
11. Mishra A, Tiwari A, Shukla M, Rose R (2018) Analysis of tools used in friction stir welding process. Int J Curr Eng Technol 8. https://doi.org/10.14741/ijcet/v.8.6.2
12. Galvão I, Leal RM, Loureiro A, Rodrigues DM (2010) Material flow in heterogeneous friction stir welding of aluminium and copper thin sheets. Sci Technol Weld Joining 15(8):654–660. https://doi.org/10.1179/136217110x12785889550109
13. Scialpi A, de Filippis L, Cavaliere P (2007) Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy. Mater Des 28(4):1124–1129. https://doi.org/10.1016/j.matdes.2006.01.031
14. Fuse K, Badheka V (2018) Bobbin tool friction stir welding: a review. Sci Technol Weld Joining 24(4):277–304. https://doi.org/10.1080/13621718.2018.1553655
15. Longhurst WR, Cox CD, Gibson BT, Cook GE, Strauss AM, Wilbur IC, Osborne BE (2016) Development of friction stir welding technologies for in-space manufacturing. Int J Adv Manuf Technol 90(1–4):81–91. https://doi.org/10.1007/s00170-016-9362-1
16. Martin J, Wei S (2015) Friction Stir Welding Technology for Marine Applications. Friction Stir Welding and Processing VIII, 217–226. https://doi.org/10.1002/9781119093343.ch24
17. Thomas WM, Norris IM, Staines DG, Clarke PJ, Horrex NL (2007) Friction stir welding–variants and process techniques. In The first international conference 'joining of aluminium structures', Moscow, Russian
18. Sued M, Pons D, Lavroff J, Wong E (2014) Design features for bobbin friction stir welding tools: Development of a conceptual model linking the underlying physics to the production process. Mater Des 1980–2015(54):632–643. https://doi.org/10.1016/j.matdes.2013.08.057
19. Mirzaei M, Asadi P, Fazli A (2020) Effect of tool pin profile on material flow in double shoulder friction stir welding of az91 magnesium alloy. Int J Mech Sci 183:105775. https://doi.org/10.1016/j.ijmecsci.2020.105775
20. Okamoto K, Sato A, Park SHC, Hirano S (2012) Microstructure and mechanical properties of FSWed aluminum extrusion with bobbin tools. Mater Sci Forum 706–709:990–995. https://doi.org/10.4028/www.scientific.net/msf.706-709.990
21. Wu D, Li W, Gao Y, Yang J, Su Y, Wen Q, Vairis A (2020) Effect of an improved pin design on weld formability and mechanical properties of adjustable-gap bobbin-tool friction stir welded Al-Cu aluminum alloy joints. J Manuf Process 58:1182–1188. https://doi.org/10.1016/j.jmapro.2020.09.015
22. Wang F, Li W, Shen J, Hu S, dos Santos J (2015) Effect of tool rotational speed on the microstructure and mechanical properties of bobbin tool friction stir welding of Al–Li alloy. Mater Des 86:933–940. https://doi.org/10.1016/j.matdes.2015.07.096
23. Zhao Y, Wang C, Dong C (2018) Microstructural characteristics and mechanical properties of water cooling bobbin-tool friction stir welded 6063–T6 aluminum alloy. MATEC Web Conf 206:03002. https://doi.org/10.1051/matecconf/201820603002
24. Xu W, Luo Y, Fu M (2018) Microstructure evolution in the conventional single side and bobbin tool friction stir welding of thick rolled 7085–T7452 aluminum alloy. Mater Charact 138:48–55. https://doi.org/10.1016/j.matchar.2018.01.051
25. Zhang H, Wang M, Zhang X, Yang G (2015) Microstructural characteristics and mechanical properties of bobbin tool friction stir welded 2A14-T6 aluminum alloy. Mater Des 1980–2015(65):559–566
26. Yang C, Ni D, Xue P, Xiao B, Wang W, Wang K, Ma Z (2018) A comparative research on bobbin tool and conventional friction stir welding of Al-Mg-Si alloy plates. Mater Charact 145:20–28

27. Fuse K, Badheka V (2020) Hybrid self-reacting friction stir welding of AA 6061–T6 aluminium alloy with cooling assisted approach. Metals 11(1):16. https://doi.org/10.3390/met11010016
28. Li G, Zhou L, Luo S, Dong F, Guo N (2020) Quality improvement of bobbin tool friction stir welds in Mg-Zn-Zr alloy by adjusting tool geometry. J Mater Process Technol 282:116685. https://doi.org/10.1016/j.jmatprotec.2020.116685
29. Zhao S, Bi Q, Wang Y, Shi J (2016) Empirical modeling for the effects of welding factors on tensile properties of bobbin tool friction stir-welded 2219–T87 aluminum alloy. Int J Adv Manuf Technol 90(1–4):1105–1118. https://doi.org/10.1007/s00170-016-9450-2
30. Esmaily M, Mortazavi N, Osikowicz W, Hindsefelt H, Svensson J, Halvarsson M, Martin J, Johansson L (2016) Bobbin and conventional friction stir welding of thick extruded AA6005-T6 profiles. Mater Des 108:114–125. https://doi.org/10.1016/j.matdes.2016.06.089
31. singh P, Biswas P, Kore SD (2018) Finite element method and experimental study of self-reacting friction stir welding of aluminium alloy A6061-T6. Lecture Notes on Multidisciplinary Industrial Engineering, 79–102. https://doi.org/10.1007/978-981-10-8518-5_3
32. Chen S, Li H, Lu S, Ni R, Dong J (2015) Temperature measurement and control of bobbin tool friction stir welding. Int J Adv Manuf Technol 86(1–4):337–346. https://doi.org/10.1007/s00170-015-8116-9
33. Sued MK, Pons D, Lavroff J (2014) Compression ratio effects in bobbin friction stir welding. In Proceedings of the 10th international friction stir welding symposium, Beijing, China, pp 292–310
34. Thomas WM, Wiesner CS, Marks DJ, Staines DG (2009) Conventional and bobbin friction stir welding of 12% chromium alloy steel using composite refractory tool materials. Sci Technol Weld Joining 14(3):247–253. https://doi.org/10.1179/136217109x415893
35. Wan L, Huang Y, Wang Y, Lv S, Feng J (2014) Friction stir welding of aluminium hollow extrusion: weld formation and mechanical properties. Mater Sci Technol 31(12):1433–1442. https://doi.org/10.1179/1743284714y.0000000721
36. Huang YX, Wan L, Lv SX, Feng JC (2013) Novel design of tool for joining hollow extrusion by friction stir welding. Sci Technol Weld Joining 18(3):239–246. https://doi.org/10.1179/1362171812y.0000000096
37. Węglowska A (2018) The use of a bobbin tool in the friction stir welding of plates made of aluminium alloy EN AW 6082–T6. Biuletyn Instytutu Spawalnictwa 5:35–43. https://doi.org/10.17729/ebis.2018.4/4
38. Hou JC, Liu HJ, Zhao YQ (2014) Influences of rotation speed on microstructures and mechanical properties of 6061–T6 aluminum alloy joints fabricated by self-reacting friction stir welding tool. Int J Adv Manuf Technol 73(5–8):1073–1079. https://doi.org/10.1007/s00170-014-5857-9
39. Sahu PK, Vasudevan NP, Das B, Pal S (2019) Assessment of self-reacting bobbin tool friction stir welding for joining AZ31 magnesium alloy at inert gas environment. J Magnes Alloys 7(4):661–671. https://doi.org/10.1016/j.jma.2019.05.011
40. Zhou L, Li GH, Zha GD, Shu FY, Liu HJ, Feng JC (2018) Effect of rotation speed on microstructure and mechanical properties of bobbin tool friction stir welded AZ61 magnesium alloy. Sci Technol Weld Joining 23(7):596–605. https://doi.org/10.1080/13621718.2018.1432098
41. Shen Z, Ding Y, Gerlich AP (2019) Advances in friction stir spot welding. Crit Rev Solid State Mater Sci 45(6):457–534. https://doi.org/10.1080/10408436.2019.1671799(sameasref5inshoulderdimensioning)
42. Bakavos D, Prangnell PB (2009) Effect of reduced or zero pin length and anvil insulation on friction stir spot welding thin gauge 6111 automotive sheet. Sci Technol Weld Joining 14(5):443–456. https://doi.org/10.1179/136217109x427494(sameasref6inshoulderdim)
43. Tozaki Y, Uematsu Y, Tokaji K (2010) A newly developed tool without probe for friction stir spot welding and its performance. J Mater Process Technol 210(6–7):844–851. https://doi.org/10.1016/j.jmatprotec.2010.01.015
44. Tier M, Rosendo T, dos Santos J, Huber N, Mazzaferro J, Mazzaferro C, Strohaecker T (2013) The influence of refill FSSW parameters on the microstructure and shear strength of 5042 aluminium welds. J Mater Process Technol 213(6):997–1005. https://doi.org/10.1016/j.jmatprotec.2012.12.009

45. Badarinarayan H, Yang Q, Hunt F (2008) Effect of pin geometry on static strength of friction stir spot welds. SAE Technical Paper Series. Published. https://doi.org/10.4271/2008-01-0147
46. Bilici MK, Yükler AR (2012) Influence of tool geometry and process parameters on macrostructure and static strength in friction stir spot welded polyethylene sheets. Mater Des 33:145–152. https://doi.org/10.1016/j.matdes.2011.06.059
47. Ohishi K, Sakamura M, Ota K, Fujii H (2015) Novel dissimilar spot welding of aluminium alloy and steel sheets by friction stirring. Weld Int 30(2):91–97. https://doi.org/10.1080/09507116.2014.921088
48. Badarinarayan H, Shi Y, Li X, Okamoto K (2009) Effect of tool geometry on hook formation and static strength of friction stir spot welded aluminum 5754-O sheets. Int J Mach Tools Manuf 49(11):814–823. https://doi.org/10.1016/j.ijmachtools.2009.06.001
49. Hirasawa S, Badarinarayan H, Okamoto K, Tomimura T, Kawanami T (2010) Analysis of effect of tool geometry on plastic flow during friction stir spot welding using particle method. J Mater Process Technol 210(11):1455–1463. https://doi.org/10.1016/j.jmatprotec.2010.04.003
50. Retracted: "Effect of Pin and Shoulder Geometry on Stir Zone and Mechanical Properties of Friction Stir Spot-Welded Aluminum Alloy 2024-T3 Sheets" (2015) J Eng Mater Technol 137(3). https://doi.org/10.1115/1.4030197
51. Santella M, Hovanski Y, Frederick A, Grant G, Dahl M (2010) Friction stir spot welding of DP780 carbon steel. Sci Technol Weld Joining 15(4):271–278. https://doi.org/10.1179/136217109x12518083193630
52. Miles MP, Ridges CS, Hovanski Y, Peterson J, Santella ML, Steel R (2011) Impact of tool wear on joint strength in friction stir spot welding of DP 980 steel. Sci Technol Weld Joining 16(7):642–647. https://doi.org/10.1179/1362171811y.0000000047
53. Hartman T, Miles M, Hong ST, Steel R, Kelly S (2015) Effect of PCBN tool grade on joint strength and tool life in friction stir spot welded DP 980 steel. Wear 328–329:531–536. https://doi.org/10.1016/j.wear.2015.03.001
54. Lin P, Pan J, Pan T (2008) Failure modes and fatigue life estimations of spot friction welds in lap-shear specimens of aluminum 6111-T4 sheets. Part 2: Welds made by a flat tool. Int J Fatigue 30(1):90–105. https://doi.org/10.1016/j.ijfatigue.2007.02.017
55. Bakavos D, Chen Y, Babout L, Prangnell P (2010) Material interactions in a novel pinless tool approach to friction stir spot welding thin aluminum sheet. Metall Mater Trans A 42(5):1266–1282. https://doi.org/10.1007/s11661-010-0514-x
56. Uematsu Y, Kakiuchi T, Tozaki Y, Kojin H (2012) Comparative study of fatigue behaviour in dissimilar Al alloy/steel and Mg alloy/steel friction stir spot welds fabricated by scroll grooved tool without probe. Sci Technol Weld Joining 17(5):348–356. https://doi.org/10.1179/1362171812y.0000000014
57. Ji S, Wang Y, Li Z, Yue Y, Chai P (2016) Effect of tool geometry on material flow behavior of refill friction stir spot welding. Trans Indian Inst Met 70(6):1417–1430. https://doi.org/10.1007/s12666-016-0937-1
58. Lacki P, Kucharczyk Z, ŚLiwa R, Gałaczyński T (2013) Effect of tool shape on temperature field in friction stir spot welding. Arch Metall Mater 58(2):595–599. https://doi.org/10.2478/amm-2013-0043
59. Shen J, Wang D, Liu K (2012) Effects of pin diameter on microstructures and mechanical properties of friction stir spot welded AZ31B magnesium alloy joints. Sci Technol Weld Joining 17(5):357–363. https://doi.org/10.1179/136217112x13333824902125
60. Xu L, Wang L, Chen YC, Robson JD, Prangnell PB (2015) Effect of interfacial reaction on the mechanical performance of steel to aluminum dissimilar ultrasonic spot welds. Metall Mater Trans A 47(1):334–346. https://doi.org/10.1007/s11661-015-3179-7
61. Reilly A, Shercliff H, Chen Y, Prangnell P (2015) Modelling and visualisation of material flow in friction stir spot welding. J Mater Process Technol 225:473–484. https://doi.org/10.1016/j.jmatprotec.2015.06.021