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A study of Friction stir welding with influence of tool variables

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Abstract

The innovative technology known as friction stir welding (FSW) is gaining popularity for joining metals and their alloys. FSW made it simple to join materials that are challenging to join because of flaws that develop during the joining process, like porosity and partial penetration. Innovative solutions are required to meet the transportation department's high speed and energy-saving demands in order to meet increased productivity and cost-saving requirements. The increasing demand for lightweight structures has led to a rise in popularity for materials with a higher strength to weight ratio. Numerous industries, including transportation, railroads, aerospace, maritime, construction, and many more, could benefit from the use of the FSW. This study article's goal is to demonstrate how tool factors affect the field of FSW. This work has studied the impact of tool factors, including FSW tool geometry, tool material, and desirable qualities, and critically examined the FSW tool. In spite of this, there is still much to learn about the processes, and new study possibilities are noted.

Keywords: Innovative technology, FSW, Energy-saving,

1. **Introduction**

The discovery of gold round boxes during the Bronze Age gave rise to the joining techniques. Boxes were anticipated to be constructed using a welding procedure. Three thousand-year-old tools and weaponry were discovered in Egypt[1].These objects were made of iron and bronze. These objects appear to have been created using forge welding. With traditional welding procedures, alloys may be joined with ease. Nonetheless, imperfections like as porosity, fissures, insufficient fusion, inadequate penetration, and environmental issues contribute to the advancement of specialized processes. Friction stir welding (FSW) is one method of preventing or minimizing these faults[2]–[4]. FSW emerged in 1991 by the Welding Institute (TWI)[5]. This method was developed from traditional friction-welding methods. Almost every shape of component, including pipes, T sections, hollow sections, and flat shapes, can be joined using FSW. Since effectively combining aluminium alloys, FSW has now gained a lot of popularity for joining titanium, magnesium, and metal matrix composites[6], [7].FSW is also used to combine steel with increased strength to plastic[8]. The use of FSW is constantly growing in a number of engineering domains, including high-speed rail, aircraft, cars, and marine. Because of their advantages over traditional welding techniques, FSW variants like friction stir additive manufacturing, friction stir processing, friction stir welding utilizing interlayer, friction stir channelling, and friction stir spot welding are also becoming more and more popular among researchers[9]–[14].The workpiece is fixed firmly on the fixture to avoid object displacement. A non-recyclable rotating cylindrical tool was inserted into the work piece's adjacent edges. Heat generation results from the friction between the work piece and the FSW tool. As a result of which the material that comes into contact softens. The process zone was obtained behind the tool end when the non-consumable rotating tool moved longitudinally along the workpiece's abutting edges. The heat allows for the plastic deformation of the workpiece. The FSW joint is made feasible by the mixing of the plastically deformed metal from the back to the front. Fig. 1 provides an illustration of the FSW procedure. When the tool's rotational motion aligns with the traverse direction, it is referred to as the advancing side; when they diverge, it is referred to as the retreating side.

Base metal, heat affected zone (HAZ), thermo mechanically affected zone (TMAZ), and stir zone (SZ) are the four zones that make up the FSW processing region. Four actions are taken by the FSW tool when it comes into contact with the work piece: plunge-in, dwell, traverse, and retract[1].The foundations of FSW and the impact of tool variables on the FSWed joints are critically reviewed in this work. A logical order is used to present the many tool elements so that readers can come to a meaningful conclusion. The essay begins with the evolution of welding historically, the advent of FSW, and the process parameters and how they affect the mechanical characteristics of friction stir welded connections. Next, a brief discussion of the effects of tool variables such tool shape and material follow. In order to help readers, a summary is provided at the conclusion of this piece.

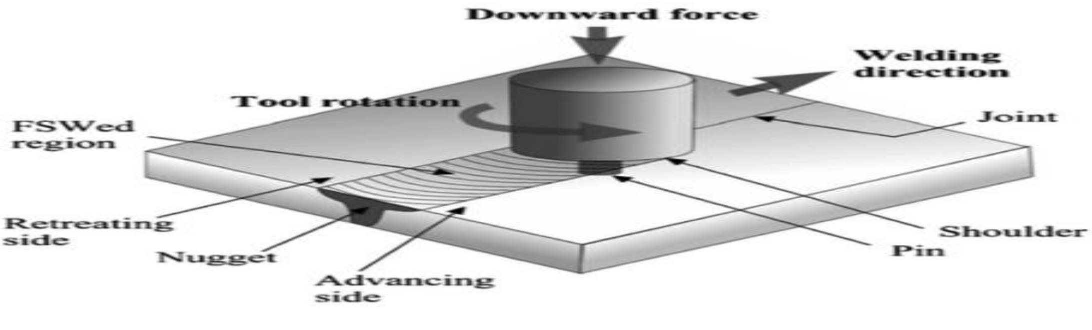

Fig. 1. Illustration of FSW process [15].

2. Influence of process parameters on FSW

The mechanical characteristics and micro structure of the FSWed joint are determined by many FSW process parameters, including material attributes, machine variables, and tool variables. The FSW parameters determine the FSWed joint's strength as well. Temperature distribution and material flow pattern are governed by these characteristics. In the FSW process, the material flow is extremely intricate. The FSW process involves a highly complex material flow that varies based on the range of process parameters from trial to experiment. There is very little knowledge about this material flow during FSW. The FSW process parameters shown in Fig. 2 regulate the quality of the weld[16]–[20].Optimizing these process settings could result in the production of the defect-free FSWed joint.

The weld quality is greatly impacted by the welding parameters, including plunge, tilt angle, traverse speed, and rotation speed of the tool. The mechanical characteristics and microstructure of the FSWed joint are also governed by the tool variables, which include tool material, tool shoulder dimension, tool probe and shoulder to probe diameter. Tool geometry out of all the process variablesis the most important in determining the FSWed joint strength because it influences the flow of material throughout the welding process. The FSW tool geometry was initially straightforward and limited both the welding speed and the mixing of the materials during the welding process. Subsequently academics have made significant strides to improve it for commercial uses.

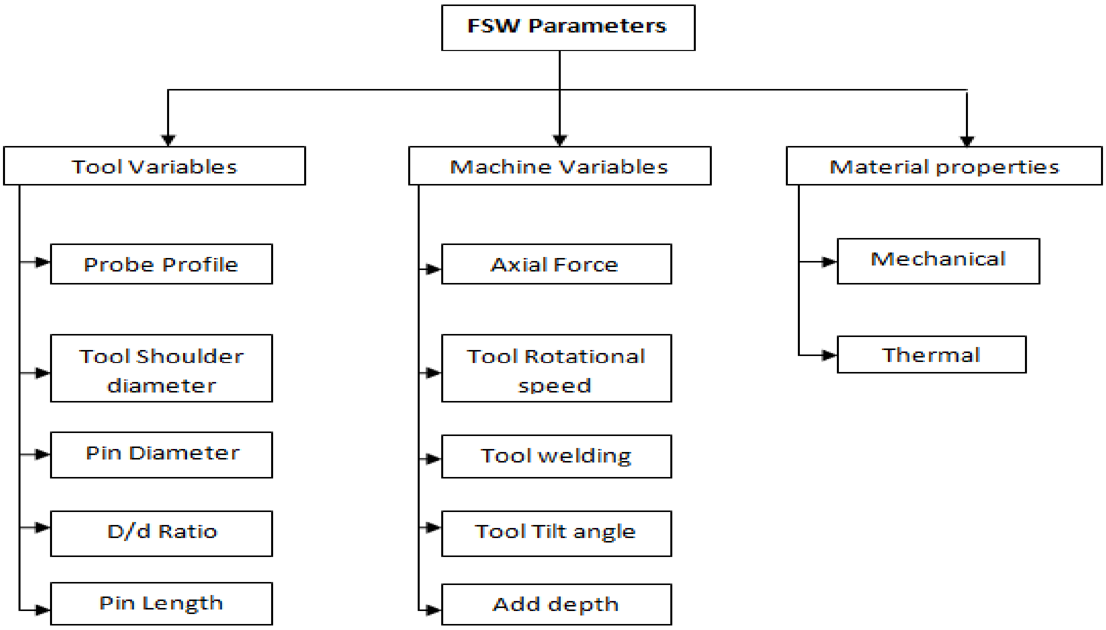

Fig. 2. Illustration of FSW parameters[1].

3. Influence of tool variables :

The microstructure and mechanical characteristics of the FSW joint are significantly influenced by the tool variables. Material flow rate is determined by the geometry of the tool. The FSW tool guarantees material flow, heat generation and metal plastic deformation[21], [22].Heat from friction softens the material. By using the FSW tool shoulder, the material is reconsolidated. The fundamental purpose of the FSW tool is to heat the base metal (BM) in order to improve material flow and plastic deformation. The tool rotation speed (TRS) controls how the material is mixed and stirred.Because more heat is generated, increased TRS causes more stirring and mixing. Heat input is significantly impacted by the FSW process parameters, including tool rotation speed, applied force and tool shoulder diameter (TSD).The probe's diameter, shoulder diameter, length and shape are all included in the FSW tool variable. The diameter of the tool shoulder significantly affects heat generation and leading to a flawless FSWed joint. Heat input is significantly impacted by FSW process parameters such as applied force, tool rotation speed and shoulder diameter[22].Regardless of other factors, the increased shoulder diameter raises the heat input when the FSW tool's contact area with the base metal (BM) increases. An ideal TSD value results in a flawless FSWed joint. According to a number of studies TSD and BM thickness follow a straight line equation[23].A sound and defect-free joint can be achieved in part by using the FSW tool design. Shoulder, probe, body and shank make up the geometry of the FSW tool. Warming and agitating the workpiece is the FSW tool's primary purpose[24].The primary factors determining the quality of the weld are the geometry of the tool shoulder and probe. The FSW joints quality is determined by the probe and shoulder designs. A key factor in assessing whether a tool is appropriate for a given application is the choice of tool material. A typical example of an FSW tool is shown in Fig. 3.

3.1. Effects of FSW tool shoulder :

The design of the FSW tool's shoulder diameter increases the workpiece's deformation and frictional heating.Concave shoulder shapes are the most prevalent for FSW tools. During FSW, the concave shape minimizes material extrusion from the sides. Researchers were drawn to this design because of this feature[24]–[27].Concavity in the FSW tool shoulder is simple to create. What the concave shoulder does is serve two purposes. When the material is displaced during the plunge-in process by the FSW tool probe, gather it into the cavity. During the FSW tool's traversal speed, the work-piece material is pushed behind the tool probe. Giving the FSW tool a tilt of roughly 2-4˚ would increase the effectiveness of the aforementioned action. According to Chen et al., convex tools enhance metal flow[28].It has been observed that in the stir zone, the mean grain size increases as the tool rotation speed increases when using a convex tool[29]. In the stir zone randomizing the convex tool produces the desired tensile behaviour. The impact of tool shoulder features on the microstructure and mechanical characteristics of the FSWed joint was investigated by Trueba et al[30].In this work, AA6061-T6 alloys underwent FSW, and the metal flow of the FSWed joint was examined. For this investigation, six FSW tools produced via additive manufacturing were utilized.

Following a successful FSW, the microstructure and mechanical characteristics were assessed. It was stated that, when compared to other tools, the FSW tool with a raised spiral design produced excellent results. The impact of the tool shoulder feature on the 6082 aluminium alloy was examined by Mugada and Adepu[31].A featured tool was said to lessen the axial force during FSW. Utilizing a tool with shoulder features also results in increased heat generation[32].Reduced axial force during FSW and superior mechanical properties are the outcomes of the tool shoulder with ridges feature.

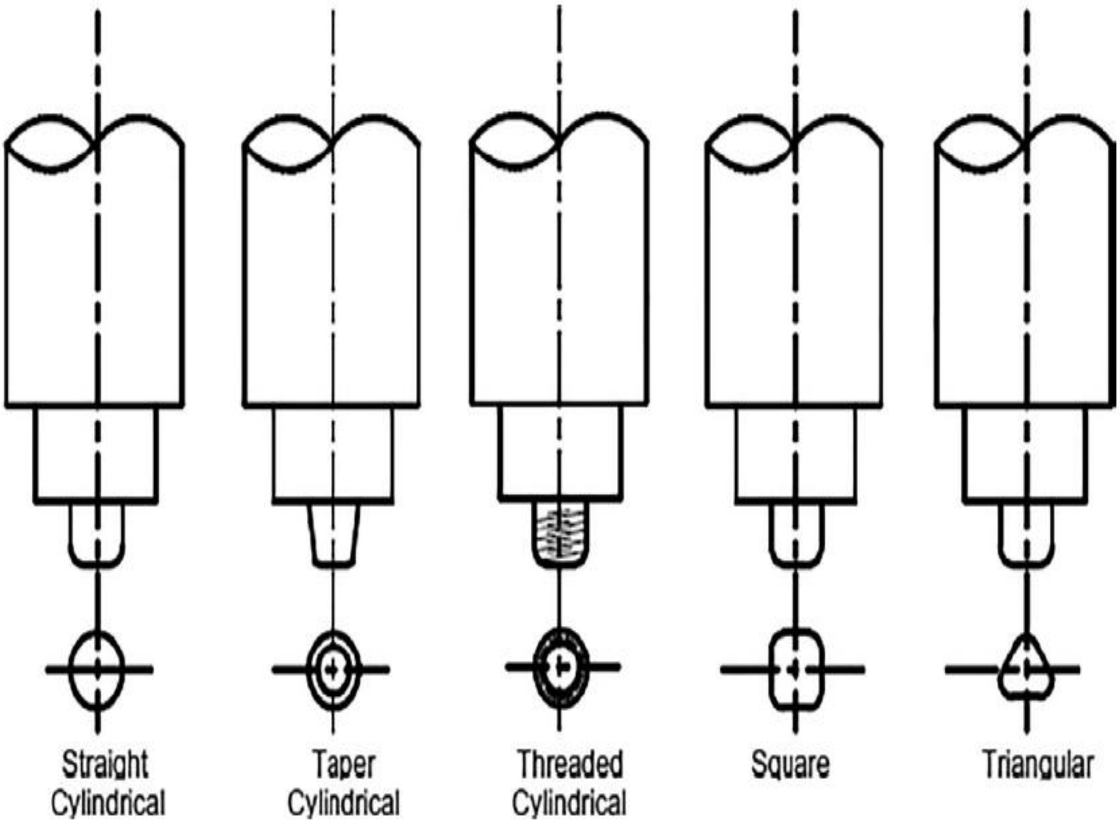

Fig. 3. Common type of FSW tools[33].

3.2. Effects of FSW tool probe :

The FSW tool probe's purpose is to cause frictional heating and deformation. It was completed by shearing the material of the work piece and disturbing its surface[34]. Fig. 4 shows the different forms of probes. The probe end can be domed or flat in shape. Although it is simple to manufacture, the flat end probe is subjected to high force during plunge-in, which causes FSW tool wear. Making the tool domed type increases tool life by reducing force. According to Aissani et al., a cylindrical outer surface is used to create a tool probe for FSW work pieces that can be welded up to 12 mm thick[35].Because it increases the contact area, tapered tool probes are frequently used to weld thick plates. The frictional heat generated by the larger contact area causes more plastic deformation. The FSW tool probe's increased contact area and subsequent increase in frictional heat are caused by its various shapes, such as threads and flutes, in addition to its flat shape. It causes more plastic deformation[8], [36].Increased material stirring is caused by the threads. A better understanding of material flow through the most recent research studies has lead to significant advancements in probe geometry recently. Using MX Triflute and Whorl probes can lower the welding force[37].Moreover, this facilitates the flow of plasticized material. The growing area between the FSW tool probe and the work-piece material causes more heat to be produced[1].The FSWed 6061 joint's microstructure and mechanical characteristics were examined. In this experimental work, probe profiles such as square, cylindrical, threaded tapered and triangle were used. When compared to other probes, response from the triangular profile was excellent. The relationship between heat produced, forge force, and rotational speed is represented by the equation[37].

q0 ¼ 4=32lPxR3

The existing research studies lead to the conclusion that the FSW tool shoulder diameter is 2.2 times the FSWed plate thickness plus an additional 7.3 mm constant. With an extra constant of 2.2 mm, the FSW tool probe is 0.8 times the thickness of the work piece[38].The FSW tool shoulders to probe diameter ratio is typically used in a ratio of 3[1].

4. Friction stir welding tool material :

Tool wear is an aspect that must be taken into account before choosing a material for the FSW tool. The work piece that needs to be welded determines which FSW tool material should be used for the FSW of aluminium alloys, dissimilar welding and other alloys. Tables 1, 2, and 3 shows the FSW tool geometry, tool materials and welding variables respectively. Higher yield strength, wear strength, co-efficient of thermal expansion, dimensional stability and other characteristics must be confirmed before selecting the material.

4.1.Carbides and metal matrix composites:

When choosing carbide as an FSW tool material, desirable attributes like wear resistance and fracture toughness are important[39].Carbines work better at higher temperatures which make them useful as a friction stir welding tool[40].Metal-matrix composites (MMCs) brittleness causes fractures when friction stir welding tools are plunged.

4.2. Refractory metals :

These materials ability to tolerate higher temperatures makes them suitable for use in the FSW tool. Typically, tungsten, niobium, tantalum and molybdenum are utilized to create the FSW tool. Using alloys based on tungsten, titanium, steel and copper can be friction stir welded with ease. Cobalt is added to tungsten as an alloying element to increase its durability[41].Refractory material is more expensive, more difficult to obtain and more challenging to machine which limits its uses as an FSW tool.

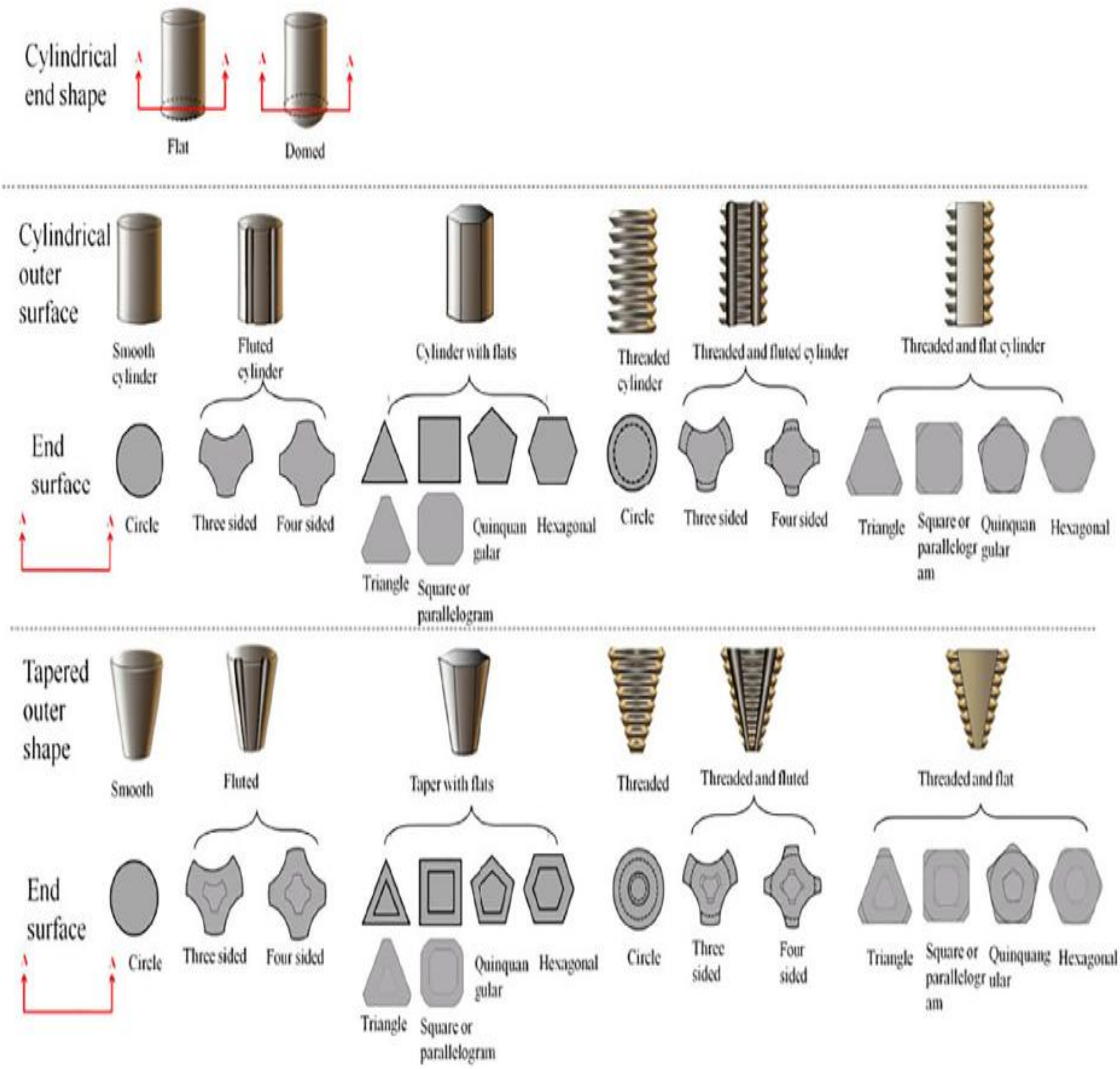

Fig. 3. Common type of FSW tools[33].

Table 1

Base metal, tool materials, welding parameters used for FSW of Al- alloys.

Investigators	Base & Tool Material	Tool geometry	Operating parameters	Remarks

Hariri et al. [42]	AA5052 H-13 steel	SD-20, TC BD-5	TA-2.5 WS-50-250mm/ min RS-400-2500 rpm Plunging force-800 kg	Optimum corrosion& mechanical properties
Morisada et al.[43]	5083-0 and 6061-T61050-H24	PL-4.7 PD-6 SD-15	TA-3 WS-100-700,100-1000 &25-200 mm/min respectively	For 1050 columnar tool without threads produces weld with the best mechanical properties.
Chengchao et al.[44]	6061-T6 H-13 steel	SD-30 PD-16 PL-15.8	TA-2.5 WS-120 mm/min RS-500,700&900 rpm Axial force-15,18&22 KN	The average microhardness of the FSW weld zone is lower than that of the base material.
Xu et al[45]	2219-T62 H-13 Steel Threaded & Tapered with three spiral flutes with triangle	SD-26 Threaded P-5.9-11.8 PL-11.7	TA-2.5 WS-60-100-mm/min RS-300-500 rpm	Thermo-mechanically affected zone and boundary were more optically distinct on the advancing side.
Yuqing et al. [46]	AA7075 H-13 die steel	TL-19.5 SD-42 Plunge-0.5	Tilt-2 WS-47.5 mm/min Rs-300 rpm	Improved plastic flow gave defect-free joints stronger stirring power and pulsating action reported.

Note: SD: Shoulder diameter; PL: Pin length: PD: PIN DIAMETER; TC: Threaded conical; TL: tool length; TA:tilt angle; BD: base diameter; WS: welding speed; RS: rotational speed (all dimensions are in mm).

Table 2

Base metal, tool materials, welding parameters used for dissimilar FSW of AL alloys.

Investigators	**Base & Tool Material**	**Tool geometry**	**Operating parameters**	**Remarks**
Simar et al.[47]	AA2017-6005A	SD-15 PD-8 PL 5.7 Threaded Flute	WS-200 mm/min RS-1000 rpm	Comparatively strong dissimilar weld. Localization of deformation at 60005A side results in reduces ductility.
M. Koilraj et al.[48]	AA2219- AA5083 75x125x5	H-13 steel SD-15 FSTP6-4 TA-2^0	WS-30-750mm/min RS -400-2000 rpm Tool offset-2 to +2	97% joint efficiency obtained. Welding parameters affect mixing in nugget zone.
Khodir et al.[49]	2024-T3 7075-T6	SD-12 PD-4[49] Threaded pin	WS-0.7-3.3mm/sec RS-20 rps	Welding speed increases hardness. Tensile strength was obtained 423 MPa at 1.7 mm/Sec.
Zhang G. et al.[50]	AA2024-T6 AA7075-T6 150x75x5	D/d-2 to 4	WS-12mm/min RS-1200 rpm	356 Mpa tensile strength obtained at 3 D/d ratio. Max hardness obtained at stir zone(151 HV).
Cavaliere et al.[51]	AA2024-T3 AA7075-T6 T-2.5 mm	D-20 d-6 PL-2.5 TA-3^0	WS-2.67 mm/ sec	No macroscopic defect was found. Excellent joint properties reported.

Table 3

Base metal, tool materials, welding parameters used for dissimilar FSW of other alloys.

Investigators	**Base & Tool Material**	**Tool geometry**	**Operating parameters**	**Remarks**
Woo and Choo[52]	AZ 31 B-H24 AZ91 D AA6061-T6	Tool steel SS SD-19 TA-1^0	WS-1.5 mm/s RS-2000rpm	No porosity reported. Homogenous, fine-grained and equiaxed structure reported.
Firouzdor and Kou [53]	AA6061-T6 AZ31 B-H 24 Mg	H 13 SD-10 PD-4,PL-1.3	WS-38 to 305 mm/min RS-1000-2200 rpm	Welding conditions affect the heat input. Formation of intermetallics and material flow depends on heat input.
Sahu et. Al [54]	1050 Al alloy and pure Cu plates 150x100x4	H13 tool steel SD-25 PD-6 PL-3.5	WS-20-40mm/min RS-600-2400 rpm Tool offset-0.5 to 2 mm	Excellent mechanical properties reported as specific critical offset towards the aluminium side. The maximum UTS reported 95% of the BM.
Jiang and kovacevic[36]	6061 AISI 1018-T-6	H13 tool steel S-25 PD-5.5	WS-140 mm/min RS -914 rpm Tool offset-0.5 to 2mm	Average hardness was substantially higher of nugget Al- Fe intermetallic compounds formation reported.
Genevois et al.[55]	AA1050-H16 ASTM A-284 T-4	SD-20 PD-6.5	WS-100 mm/min RS-900 rpm	82 MPa tensile strength was obtained. At joint interfaces higher joint strength obtained with intermetallic reaction layers.
Liu et al.[56]	6061-T6511 TRIP 780/800 Steel T-1.5	Tungsten carbide with 10% cobalt content, SD-	WS -90 mm/min RS-1800 rpm	Maximum UTS reported about 85% of BM. IMC layer contributed for the

		12.7,PD-2.5		joint strength.

Table 4 : Characteristics of FSW tool materials.

Tool Material	Advantages	Disadvantages	Remarks
AISI H13	Good machinability	High tool wear	Wear resistance improved by surface hardening
AISI 4340	Strength at elevated temperature	Severe tool wear	Probe shape can be optimized
Ni/ Co	Excellent strength & corrosion resistance	Precipitate overaging and dissolution	Used for Al and Cu alloys
Nimonic 90,105 refractory metals	Melting temperature is quite high	Ductility degradation is possible	Used for Ni alloys and other high melting point alloys
MMCs and carbides	Excellent wear resistance	Not for use with Cu alloys	Probe without thread is used
PCBN	Excellent hardness	Welding depth limit on use	Used for wear resistance material

4.3. Nickel and cobalt based alloys :

Because of their exceptional strength and ability to withstand corrosion, nickel and cobalt alloys are used in aerospace and aircraft. Because of precipitate dissolution and excessive aging, the temperature range for nickel and cobalt alloys is 600–800 C. Nimonic 90, IN738LC, Stellite12, and Nimonic 105 can form the sound FSW joint of copper alloys. Due to its ease of machining, MP159 is utilized to create FSW joints in the 7XXX series of aluminium alloy[5].Superalloys low machinability restricts the intricate probe-making (25).

4.4. Tool steel :

One FSW tool material that is frequently used for welding aluminium alloys is tool steel. Because of its advantageous qualities, such as wear resistance, thermal fatigue and high strength at elevated temperatures, AISI 13 is the most commonly used tool steel[57].The features f FSW tool materials are shown in Table 4.

5. Conclusion:

Over the past 20 years, there has been significant advancement in the field of FSW tools.To adjust the characteristics of the FSW joints, a number of researches employed different FSW tool shoulders and probes. Researchers work very hard to create innovative FSW tool materials and tool designs for particular uses.While titanium, nickel and steel are used to make FSW tools with higher strengths and for low strength material other materials used to make FSW tools because of their low cost.With an increase in the contact area between the FSW tool and base metal (BM), the increased shoulder diameter increases the heat input independent of other parameters.A fault-free FSWed joint is produced by using the optimal TSD value. The strength at elevated temperatures, wear resistance, low coefficient of thermal expansion and corrosion resistance of tool materials are factors that impact the required strength and weld quality of FSW joints.

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