J. Inst. Eng. India Ser. D (July–December 2021) 102(2):549–565
https://doi.org/10.1007/s40033-021-00276-z

REVIEW PAPER

Friction Stir Spot Welding-Process and Weld Properties: A Review

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Received: 25 May 2021 / Accepted: 28 June 2021 / Published online: 5 September 2021

Abstract The need for weight reduction in aerospace and automotive industries requires use of lightweight materials. In order to attain the aforementioned, joining of dissimilar materials such as steel and aluminum came into practice. Friction stir spot welding is a solid-state welding technique capable of joining the materials with wide variation in their properties. This paper discusses the friction stir spot welding process and its variants along with effect of heat generation and material flow on the macrostructure, and mechanical behaviour of FSSW aluminum alloys. Finally, the major issues in friction spot stir welding will be discussed followed by the summary of outcomes and the scope for future work.

Keywords Friction stir spot welding · Aluminum · Mechanical · Aerospace

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Introduction

Weight reduction is becoming more and more important in manufacturing units such as automobiles and aircraft, to achieve improved performance and better fuel economy. This necessitates the use of lightweight materials to replace heavy steel alloys in structural components [1, 2]. Aluminum alloys are widely used to meet such requirements because of their high strength to weight ratio, good thermal and electric conductivity and excellent corrosion resistance [3]. However, weldability of aluminum alloys is a major concern in assembly operations, as certain aluminum alloys (viz. 2024, 2219, 2198, and 7020, 7039, 7050, 7075, 7449 etc.) are difficult to weld using traditional welding techniques and need expertise. High thermal conductivity, low melting point, existence of natural oxide layer, solute elements and higher solubility of hydrogen imposes excessive difficulties in fusion welding of most of the aluminum alloy but also adversely affect weld quality and performance owing to defects, e.g., porosity, oxide inclusions, alloying element loss, distortion, residual stresses, hot cracking etc. Moreover, dissolution/overaging causes softening and formation of heat affected zone is inevitable [4]. In addition to fusion welding, several other types of solid-state joining techniques, such as friction and resistance welding, are also opted and may often be associated with fewer weld defects for producing aluminum joints [5, 6].

Variety of single point joining techniques such as self-piercing riveting [7], laser spot welding [8, 9] resistance spot welding [10], ultrasonic welding [11], friction stir spot welding (FSSW) [12] were used to assemble, assemblies or sheets. Spot welds were generally preferred for aviation, automotive, railway and marine industries to obtain a light weight structure. Resistance spot welding, a most widely used technique, consumes electrode and leads to formation of defects in nugget of aluminum sheet resulting in poor weld strength. In laser spot welds, porosity cannot be eliminated completely and thus the joint strength is impaired. Mechanical fasteners, such as rivets, nuts, and bolts, on the other hand, need drilling and add to the component's weight, lowering the strength-to-weight ratio [7, 13, 14].

To eliminate above-mentioned weldability problems, FSW is developed by TWI, U.K., 1991 for welding of alloys of aluminum [15, 16]. At present, it has been effectively used for welding of magnesium alloys, titanium alloys and even MMCs [17]. FSW is a solid state welding method and do not require material to be in liquid state; thus most of problems related with fusion welding were eliminated on their own [18]. For intermittent welding, a new spot welding procedure for joining of aluminum is developed by Kawasaki Industry Ltd known as FSSW [19]. This method is derivative of FSW, works on the principle of joining without melting. FSSW is becoming more and more popular to produce spot welds in similar as well as dissimilar materials owing to a number of advantages such as extremely low energy requirement, little/no distortion, long tool life, short cycle time, no need of consumable electrode and work preparation, etc. [10]. Despite solid-state welding, FSW/FSSW welds exhibit a softened region comprising stir zone, TMAZ and HAZ [20, 21]. Softened region is created due to dissolution/over aging of strengthening precipitates and loss of strain hardening effect for precipitate and solution strengthening of aluminum alloys, respectively. Softening resulted in weak region where strength is least and failure of weld took place. Softening can be minimized by optimization of process parameters like in process cooling, under water cooling, pre- and post-weld heat treatment [22–24].

Overview of Single Point Joining Techniques

The use of high specific strength materials such as light weight steels, aluminum, plastics, and composites, as well as novel approaches such as the usage of tabular parts, is required to reduce the weight of structure and components in automobiles and other industrial units. Without an effective joining technique capable of joining different combinations of materials and pieces, these approaches cannot be used to build light weight structures/automotive. The type of joining technique to use is determined by the functional needs as well as the nature of the joining, which might be temporary, semi-permanent, or permanent. Various ways for producing single point joints will be briefly described in the following sections.

Mechanical Fastening

Mechanical fastening is the most suitable, reliable and economic method when assembling and dismantling of components is necessary either for maintenance or replacement of parts. It can join similar or dissimilar parts or assemblies by means of bolts, screws, rivets and couplings. However, structures are bulky, prone to corrosion, need sealant and costly when compared to welding [25].

Bolts, screws, and rivets, in general, require a hole, which necessitates machining, thus causes stress concentration and weight add-on. Fastener heads must also be chosen with care. Conical heads cause tensile strains in mating components, whereas round heads cause less damaging compressive pressures. The use of a flat washer under the nut and fastener head reduces assembly force. Riveting creates semi-permanent joints since the only way to separate pieces is to damage the rivets. It is a low-cost method that's also simple to automate. Riveted joints are more durable, but the resulting structures are bulky and corrosive. Self-piercing rivets and press joining do not require a pre-drilled hole and may be automated in the same way as resistance spot welding. A tabular rivet is pushed through the sheet and extended in the bottom sheet without piercing it with the assistance of a punch and die in self-piercing riveting. Both sheets are held together by the mechanical interlocking that has been created. Apart from a suitably thick bottom sheet for rivet flaring, the primary constraint of this method is the need for multiple rivet and die configurations for manufacturing various types of joints [7]. The deformation of sheets into a specific die with a punch to produce interlock in sheets and a button on one side is known as press joining. Steel rivets provide greater peel and shear strengths in self-piercing joints than spot welds, but both of these strengths were less than half in press joints. Mechanical fastening can link incompatible material combinations, such as aluminum-steel and aluminum-plastic, that would normally be impossible to join using spot welding [26].

Resistance Spot Welding (RSW)

In the RSW joining process, sheets heated by resistance heating are fused together by applying pressure [10]. It is a popular technology for connecting thin sheets in the automobile sector to produce white bodies, refrigerator bodies, and high-quality work in the aerospace industry. This method can join advanced high strength dual phase steel and other metals in a variety of combinations and thicknesses. Furthermore, multilayer stacks of aluminum alloys may be welded with ease. This method has a few drawbacks, including visible spot markings, distortion, electrode wear, limited electrode life, and poor uniformity

[7, 27, 28]. Spot markings and deformation can make welded items unsuitable for use, necessitating grinding or polishing to enhance the surface quality of the welds. Projection resistance welding is a type of spot resistance welding that uses the projection offered in one sheet to produce spot welds. This approach is more efficient and cost-effective than spot welding, and it creates superior consistency and aesthetics [7, 29].

Laser Spot Welding

The laser beam is concentrated in laser spot welding to melt and produce small joints in metallic materials [8]. To produce high power, a beam of electromagnetic waves is focused on the workpieces using optical medium/lenses. When a high-power beam is concentrated, a portion of it is reflected and absorbed, resulting in a keyhole due to material fusion. The balance between the pressure of molten metal vaporisation, which tries to increase the depth, and hydrostatic pressure, which wants to close the hole, determines the depth of the hole on the workpiece. Weld penetration and geometry of laser spot welds are affected by a variety of process parameters such as laser power, power density, beam diameter, pulse duration, material physical characteristics, and environment. Porosity, solidification features, and under filling are just a few of the laser spot welding flaws. A laser beam with high power density fired for a longer duration is required for a deeply penetrated spot weld [8, 26].

Friction Stir Spot Welding

In the FSSW method, a rotating tool is introduced into the plates placed in a lap joint arrangement as illustrated in Fig. 1 [19] at a pre-specified speed. After reaching the desired depth, the FSSW tool remains stationary for a period of time known as holding time. Following that, the tool returned from the specimen, leaving a solid state bond in the middle of the two plates with the key hole. The downward force, along with the rotating motion, creates heat through friction and plastic deformation, softening the material in the tool's proximity, mixing it, and forming a firm bond [30]. As a result, unlike the FSW process, the plunging FSSW tool does not traverse in the lateral direction, resulting in the formation of only intermittent joints, i.e., spot welds. This FSSW technique is known as traditional FSSW, and it has a keyhole as a distinguishing feature. Keyholes can cause significant stress concentration, making the joint prone to corrosion and therefore affecting the mechanical characteristics. [31–33].

Several FSSW process variations were developed to improve joint strength, minimize flaws, and/or remove keyhole, and are detailed below.

Variant of FSSW

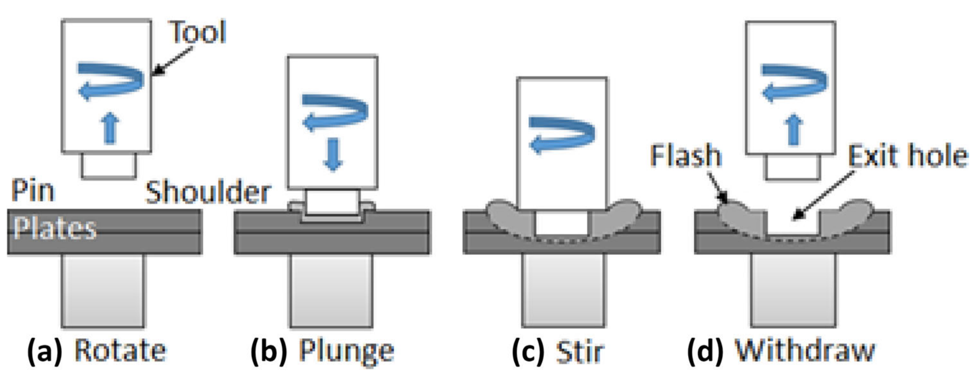
This section describes several distinct types of FSSW, such as Refill, Pinless, Stitch and Swing, Two-Step Spot FSW, and Protrusion FSSW, to distinguish them from traditional FSSW.

Refill FSSW (R-FSSW)

The Helmholtz-Zentrum Geesthacht in Germany developed and patented this technique to remove keyholes in FSSW [34]. As illustrated in Fig. 2, the full procedure is completed in four phases.

Toll used in R-FSSW have pin, sleeve, and clamp. The stationary clamp holds both the plate and the anvil firmly, while the pin and sleeve rotate and move axially. The coordinated retract of pin and sleeve accommodates material during extrusion and eventually fills the keyhole at pullout, while clamp restricts material flow in an area. Despite the fact that the technique can fill the keyhole, the equipment needed and the operation are both difficult and expensive, restricting its use. The FSSW refill creates a high-strength weld with the least amount of depression and inner void [35, 36].

Fig. 1 Pictorial representation of FSSW Process



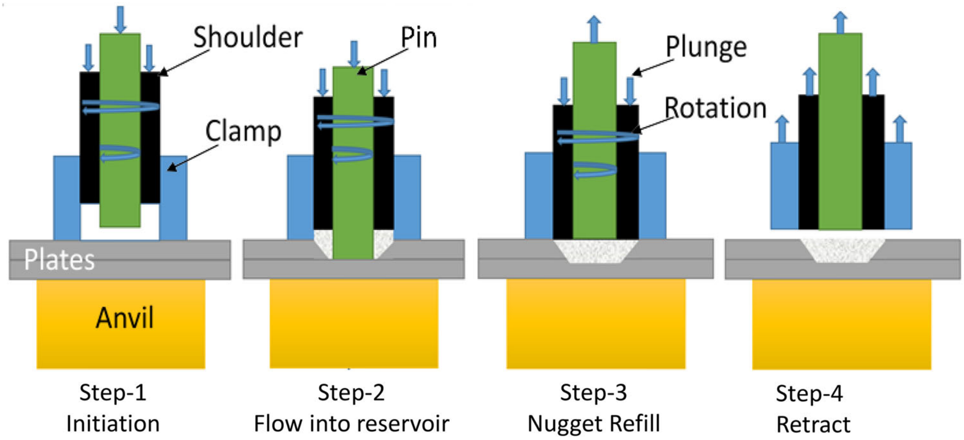


Fig. 2 Pictorial representation of Refill FSSW Process

Pinless FSSW

Tozaki et al. (2010) [27] proposed a tool with a scroll groove at the shoulder instead of an extended pin. This pinless tool performed better than a traditional tool with no keyhole. Similar to the traditional FSSW method, the procedure is completed in three steps viz. plunging, stirring, and retracting, as shown in Fig. 3. The inherent simplicity, high strength welds, and reduced dwell time are all major advantages of this technique.

Stitch FSW and Swing FSW

Stitch FSW and Swing FSW are small-length linear welds that result in a greater weld area and higher joint strength than spot welding. The tool will use this approach to conduct standard FSW over a short distance. As shown in Fig. 4b, the pin of a rotating tool is pushed into the plate until the shoulder meets the plate surface, then fed linearly and withdrawn. The tool swings in a circular motion with a high radius and small angle in swing FSW, as shown in Fig. 4c. When compared to FSSW and resistance welding, stitch welds provide a better performing weld. However, in comparison to conventional FSW, Stitch FSW requires additional motor for horizontal movement whereas Swing FSW requires additional swing axis and drive mechanism for swing motion 6.

Two Step Spot Friction Stir Welding

This approach uses a two-step process to create a keyhole free spot weld. To produce a bump on the rear of joints, traditional FSSW was performed first on a backing plate with a circular depression instead of a flat anvil. In the second stage, a pinless rotating tool was used to eliminate the protuberance and produce a smooth surface on a flat backing plate, as illustrated in Fig. 5. [37].

Protrusion FSSW

It's an FSSW version that aims to eliminate the keyhole. This technique appears to be identical to pinless FSSW with the exception of the use of an anvil with a protruded integral disc, thus the term protrusion FSSW. The approach is depicted in the pictorial view in Fig. 6. The three steps of this approach are (i) rotation, (ii) diving, and (iii) drawing out. Due to the supplied vertical force, the tool spinning at a specified speed is lowered to make contact with the top plate's surface. The friction between the revolving tool and the sheet surface raises the temperature, causing the material beneath the tool to soften. Stirring combined with vertical compression causes the sheet material to mix, and the tool is then removed at the end of the prescribed dwell period. The protrusion FSSW joint has a smooth appearance with a slight indentation. The development of a

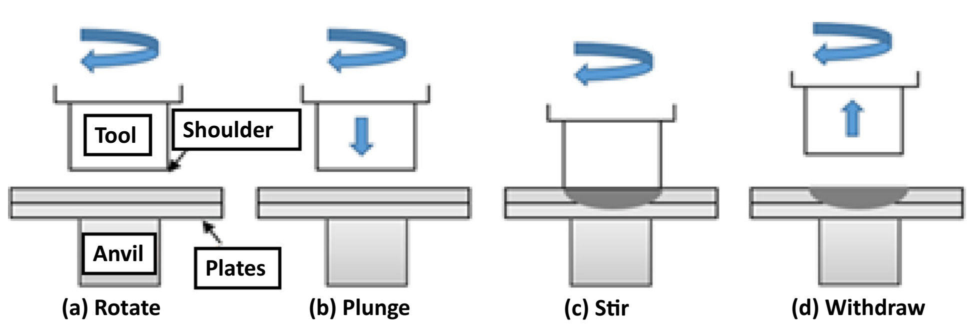


Fig. 3 Schematic of pin less FSSW

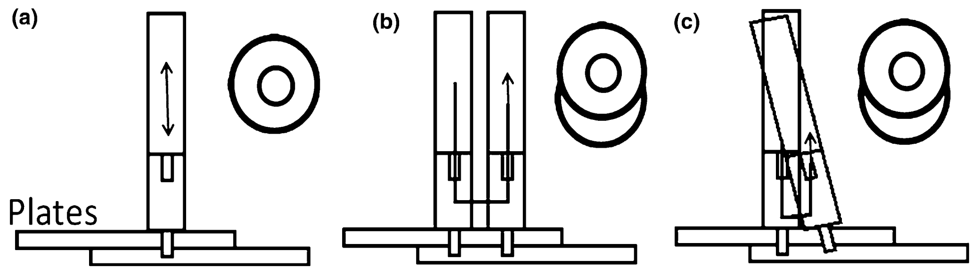


Fig. 4 Schematic of Stitch and Swing FSW and comparison of tool drive and top view of variant of FSW **a** FSSW, **b** Stitch-FSW and **c** Swing-FSW

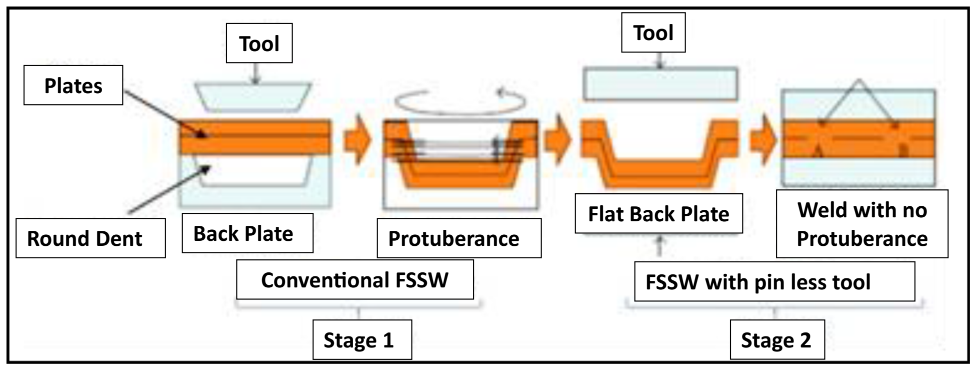


Fig. 5 Schematic of two step spot friction stir welding

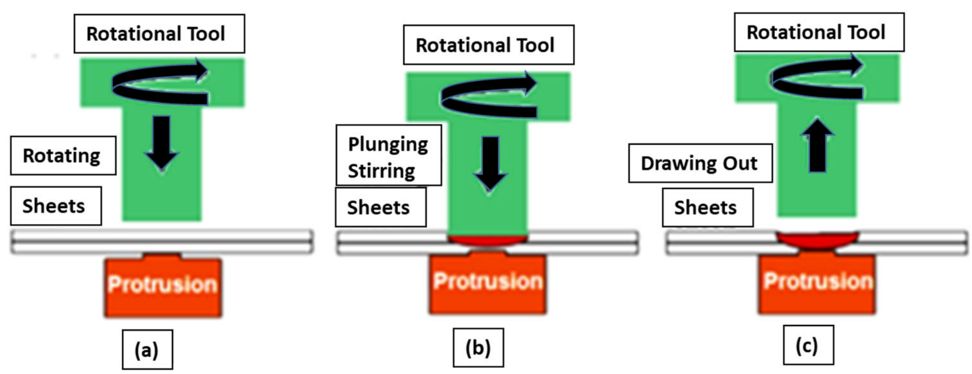


Fig. 6 Schematic of Protrusion FSSW process [28]

keyhole is prevented by minimal vertical material movement. The excellence of a joint's surface can enhance painting quality, corrosion resistance, and stress concentration [28].

Influence of Process Parameters on the Characteristics of FSSW Joints

Macrostructure

In general, FSSW joints have a central exit hole surrounded by a raised ring with a diameter that is roughly equal to the diameter of the pin and shoulder [12]. The tool impacts the form and other aspects of the weld joints by transferring geometrical parameters such as pin and shoulder angles. Depending on the shoulder design, the upper surface of the joint may be flat or sloped. Similarly, depending on the pin type, the exit hole may be cylindrical or truncated conical. The insertion of the tool expels the material from the plate and deposits it on the shoulder's outskirts, producing an outside ring. With the passage of dwell time, the ring grows in size. The center section of the joint may also be raised or lowered as a result of the pin insertion rather than the plate surface. Due to increased plunge pressure, the elevated center section was discovered lower than the plate surface with longer dwell time, whereas it was found higher than the plate surface with short dwell time. With the passage of time, the narrower oval-shaped agitation zone created in the bottom plate expanded in size, and discontinuity and bulging at the interface became visible. Bulging at the interface decreased when the dwell duration was increased, and the interface migrated toward the top plate [38]. Stir zone (SZ), thermo mechanically affected zone (TMAZ), heat affected zone (HAZ), hook, and the unaffected base metal (BM) may all be found on FSSW joints (Fig. 7). The

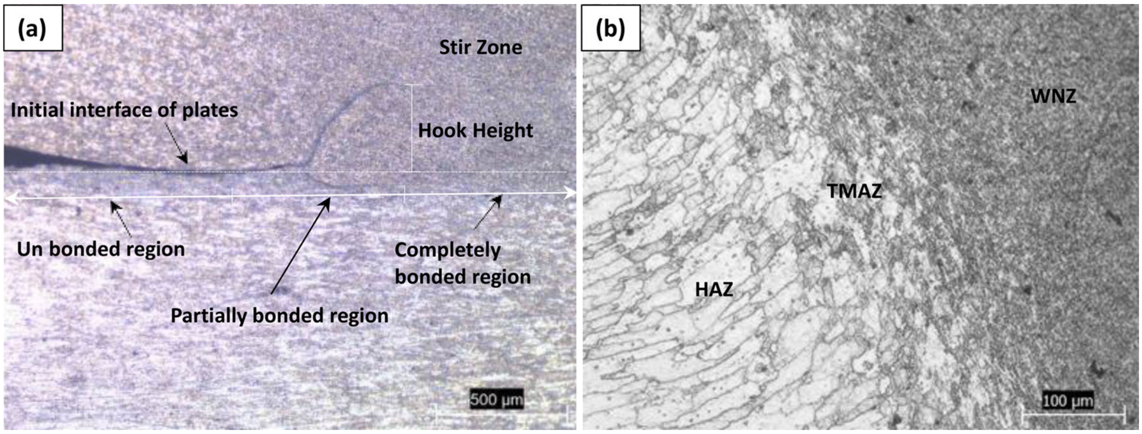


Fig. 7 **a** Macrostructure showing hook formation and bonding of plates, **b** Microstructure of FSSW joints showing different zones

SZ zone, which is closest to the tool pin, includes recrystallized grains. Because extended rotary speed generates more heat, the size of the stir zone grows as the rotational speed rises [39]. Next to SZ is TMAZ, in which grains have undergone plastic deformation in tandem with the heat cycle, whereas HAZ has a thermal cyclic effect but no plastic distortion. BM is the region that is untouched by the procedure and so retains its original characteristics. Hook is a characteristic feature of FSSW in lap configuration [12, 40]. The weld quality and properties are influenced by the macrostructure of the FSSW joints viz, (a) exit hole, (b) size of SZ, and (c) hook. The exit hole reduces the effective bond area so as reduces the tensile strength of joints. Formation of SZ is controlled by process parameters and size of SZ increases with increasing heat input, i.e., rotary speed and dwell time. The tensile strength is found to improve with SZ size because of longer bond length. Hook involves partial metallurgical bonding and decreases both tensile shear strength and fatigue strength of FSSW joints as it facilitates crack propagation.

Microstructure

Microstructure of FSSW joints changes with process parameters as pin length, tool rotational speed and hold time [28, 38]. Increase in pin length results in severe and intense stirring of the material forcing lower sheet to move upward, therefore decreasing the thickness of upper sheet of AA6061 aluminum alloys. Similar effect was reported with increase in rotary speed or dwell time, however difference in upper sheet thickness was indiscernible due to vigorous stirring and greater top flow of lower sheet material [41, 42]. The bond length also improves by enhancement in pin length, rotary speed and dwell time which results in higher heat input. Intense stirring enhances the size of stir zone so as the bond length. Pin length affects the amount of upward material flow of lower sheet which increases with pin length irrespective of rotary speed and dwell time [41].

Tool penetration depth (TPD) and position of plates also influence the plastic deformation and flow of material and therefore had a great influence on various weld characteristics such as effective weld width, hook height, fracture load, etc. With increase in tool penetration depth, effective weld width or bond length increases whereas hook height decreases irrespective of plate position. However, plate position influences the magnitude of both effective weld width and hook height. FSSW carried out by keeping AA6063 at top and AA5052 at bottom showed higher effective weld width and lower hook height than reverse position of plates. The change in position of plates changed the action of shoulder on plate interface [42]. The plunge depth does not remain constant but in fact varies from sample to sample. The plunge depth increased with dwell time at fixed rotary speed. Longer dwell time caused higher peak temperature owing to greater heat input and thermal expansion of sheets and tool yielded deeper plunge depth [38]. During a new type of FSSW called as protrusion FSSW, fixed plunge depth and joint bond length increased while stir zone depth decreased with dwell time. Stir zone depth is the thickness of the recrystallized zone and measured perpendicularly between top face of weld to bottom of stir zone [28].

Hook Formation and its Characteristics

In FSSW lap joints, hook is characteristic geometric defect occurring at the edge of plates due to upward bending of the plate interface [43]. A thin oxide layer is generally presented on plate's surface and protect them from corrosion. As rotating tool plunged, the matting surface of plate bents upward and breaks the oxide layer. Dispersion of these oxide particles hinders metallurgical bonding of the sheets and may result in partial bonding of lapped sheets

[44]. Thus, hook defect is basically a transition region of partial metallurgical bonding, sand witched between unbonded and fully bonded regions [40].

Tool pin geometry [43], plunge depth [40], plunge speed of tool pin and tool shoulder [45] all influences hook shape. Figure 8 presents the effect of the tool pin profile on hook geometry. The hook in welds made using cylindrical pin with right hand thread made upwards and then detours stir zone and finally moves downwards near the bottom of joint where partial bonding is less significant. While in welds made with triangular pin, hook points on the way to stir zone then terminates having a small flat terrain. This difference in hook geometry is attributed to different material flow for circular and triangular pin geometries. Triangular pin rotates asymmetrically, moves material back and forth in radial direction and rigorously deforms the material. The intense plastic deformation disperses the hook, radial back and forth movement of material inhibits the formation and growth of continuous hook. Cylindrical pin rotates symmetrically and causes the shearing of material around pin. Threads on pin transports the upper plate material downwards toward lower plate and pushes lower plate material outwards as well as upwards forming and bulging the hook [43].

The hook may be located either in stir zone or TMAZ depending on the plunge depth. At smaller plunge depth (1.9 mm) curve shaped hook defect was located in the stir zone. The extrusion of deformed material from lower plate to upper plate resulted in the formation of an inverted V shape at the original interface of plates, which could not be eliminated due to sluggish material flow and resulted in hook formation. At higher plunge depth (i.e. 2.1 and 2.3 mm) TMAZ leads to have hook formation which had notable rising modification in TMAZ, prior to descendent near the stir zone [40]. The top side deflection of the interface because of tool penetration in bottom plate is responsible for such hooks [43]. In another work, hook moved upward prior to moving downward toward lower plate indicating no upward flow of material underneath the hook from lower plate into upper plate [21].

The plunge speed of pin and shoulder are believed to affect the stir time and material flow and hence the stir zone size. Higher plunging speed will lead to shorter stirring period reducing material deformation and plasticity, resulting in small size stir zone. Thus, increase in shoulder plunge speed reduces the stir zone size and bond width and increases effective plate thickness. While at slow plunge speed of shoulder, intense material deformation occurs flowing the material outside the stir zone toward the key hole i.e., curved hook. While at higher plunge speed of shoulder, hook was curved upward and outward from the axis of key hole. On the other hand, pin plunge speed did not affect the size of stir zone therefore all hooks were curved upward and outward from the axis of the keyhole [45].

The appearance of hook defect is influenced by the rotational speed, plunge depth, joining time, i.e., dwell time [40], pin length and pin profile [46]. Hook height is an important geometric feature and it is measured from hook tip to original interface where partially bonded interface

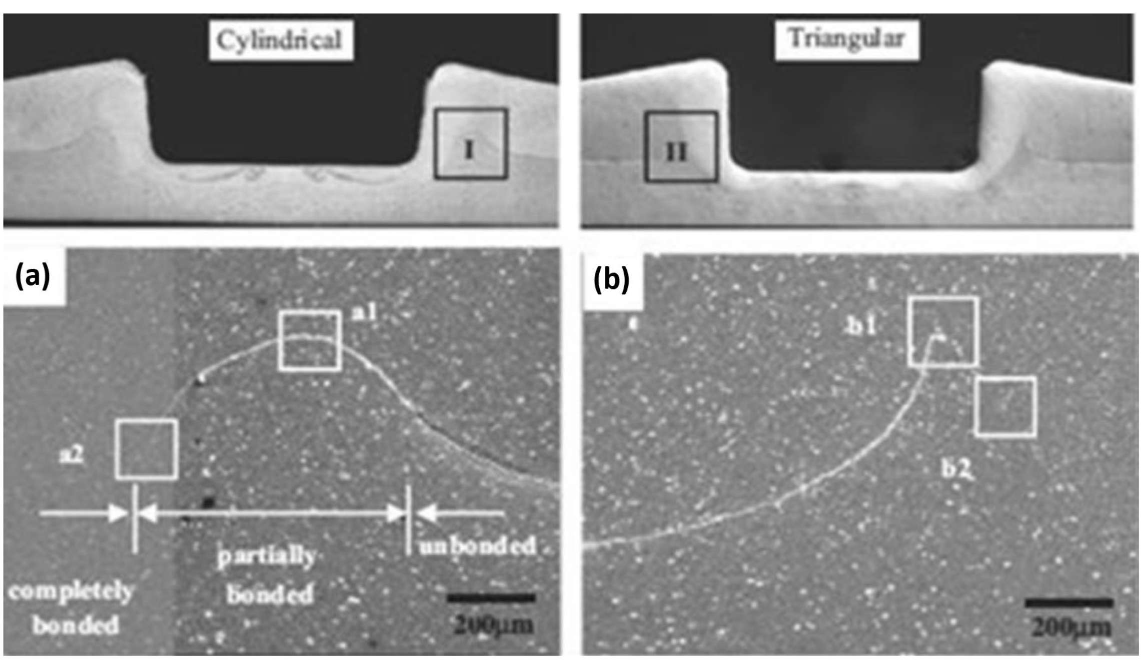


Fig. 8 Outcome of tool geometry on macrostructure and hook geometry **a** cylindrical tool joint, **b** triangular pin tool [43]

begins (Fig. 7 a). If hook tip lies below the interface, the hook height will be negative and vice versa. Hook height depends on volume of deformed material and upward movement of same. It was found to increase with increase in revolving rate, plunge depth and hold time as shown in Fig. 9.

Higher the revolutionary speed and hold time, greater will be the heat generation and material deformation. Thus, at constant plunge depth, enhancement in revolution speed or hold time will increase the heat generation as well as amount of deformed material. Also, the taller hook at higher rotation speed or dwell time is due to greater heat generation and quantity of deformed material in the vicinity of tool. Similarly, deeper plunge depth creates greater upward movement of the deformed material leading to higher hook height [40, 41].

Pin length, shape and threading locations affects the plunge depth so as the permanent warping and inter mixing of material from both sheets [46, 47]. The uprising of bottom sheet material increases with increase in pin length whereas for short pin tool, very less amount of material is mixed causing limited intermixing and compression hence shallow stir zone with very small effective weld width. On the other hand, long probe tool exhibited well developed deeper and wider stir zone and higher effective weld width owing to greater volume of extruded and displaced material. Further, key hole was also larger than obtained with short probe tool. Welds produced with short probe and long probe tool showed hook defect with different geometry. For short probe tool, plunge depth was low therefore stirring was insufficient resulting in negligible rising of bottom sheet material. This resulted in longer flat hook reducing the weld width. In case of long probe tool, the insertion of tool shoulder into top plate and insertion of probe into bottom plate through dwell time caused the flow of bottom plate material and hook formation. Hook originates at unbonded sheet interface, grows upward and outward in partially bonded region of stir zone and finally ceases in completely bonded upper region of stir zone. As soon as the lower sheet material flows upward, hook moves outward. Partially bonded region of hook exhibited discontinuous array of fragmented oxide layer, while same was not observed in completely bonded region where intense stirring resulted in dispersed distribution of fragmented

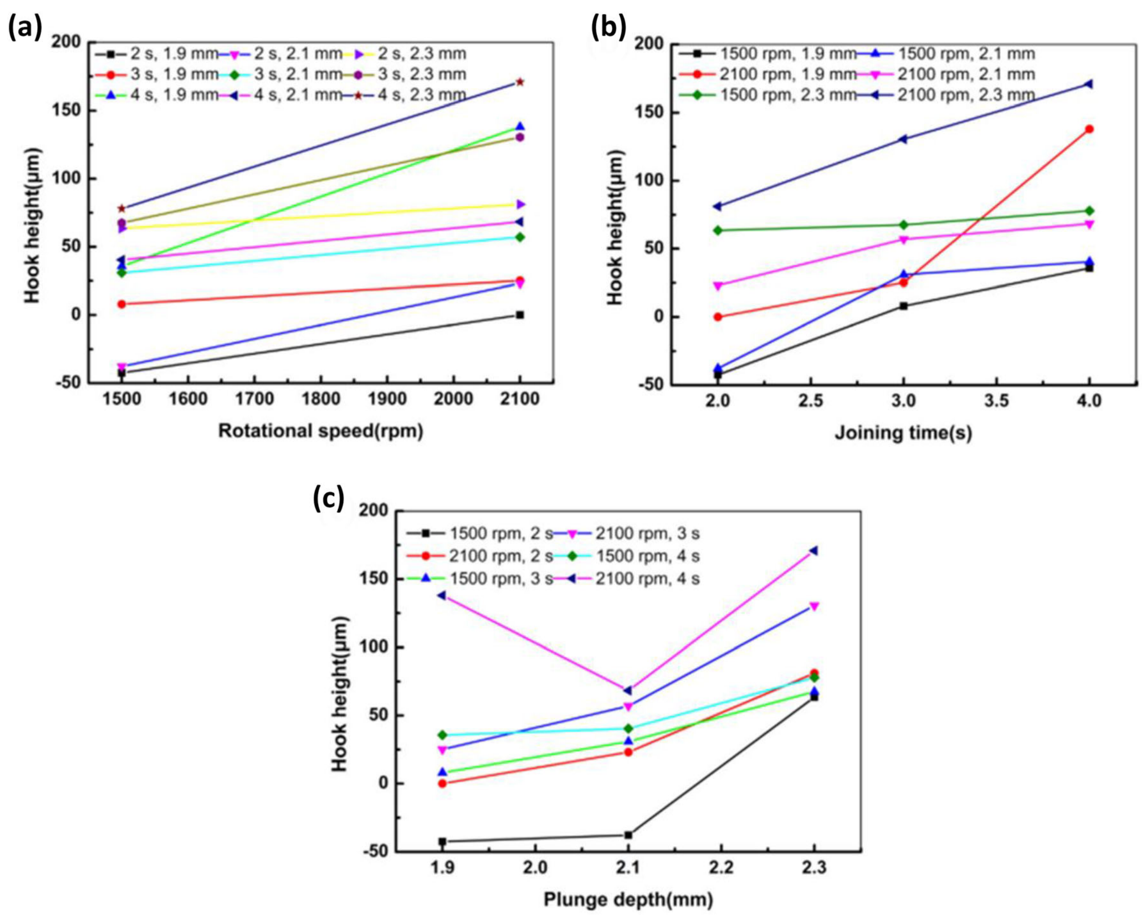


Fig. 9 Hook height with varying **a** rotational speed, **b** joining time, **c** Plunge depth [40]

oxide layer [41]. Extending the height of pin to 5 mm from 4.5 mm increased the bond width due to deformation of more material hence increasing the bond width but further enhancement in pin height up to 5.5 mm will result in enhancement of hook height in place of improving bond size. The tool plunge should be sufficient enough to ensure better connection among shoulder and top plate for generating sufficient heat due to friction and deformation. Deep tool plunge should be avoided as they increased the hook height. The tool pin profile influenced the formation of hook and its height. The tool with taper cylindrical pin did not result in hook defect formation. No discernible change was observed on hook height in case of tool with straight cylindrical and triangular pin despite of different material flow associated with them. In former case straight cylindrical pin creates rotational flow of plasticized material, i.e., around the tool axis. While for triangular pin, back and forth material movement in radial direction beside rotational flow resulted in intense material deformation over wider region [46]. Thread position can change material flow behaviour as threads accelerate the material flow in thread grooves. Threading location on the pin influenced the degree of intermixing of material. Early intermixing was observed for bottom threaded tool than middle and top threaded tool irrespective of the rotary speed. Further, threading location on the pin is found to control the material flow and stir zone height [47]. The bond width at lap interface was found to be greater for half threaded pin than full threaded pin because of higher material flow velocity despite lower peak temperature [48].

Type of hook affects the path of crack propagation in initial stage during tensile shear testing, e.g., crack was found to propagate along partially bonded interface for the hook located in stir zone and for the hook located in TMAZ, crack first propagates upward along the thickness prior to penetration in the SZ. Thus, the type of hook, i.e., path of crack propagation influences the shear strength in tensile of the weldment. Former hook type is reported stronger than later one [40]. The presence of pin hole and hook defect largely diminishes the tensile shear strength and fatigue strength of FSSW joints. The quality and mechanical enactment of FSSW weldment is primarily dictated as hook defect in weld region hence it is imperative either to control or avoid its formation. As hook defect is a partial metallurgical bond so can be controlled and avoided by improving the material flow. The hook defect can be eliminated by (i) optimization of processes parameters (ii) changing tool geometry (iii) use of innovative techniques e.g., FSSW followed by FSW [49] (iv) under water FSSW [50]. The FSSW-FSW process is carried out in three stages as shown in Fig. 10.

In step I, a pinless tool was used to make friction stir spot weld. This weld had a hook defect and the pinnless tool was moved on the hook defect. Finally, a circular weld was made on weld modified in second stage using pinless tool. The circular weld creates a superficial nugget zone around hook defect. The second nugget zone around the nugget zone of FSSW joint eliminates the hook defect. A small white region, enriched in pure aluminum was seen at the bottom of second nugget zone which is not a hook defect but a compact metallurgical bond formed due to extrusion of pure aluminum from nugget zone as a result of circular weld. The fracture from the boundary of nugget zone first and second also confirms the above fact which otherwise should fracture from the region of hook defect, i.e., white region. Moreover, this white region does not have any harmful effect on mechanical properties of FSSW-FSW joints [49]. Under water FSSW reduced inter material hooking as water is effective heat sink and reduces peak temperature and material flow. Further, size of stir zone, circular marks and grains were also reduced by underwater FSSW [50].

Mechanical Properties

The quality and performance of joints formed by FSSW are greatly influenced by the constraints like rotary speed, plunge rate, hold time, etc. [47, 51]. The combination of these parameters also determines the level of heat generation. Heat input rate thus governs the degree of stirring and softening and hence the material flow. The rotary speed and shoulder diameter determine the rate of heat produced. Higher the rate of rotation greater will be the generation of heat per unit time. Similar is the effect of increase in shoulder diameter on heat generation. Plunge rate determines the time spent by the tool with deforming material, i.e., faster the plunge rate, lower will be the rate of heat input per unit time in the weld zone. High rotation speed and low plunge rate result in highest heat input per unit depth of weld.

Optimization of constraints like rotary speed, plunge rate, hold time, plunge depth and tool geometry, i.e., shape and dimension are must, not only for forming sound weld joints but also for maximizing the joint properties. In general, the mechanical behaviour/characteristics of FSSW weldment are assessed through tensile shear test which determines failure load, hardness test which describes the variation of microstructure with constraints. Tensile strength of FSSW weld is defined as the maximum load which causes the failure of the weld joint and is affected by the process constraints.

Tensile Properties

Shear strength in tension FSSW weldment is influenced by the rotary speed, shoulder diameter, dwell time, plunge

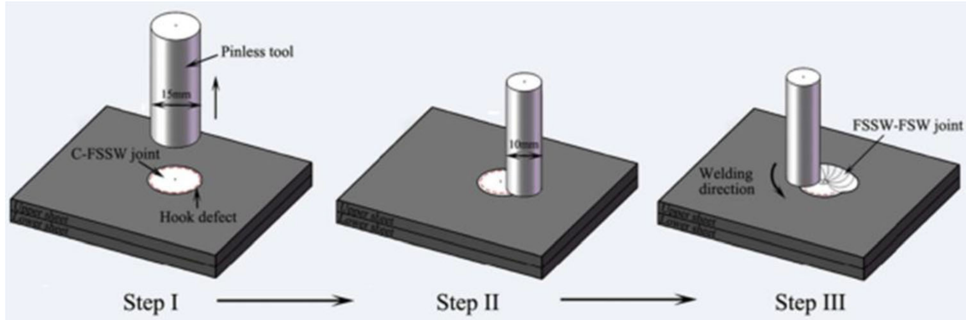


Fig. 10 Pictorial view of the FSSW [49]

rate, type of tool, pin length and thread location. For a given tool geometry, tensile shear strength of weld joint decreases significantly with increase in rotary speed from 900 to 1800 rpm, e.g., from 7 kN to 4 kN for 3 s dwell time and bottom threaded tool. At lower rotary speed, frictional heat generation was small resulting in inferior intermixing of the material flowing from bottom plate to the top plate. Despite inferior intermixing, weld joints produced using lower rotary speed showed superior tensile shear strength than weld joints produced using highest rotary speed of 1800 rpm. For a given rotary speed and tool geometry, tensile shear strength was found to enhance from 3.6 kN to 4.6 kN as dwell time increases from 1.5 s to 9 s. Thread location did not exhibit any significant influence on the tensile shear strength of weld at lower rotary speed of 900 rpm however, an opposite trend was observed at higher rotary speed of 1800 rpm. At higher rotary speed, bottom threaded tool exhibited higher tensile shear strength than middle and tip threaded tool. The effect of thread location on tensile shear strength diminishes with increase in dwell time and at hold time of 9 s the tensile shear strength was approximately the same [47]. The length of threads on the pin was found to influence the peak temperature, bond length and cross tension failure load. For partial threaded pin welds, the maximum temperature was lower while cross tension failure load was higher than thoroughly threaded pin welds. Partial threaded pin produced higher metal flow velocity and caused larger bond length hence greater cross tension failure loads [48].

Figure 11 shows the influence of revolution speed, plunge rate and hold time on the tensile shear strength of FSSW joints of AA2024-T3 aluminum alloy. Tensile shear failure load reduced with improvement of rotary speed beyond 750 rpm. The improvement in plunge rate up to 30 mm per min initially increased the failure load to maximum value of 6.3 kN. Further enhancement in plunge rate up to 50 mm/min has a negative effect on the failure load. Similar to plunge rate, the failure load was increased promptly to maximum value of 6.5 kN thereafter it decreased and remained approximately same with improvement in hold time. The tool revolution speed, hold time are more influential parameters on breaking load. The increase of shoulder diameter from 15mm to 23 mm slightly improves the failure load due to smaller size of hook defect from where failure of joints occurrs. FSSW-FSW demonstrated highest failure load of 12 kN than conventional pinless FSSW joints owing to the elimination of hook defect [49]. Use of dwell time during FSSW can raise failure load. The increase in dwell time from 0 s to 1 s initially increases the failure load significantly for AZ31 FSSW joints beyond which failure load was found to decrease with further increase in dwell time [51].

The tensile strength of weld joints varies with the type of tool, i.e., probe and pinless tools and length of tool pin. Bond length is the supreme width of the weld without unbonded regions and influences tensile strength of welds strongly. Weld tensile strength increases with bond length. Pinless tools had longer bond length than probe tools. Bond length increases with pin length as well as with groove geometry of shoulder. Hence, pinless tools results in stronger welds than probe tools. The absence of keyhole and higher heat input owing to larger cross-sectional area of tool shoulder are believed to enhance tensile strength of welds made by using pinless tools despite low bond quality of interface. The type of groove on shoulder of pinless tools also influences tensile strength of welds. L shaped grooves on tool shoulder produces stronger joints than scrolled grooves whose strength was 2.6 kN and 2.2 kN, respectively. For probed tools, tensile strength increased from 0.6 kN to 1.7 kN as the pin height enhances from 2 mm to 3 mm. Threefold improvement in tensile strength with pin height can be attributed to larger bond length as longer pin results in deeper penetration hence more plastic deformation and intense mixing [52].

Type of tool also influences the tensile behaviour of welds. Probed tool welds exhibited significant deformation after peak load whereas pinless welds exhibited negligible deformation and failed immediately after attaining peak load. This suggests different failure mechanism for welds made with probed and pinless tools. In case of pinless welds, failure initiated from partially bonded region which then propagated through strongly bonded region prior to

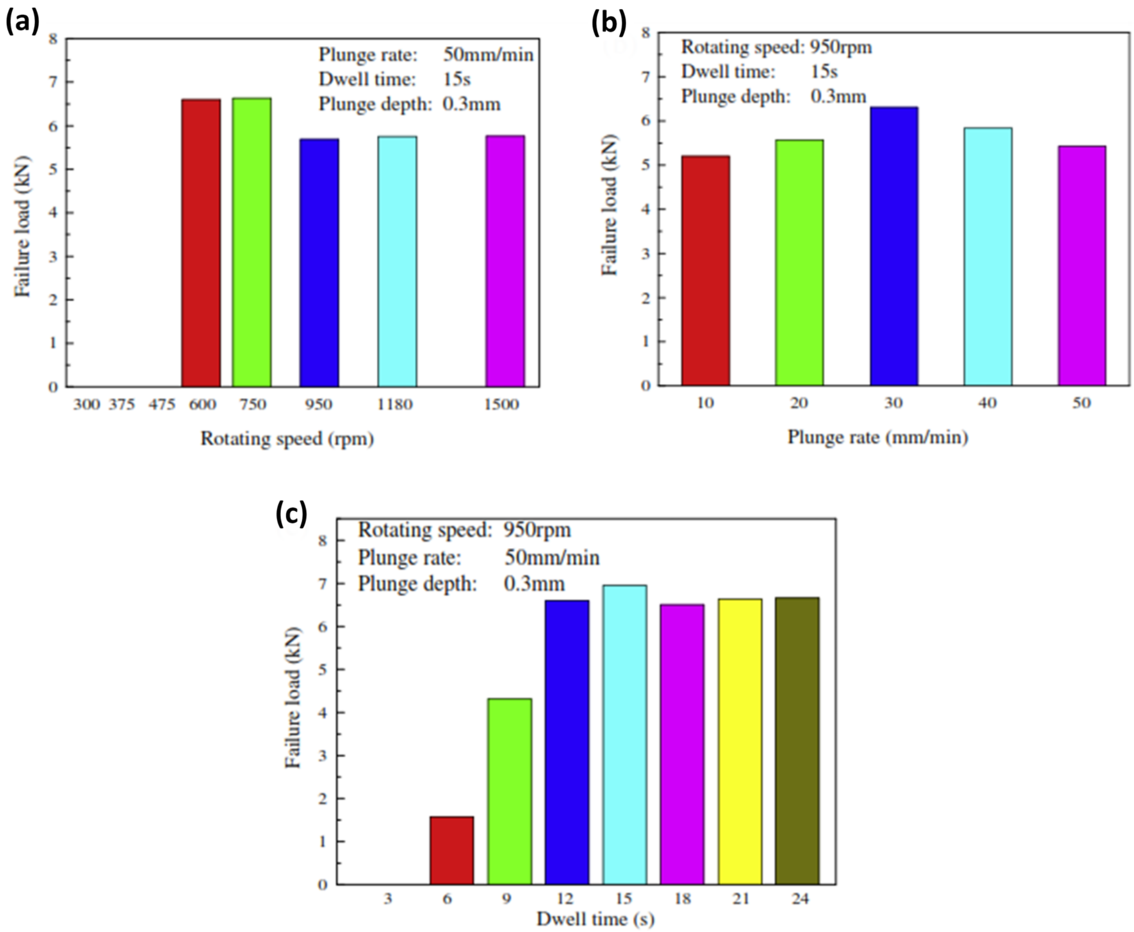


Fig. 11 Influence of **a** rotary speed, **b** plunge rate, and **c** dwell time on the tensile shear strength of FSSW joints [49]

separation of two sheets. While for probed welds, propagation of crack was along the hook, stir zone and nugget circumference and reduced the effective area of weld hence fracture results in gradual drop in failure load [52]. Lap shear strength of weld joints determined by cross tension test is found to vary with tool pin profile as triangular pin showed greatest failure load followed by straight cylindrical pin and taper cylindrical pin [46]. During peel test, increase in tool penetration depth resulted in increase of fracture load. Effective weld width increased with indentation, i.e., tool penetration whereas hook height decreased which in turn enhanced the failure load. FSSW configuration in which AA6063 plate was at top and AA5052 was at bottom, exhibited a higher failure load for all the tool penetration depths than other configurations. With increased indentation or tool penetration depth, interface distance diminishes bringing the tool shoulder near to sheet interface which increases thermo mechanical action resulting in better metallurgical bonding and higher failure load [42]. Fracture load in peel test improves as the tool insertion depth for both plate positions, was greater for AA6063 as top plate. Though, the increase in failure load has a limited effect of tool insertion depth, which leads to convert fracture phenomena from interfacial to circumferential. Tensile shear strength of AA6061 FSSW weld improves with increasing pin length at all rotational speeds as well as with dwell time as shown in Fig. 12.

Pin length influences the stirring of the material hence the heat input to the sheets. At low pin length, the bond length is small owing to low heat input. The situation gets worsen specially at low rotary speed and dwell time. This facilitates shear fracture of nugget hence lower tensile shear strength. While for longer pin, bond length is large due to intense stirring and greater heat input hence large tensile shear strength of weld joints. But this decreases the upper sheet thickness adversely and fracture initiates from minimum thickness region of upper plate. Fracture then propagates along the circumference, decreases effective area resisting the load and causes final shear fracture of weld joints. The tensile shear strength improves as the dwell time and rotary speed enhances. Both these factors resulted in high heat input, higher tensile shear strength, increased bond length and effective area of joint. Cross tension strength of weld doesn't vary with pin length while

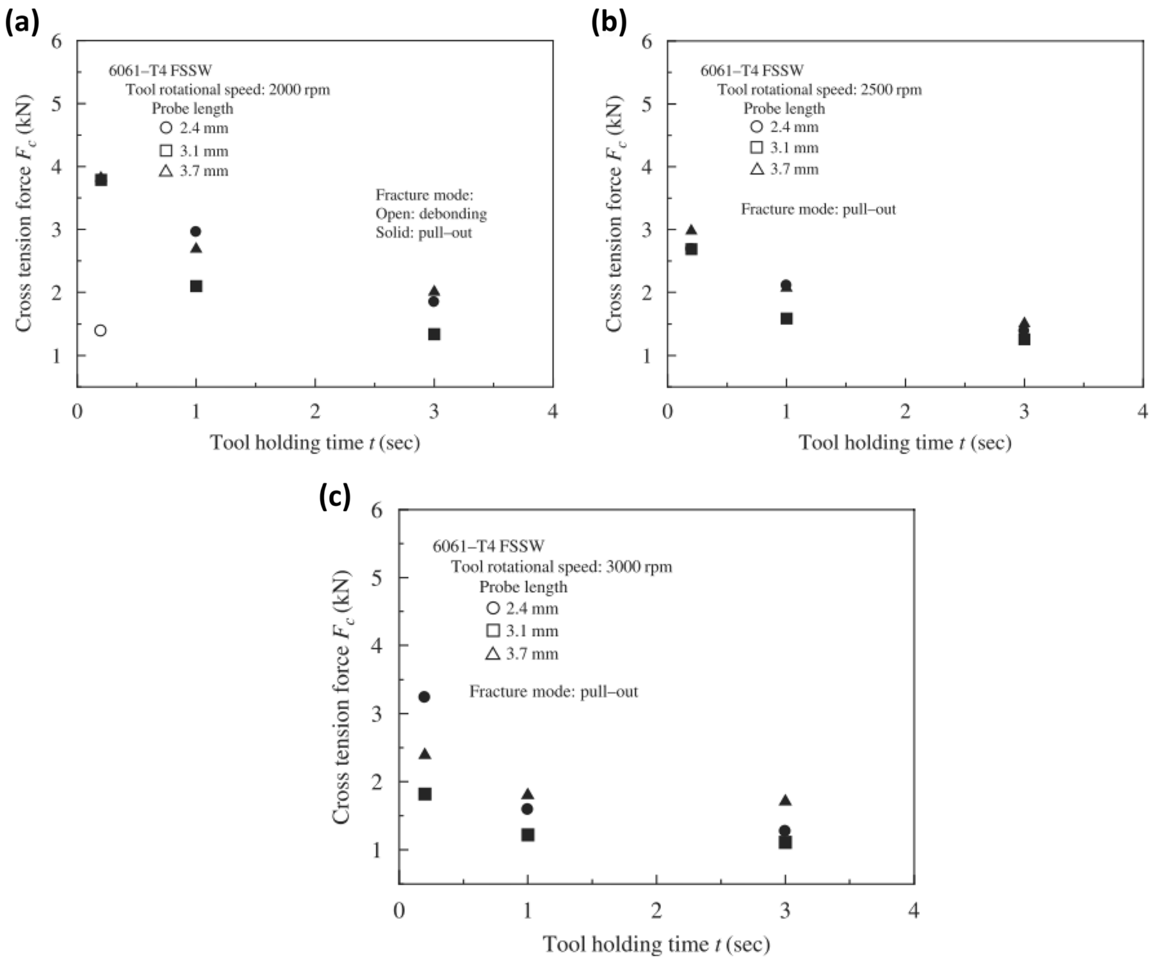


Fig. 12 Influence of pin length on tensile shear strength of FSSW welds on rpm **a** 2000, **b** 2500 and **c** 3000 [41]

it decreases with rotary speed and hold time. With tensile shear loading, fracture mode was either shear fracture of the nugget or mixed mode fracture while for cross tension loading, nugget debonding and pullout were the fracture mode. The mode of fracture depends on the thickness of top plate under shoulder penetration and nugget size [41]. It is possible to improve tensile strength by using innovative techniques such as refill FSSW. The tensile strength of conventional FSSW welds with pin hole was smaller (∼ 30%) than refill FSSW joints. The improvement in tensile strength is due to large effective nugget area because of refilling of pin hole [31].

Fracture mode, location and path are influenced by type of FSSW process [31, 49]. Despite difference in fracture location and path, shear mode of fracture was seen for both types of welds. During tensile shear test, failure of FSSW joints can occur due to (a) shear fracture of hook defect (b) nugget pull out which is the fracture of joint from the bottom of nugget zone. In case of conventional FSSW joint the mode of joint failure is shear fracture of hook defect. Outer circumference of nugget zone showed ridges suggesting the initiation and propagation of failure toward the outer circumference. The presence of large elongated dimples indicates good metallurgical bonding of lower and upper sheets. No change in mode of failure was observed with the increase in shoulder diameter for conventional FSSW joints. In case of FSSW weldments, failure occurred through edge of top and bottom plate at the nugget zone with complete shearing of faying surfaces. Nugget bottom was the site of crack initiation from where crack moves toward the center of weld and along circumferential direction [49]. FSSW joints with pin hole fractured through mixed zone while refilled weld joint fractured along the interface of top and bottom plate and fracture did not penetrate either through the top or bottom plate of the joint [31].

Hardness

The influence of FSSW on hardness of welded joint is governed by the rotary speed, dwell time, base metal type and temper and tool geometry. The microhardness profile of FSSW joints of AA5754 was nearly alike on both side of keyhole. Stir zone microhardness was better compared to both plate metal irrespective of rotary speed and dwell time. Stir zone microhardness was found to decrease slightly with increase in rotary speed and dwell time as both these parameters result in higher peak temperature and coarser grain structure [2]. In another work, the hardness of FSSW joint of AA5052-H112 was influenced negligibly by tool rotation and dwell time [21]. Hardness profile of AA5052 protrusion friction stir spot welds was comparable to FSW as the keyhole is not present and is shown in Fig. 13a.

Though the shape of hardness curve was similar but variation of hardness was distinctly different for upper and lower sheet as clear from Fig. 13a. Stir zone in the upper sheet exhibited hardness higher than lower sheet while an opposite trend was observed for HAZ hardness. As upper sheet is subjected to more plastic deformation than lower sheet, consequently the hardness of stir zone of AA5052 welds is greater. Lower sheet is subjected to lower temperature and higher cooling rate thus the extent of softening is smaller and the HAZ hardness is higher than upper sheet.

Stir zone showed finer recrystallized grains than HAZ, hence, higher hardness of stir zone according to Hall-Patch relation. The average hardness of stir zone decreased with dwell time as evident from Fig. 13 b. Increase in dwell time inputs greater heat to stir zone, raises peak temperature and results in coarser grains on account of prolonged grain growth hence lower hardness of stir zone. Further, hardness and average grain size of the SZ have an inverse linear relationship as presented in Fig. 13c [28].

Typical W shape microhardness profile with significant softening in the HAZ was observed for FSSW joints of precipitation hardening aluminum alloys [53, 54]. FSSW joints of AA6016 showed W shaped microhardness profile and significant softening in the HAZ. With increase in shoulder penetration depth, HAZ moved away from the stir zone owing to greater heat input, also the separation location. Further, no direct relationship between microhardness and separation modes was observed [53].

Tool geometry influenced the microhardness evolution in FSSW joints of AA6016-T4 aluminum alloy welded using tools with conical (HW) and scrolled shoulder (CW) as shown in Fig. 14. Flat and asymmetric microhardness

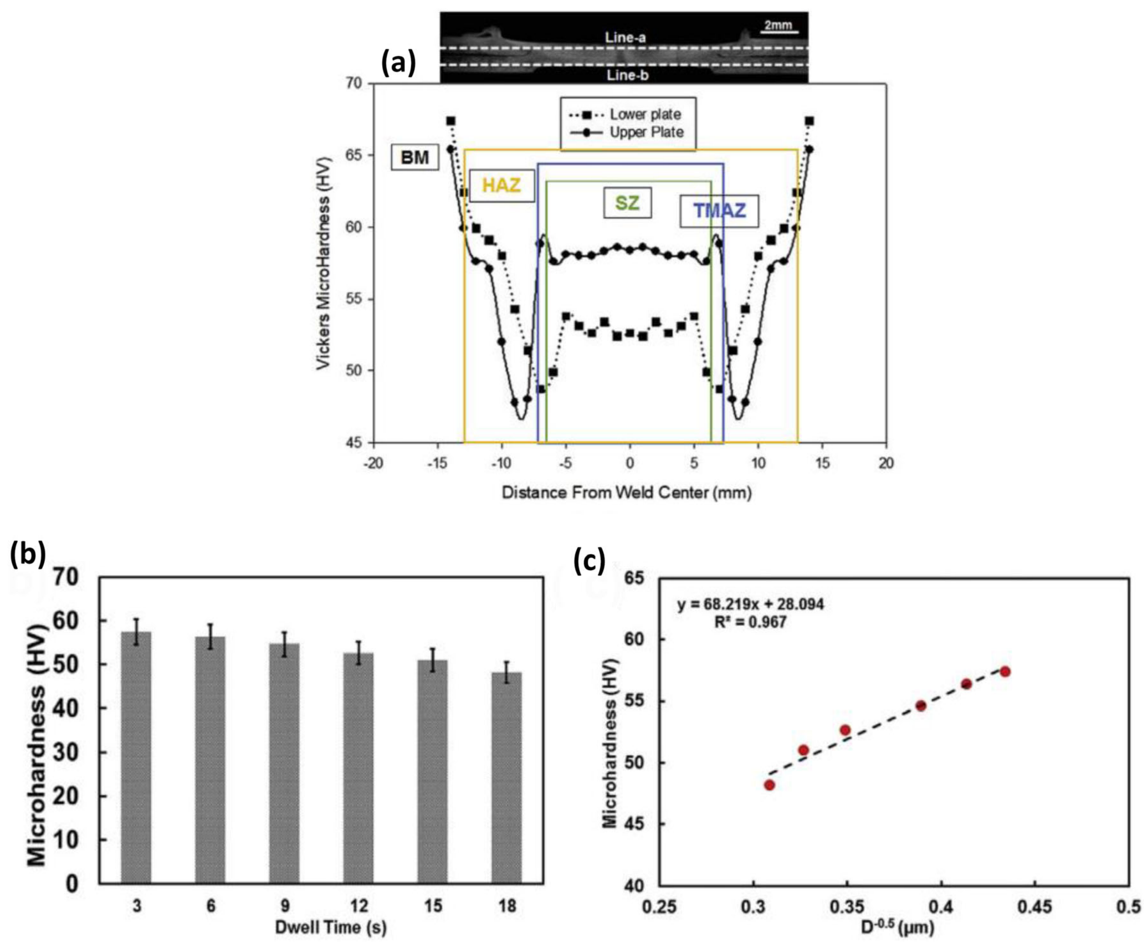


Fig. 13 **a** Microhardness profile, Variation of stir zone microhardness with **b** dwell time and **c** stir zone grain size [28]

profiles were observed for these welds. The microhardness of FSSW joints made with conical shoulder was nearly similar to the base metal while that of scrolled shoulder joints decreased sharply as evident from their flat and asymmetric microhardness profiles.

Decrease in microhardness was observed in a region of 5 mm on both sides from the center of joints made with scrolled shoulder tool. Further, variation in microhardness on advancing side was abrupt than retreating side. This variation of microhardness is due to varying microstructure and precipitate morphology of joints. The joints formed with conical shoulder showed grains of larger size with few coarsened precipitates in weld nugget zone than formed with scrolled shoulder joints which exhibited grains of smaller size and many coarsened precipitates therefore reduced microhardness. The conical shoulder joints were subjected to greater plastic deformation and higher peak temperature completely dissolving cluster of naturally aged precipitates, because of this resulting weld microstructure was similar to base metal. While in case of scrolled shoulder joints, overaged precipitates were seen as incomplete dissolution of preexisting precipitates lead to their coarsening. The asymmetric microhardness of scrolled shoulder joints was due to varying degree of plastic deformation resulting in varying precipitates distribution from inner shear layer to outer retreating side layer [55].

Base metal temper decides whether the region affected by FSSW, i.e., different zones will either be strengthened or softened irrespective of hardening mechanism. In general, FSSW strengthens the weld zones when plates welded are in annealed O temper and vice versa. In annealed condition, strengthening precipitates are dissolved into matrix leaving the base metal in super saturated condition which can't be softened further by welding. Hence, weld hardness/strength should be at least equal to base metal hardness or higher than it. Strengthening mechanism of

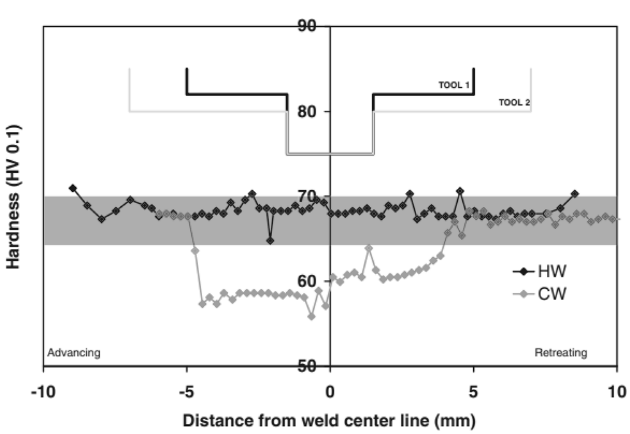


Fig. 14 Effect of tool profile on microhardness profile **a** conical shoulder (HW) and **b** scrolled shoulder (CW) [56]

weld can be explained as follows: (a) weld thermal cycle promotes the uniform re-precipitation of fine precipitates which in turn strengthens the welds of precipitation hardening aluminum alloys. Whereas, for solution hardening aluminum alloys increase in hardness is due to (b) fine grain structure and (c) strain hardening owing to intense plastic deformation. Further, finer the grains higher be the hardness i.e. strength of the material according to Hall-Patch equation.

In general, FSSW joints depicts softened region comprising all the zones when plates welded are in harden condition T or H. However, the degree of softening varied with the location. The loss of strength is because of the following reasons a) grain growth, b) loss of hardening effect, c) dissolution of strengthening precipitates in WNZ and, d) overaging of strengthening precipitates in HAZ. Post FSSW solutionized WNZ ages naturally causing uniform re-precipitation of fine strengthening precipitates which compensate the loss of hardness in WNZ of precipitation hardening aluminum alloys. On the other hand, overaging results in dissolution/coarsening of strengthening precipitates on account of higher prevailing temperature in WNZ/HAZ hence great loos of hardness in these zones. The increase in rotary speed and dwell time both increase the heat generation so as higher peak temperature were observed during welding which in turn results in higher degree of softening and strain hardening for precipitation and solution hardening aluminum alloys respectively. Higher the degree of saturation better the reprecipitation owing to natural aging and improved weld hardness in WNZ than HAZ.

Fatigue

Fatigue strength varies with the type of FSSW process. At low applied load, fatigue strength was nearly same, however at high applied load joints with pin hole exhibited higher fatigue lives than stronger refilled joints. The difference in fatigue lives of joints with pin hole and that of refilled joint can be explained with the help of fatigue fracture behavior. Stress concentration leads to crack initiation at interface of upper and lower sheet for refilled pin hole joints. The upper sheet thickness governed the nugget pull-out or plug type fracture. The increase in effective nugget area which improved the tensile strength, lost usefulness therefore at low applied load, both the joints exhibit similar fatigue strength on account of like crack growth direction and crack length. During refilling, tool shoulder squeezed the pin hole which is responsible for thinning of the upper sheet. Thickness of upper sheet of refill type joints was 726 µm while for joints with pin hole was 906 µm. This thinning of sheet shortened the growth path of cracks growing vertical to loading direction with increasing applied loads. Therefore, joints with refilled pin hole had higher fatigue life than joints with pin hole. Thus, at higher level of loads, refilling improves strength but was harmful to fatigue lives [25]. In case of joints with pin hole, the fatigue crack initiated in bottom plate at lower level of load, possibly due to independent crack growth direction and inability of fatigue crack to enter the upper sheet whereas shear fracture happened through the mixed zone due to nugget pull out irrespective of applied load. For refilled joints, at low applied load fatigue crack propagation into top plate, crack growth around nugget caused the final fracture, due to nugget pull out [57–59].

Summary and Future Scope

As can be seen from the preceding explanation, FSSW, which is essentially a derivation of the FSW process, has a wide range of industrial applications in the joining of a wide variety of sheet and plate components, and many other assembly and advanced manufacturing technologies appear equally appealing, especially if state-of-the-art technology is used. In recent years, a number of major variants of FSSW have been developed to remove or decrease the problem of a keyhole remaining in the workpiece after FSSW, which has a negative impact not only on the aesthetics but also on the joint characteristics. Apart from pinless FSW, its variations are more difficult than traditional FSSW, requiring modifications to the FSSW machine or anvil, as well as extra motion. Various process parameters such as tool pin and shoulder geometry, pin length, tool rotational speed, dwell time, tool penetration depth, and plate position all have a significant but varying effect on not only the microstructure but also other weld properties such as tensile shear strength, fatigue load, and hardness, etc., irrespective of the type of FSSW. Hook is a common geometric flaw in FSSW lap joints that occurs at the plate interface owing to upward bending of the plate interface. Tool profile and other process parameters need to be carefully controlled to reduce the adverse effect of hook defect in weld region on the quality and mechanical performance of FSSW joints hence it is imperative either to control or avoid its formation.

Though the FSSW appears to be a superior option to fusion welding and mechanical fastening, it still takes a significant amount of work to decrease or eliminate keyhole defects without increasing the complexity of the process or the FSSW machine. In addition, because the time required for FSSW is relatively longer than fusion spot welding, a reduction in weld time with enhanced weld quality is being investigated. To make this approach competitive, the relationship between tool life and number of welds must be determined, as well as an economic analysis. Another area of investigation is to see if FSSW can be utilised to weld dissimilar metals in a variety of industrial applications. The development of a suitable guideline for the welding of various combinations of incompatible materials would pave the road for the technique's wider industrial implementation.

Acknowledgements The financial support from the Seed grant under TEQIP-III (TEQIP/181/2020) from BIT Sindri is gratefully acknowledged.

Funding The funding was provided by BIT Sindri, SEED grant under TEQIP-III (TEQIP/181/2020).

Compliance with Ethical Statement

Conflict of interest The authors declare that they have no conflict of interest.

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