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A Brief Review on Friction Stir Welding Tool

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Abstract—*Friction stir welding (FSW) is a significant manufacturing process for producing welded joints in solid state. In the present scenario FSW is regarded as a mature process for joining of ductile materials such as Al and Mg alloys across the many industry sectors. For the joining of high softening temperature materials such as steels, nickel alloys and titanium alloys, the FSW has potential applications because of developments of new generation FSW tool materials (polycrystalline cubic boron nitride, Ceramic). FSW tool materials should possess a challenging combination of properties such as high temperature strength and toughness, thermal and chemical stability and oxidation resistance to survive in the high temperatures. The role of tool geometry profoundly affects the weld quality and cost. Proper selection of a tool material and shape of the pin reduces number of trials and tooling cost. Here we review and examine several important aspects of FSW tools in terms of the tool types, shapes, dimensions and materials.*

Keywords: *Friction Stir Welding Tool, Tool Materials, Tool Design.*

1. INTRODUCTION

Friction stir welding is a solid state welding processes, this remarkable up gradation of friction welding was invented in 1991 in The Welding Institute (TWI) .

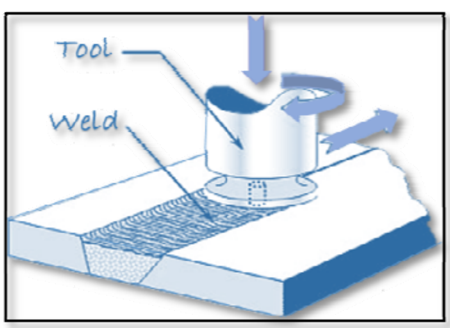

Fig. 1: The friction stir welding process [1]

The process starts with clamping the plates to be welded to a backing plate so that the plates do not fly away during the welding process. A rotating wear resistant tool consisting of a shoulder and probe is plunged on the interface between the plates being welded to a predetermined depth and traverse along the weld line. Frictional heat is generated between the mating places. During traversing, shoulder will stir the material from advancing side to retreating side at a contact surfaces. As a result the material will soften and get plasticized [1, 20]. FSW is often a preferred joining technique not only for aluminum alloys but also for other difficult-to-weld metals such as magnesium alloys, titanium alloys and metal-matrix composites to overcome limitations of fusion welding such as solidification, cracking, occurrence of micro porosity leading to a weaker joint or loss of joint strength. The welds are made below the melting point in the solid phase. The excellent mechanical properties and low distortion are attributed to the low heat input and the absence of melting [2, 23].

2. THE FUNCTION OF TOOL

The friction stirring tool consists of a pin (probe) and a shoulder. The pin plunges into the mating place of the workpiece creates frictional and deformational heating and softens the workpiece material; contacting the shoulder to the workpiece increases the workpiece heating, expands the zone of softened material, and constrains the deformed material [3]. The following Fig. 2 shows the parts of FSW tool

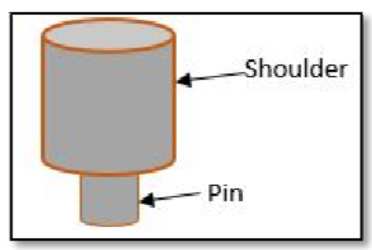

Fig. 2: Parts of friction stir welding tool

Naturally, there are important effects to the tool during welding: high temperature, abrasive wear and dynamic effects. Therefore, the good tool materials must satisfy some properties such as:

- Good wear resistance
- High temperature strength, temper resistance
- Good toughness.

3. TOOL MATERIALS

Production of a quality friction stir weld requires the proper tool material selection for the desired application. Thus, it is undesirable to have a tool that loses dimensional stability, the designed features, or worse, fractures [3]. There are several tool materials to use depending on the base material, tabulated in Table 1 and described as follows:

3.1 Tool steels

The most commonly used material, easy availability and machinability, thermal fatigue resistance, wear resistance. Materials such as aluminum or magnesium alloys and aluminum matrix composites (AMCs) are commonly welded using steel tools. AISI H13, a chromium molybdenum hot worked air hardening steel, has been the most commonly used [3, 4].

3.2 Polycrystalline cubic boron nitride (PCBN)

PCBN tools owing to high strength and hardness at elevated temperatures along with high temperature stability. It's a preferred tool material for FSW of hard alloys such as steels and Ti alloys. Because of low coefficient of friction a smooth weld surface can be obtained. However, due to high temperatures and pressures required in the manufacturing of PCBN tool, the tool costs are very high [4, 5].

3.3 W based tools

Commercially pure tungsten (cp-W) is strong at elevated temperatures but has poor toughness at ambient temperature, and wears rapidly when used as a tool material for FSW of steels and titanium alloys [4].

3.4 Carbide particle reinforced metal composites (WC, WC-Co, TiC)

Superior wear resistance, reasonable fracture toughness

3.5 Nickel- and cobalt base alloys

High strength, excellent ductility, hardness stability, creep resistance. These alloys derive their strength from precipitates, so the operational temperature must be kept below the precipitation temperature [3].

Table 1: Tool materials for different base materials [3]

Alloy to be welded	Tool material
Aluminium alloys	Tool steels, Co-WC composites
Magnesium alloys	Tool steel, WC composite
Copper alloys	Ni-alloys, W-alloys, PCBN, Tool steels
Titanium alloys	W-alloys
Stainless steels	PCBN, W-alloys
Nickel alloys	WC composite, PCBN
Low-alloy steels	PCBN

4. TOOL TYPES

There are basically three types of FSW tools, i.e. fixed, adjustable and self reacting tools as illustrated in Fig. 3

The fixed probe tool corresponds to a single piece comprising both the shoulder and probe (Fig. 3a). This tool can only weld a workpiece with a constant thickness due to the fixed probe length. . If the probe wears significantly or breaks, the whole tool must be replaced. The adjustable tool consists of two independent pieces, i.e. separate shoulder and probe, to allow adjustment of the probe length during FSW (Fig. 3b). In this design, the shoulder and probe can be manufactured using different materials and the probe can be easily replaced when worn or damaged. Moreover, the adjustable probe length can allow welding of variable and multiple gauge thickness work pieces. Both the fixed and the adjustable tools often require a backing anvil. The bobbin type (self-reacting) tool (Fig. 3c) is made up of three pieces: top shoulder, probe and bottom shoulder. This tool can accommodate multiple gauge thickness joints due to the adjustable probe length between the top and bottom shoulders. No backing anvil is needed but the bobbin type tool can only work perpendicularly to the workpiece surface. But in case of the fixed and adjustable tools can be tilted longitudinally and laterally [5].

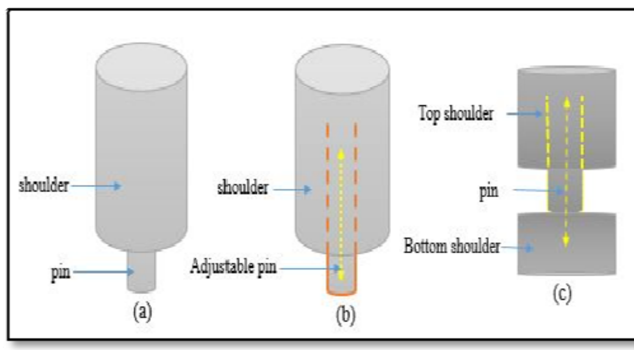

Fig. 3. a. Fixed, b. Adjustable and c. Bobbin type tool

5. TOOL GEOMETRY

Tool geometry has a great influence on resulting mechanical properties of the weld. It provides in-situ heating, stirs base material, and thus creates weld.

5.1 Tool shoulder shapes

Tool shoulders are designed to produce heat to the surface and subsurface regions of the workpiece. Particularly the tool shoulder produces a majority of the deformational and frictional heating in thin sheets. So proper geometry for shoulder is necessary. Types of shoulders are given in Fig. 4 and described as follows [3, 6]:

5.1.1 Concave shoulder

The shoulder concavity is produced by a small angle between the edge of the shoulder and the pin, between 6 and 10°.

During the tool plunge, material displaced by the pin is fed into the cavity within the tool shoulder. Forward movement of the tool forces new material into the cavity of the shoulder, pushing the existing material into the flow of the pin. Proper operation of this shoulder design requires tilting the tool 2 to 4° from the normal of the work piece away from the direction of travel [3].

5.1.2 Convex shoulder

The convex shape pushed material away from the pin. These tools for thicker material were only realized with the addition of a scroll to the convex shape. The scrolls on the convex shoulders move material from the outside of the shoulder in toward the pin.

5.1.3 Shoulder features: The FSW tool shoulders can also contain features to increase the amount of material deformation produced by the shoulder, resulting in increased work piece mixing and higher-quality friction stir welds. These features can consist of scrolls, ridges or knurling, grooves, and concentric circles and can be machined onto any tool shoulder profile. Scrolls are the most commonly observed shoulder feature. The channels direct deformed material from the edge of the shoulder to the pin, thus eliminating the need to tilt the tool [3, 16].

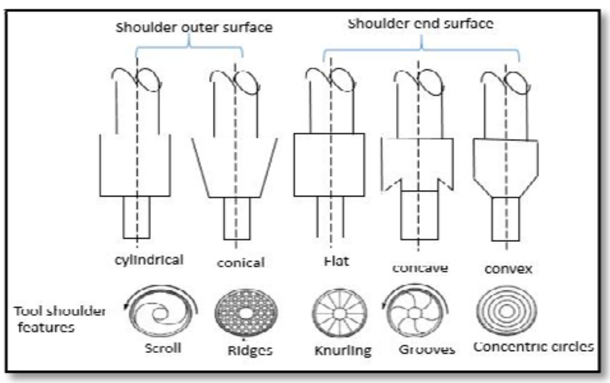

Fig. 4: Shoulder shapes and features

5.2 Tool pin shapes

The pin is designed to disrupt the faying, or contacting surfaces of the work piece, shear material in front of the tool, and move material behind the tool. In addition, the depth of deformation and tool travel speed are governed by the pin design. Different types of pin profile as shown in Fig. 5 and explained in details below [3, 16-23]:

5.2.1 Round-bottom cylindrical pin

A round end to the pin tool reduces the tool wear upon plunging and improves the quality of the weld root directly underneath the bottom of the pin. The best dome radius was specified as 75% of the pin diameter. Machining a radius at the bottom of the threads will increase tool life by eliminating stress concentrations at the root of the threads.

5.2.2 Flat bottom cylindrical pin

The friction velocity of a rotating cylinder increases from zero at the center of the cylinder to a maximum value at the edge of the cylinder. The local velocity coupled with the friction coefficient between the pin and the metal dictates the deformation during friction stirring.

5.2.3Truncated cone pin

A simple modification of a cylindrical pin is a truncated cone. Truncated cone pins have lower transverse loads (when compared to a cylindrical pin), and the largest moment load on a truncated cone is at the base of the cone, where it is the strongest.

5.2.4 MX triflute pin

It contains three flutes cut into the helical ridge**.** The flutes reduce the displaced volume of a cylindrical pin by approximately 70% and supply additional deformation at the weld line in addition it increases the tool travel speed . It can be used advantageously to welding thick section aluminum alloys.

5.2.5 A-skew

The effect of this pin geometry is similar than MX triflute. It increases travel speed, improves the tensile properties of the weld, and reduces the weld asymmetry

5.2.6 Trivex pin

It produced an 18 to 25% reduction of traversing forces and a 12% reduction in forging (normal) forces in comparison to an MX triflute pin of comparable dimensions.

5.2.7 Thread less pins

These are useful in specific FSW applications. Tools operating under aggressive environments can't retain threaded tool features without excessive pin wear. Pins for these conditions typically consist of simple designs with robust features.

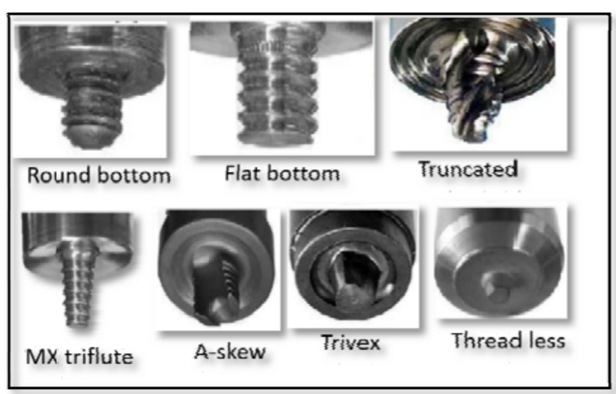

Fig. 5: Different types of pin profiles [3]

6. TOOL DESIGN

It was realized in the development of the FSW process that the tool design is critical in producing sound welds [1]. The working tool is a one of the major part In FSW process. The tool is consists various design specification according to types of work, which material to be joined, thickness of the plate or sheet. The tool is containing profile pin and tool shoulder. The shoulder is took place bottom of the profile pin. The face of the pin only penetrates into the working materials. The function of the tool shoulder is control the material flow and pin is deforming the grain size of the working material during operation [7].

Hidetoshi fujii et al. has used three types of tool (Fig. 6) to join the materials of 1050-H24, 5083-O and 6061-T6 aluminum alloys to make a butt joint. The diameter of the triangular prism and the other two types of columnar probe were had a same diameter of 6mm.length of the all profile pin were 4.7mm and a thread specification is 0.5mm pitch with respect to clockwise direction..

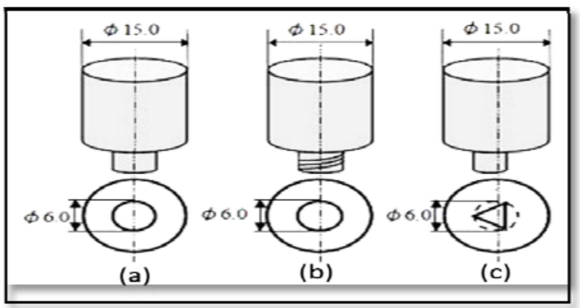

Fig. 6 (a) without threads (b) with threads (c) Triangular prism tool

End of this result, a columnar without threads tools only achieved a good weld with compare with other types of tool like columnar with threads and triangle prism tool. Because columnar without thread tool shape only reduces the defects less than triangle prism and columnar with threaded tool. [8]

G.Buffae et al. conducted a friction stir welding of 1.5mm thick plate of aluminum alloy AA6082-T6 with use of H13 steel quenched tool at 1020˚C and hardness of the tool was 2HRC, diameter of tool shoulder was 15mm with a 40˚ conical pin. The profile pin had a major diameter of 7mm and 2.2mm of minor diameter. Height of the conical pin is 2.6mm [9].

K.Kumar et al. examined AA7020-T6 aluminum 4.4mm thick FSWed plate by use of frustum shaped pin with standard of HDS (H13) and is hardened to 55 HRC tool [10]. Tool specification is tabled below:

Table 2: Details of tool [10]

Tool parameters	Dimensions(mm)
Tool diameter	6
Bottom diameter	4
Flat shoulder diameter	20
Height of the pin	4.2

Y.C.Chen et al. investigated the FSWed lap joint on 4mm thick ADC12 cast aluminum alloy and 2mm thick sheet of the pure titanium material. The working tool specification is 15mm diameter of tool shoulder and tool profile pin diameter is 5mm.the length of the probe pin is 3.9mm. During operation the welding speed reaches to 90mm/min the tip of the profile pin does not contact with the working material surface of Ti sheet because higher tool traverse speed effectively avoids serious softening of aluminum alloy in load control mode [11].

Here in the following tables we mentioned some tool materials, geometries and dimensions of tools used for FSW of different types of alloys, Table 3 for Al alloys, Table 4 for Mg alloys, Table 5 for metal matrix composites and Table 6 for Ti and its alloys from various reference journal papers.

Table 3: Tool materials, geometries and dimensions used for FSW of Aluminium alloys [4, 7]

Working materials	Tool material	Tool shape	Dimensions
AA6061-T6	H13 steel	SS: concave PS: SCT	SD: 25.4 mm; PD:5.2–7.6mm; PL: 1.8–7.1mm
AA 6111-T4	H13 steel	SS: flat with square	SD: 10 mm; PL: 0–1.6mm
AA7020-T6	HC steel	SS: concave PS: frustum and SC	SD: 10–20 mm, PD: 3–8 mm; PL: 4.2 mm
AA5754	H13 steel	SS: concave, convex, flat	SD:12mm;PD: 5mm; PL:1.6mm
AA6082-T6	HC steel	SS: scroll, cavity, Fillet PS: SC	PD: 1.7 mm; PL: 1.2mm
AA7075-T7351	H13 steel	SS: flat with scroll PS: triflute, trivex	SD:15 mm; PL: 4.7-6mm

SS: shoulder shape; SD: shoulder diameter; PD: pin diameter; PL: pin length; PS: pin shape; SC: straight circular; SCT: straight circular threaded;

Table 4: Tool materials, geometries and dimensions used for FSW of Magnesium alloys [4, 7]

Working materials	Tool material	Tool shape	Dimensions
AZ31 Mg	H13 steel	PS: SCT 3F with M4 threads	SD: 10 mm; PD: 4 mm; PL: 1.8 mm
AZ31B-H24 Mg alloy	H13 steel	PS: SC, LHT, RHT	PD: 3.175 mm; PL: 1.65 mm
AZ31B Mg alloy	Mild steel, Stainless and armour steels, high carbon, high speed steels	PS: SC, TC, SCT, triangular and square	SD: 15, 18, 21 mm; PL: 5.7 mm; PD: 6 mm

AZ31 Mg, 46–48 HRC	H13 steel,	PS: SCT, and Threaded and unthreaded 3F	SD: 10 mm; PD: 4 mm; PL: 1.8 mm;
AZ31B-H24 Mg alloy	H13 steel		SD: 19 mm; PL:3.5mm; PD: 6.35 mm

SD: shoulder diameter; PD: pin diameter; PL: pin length; PS: pin shape; SC: straight circular; TC: tapered circular; SCT: straight circular threaded; LHT (RHT): left (right) handed thread; 3F: 3 flats

Table 5: Tool materials, geometries and dimensions used for FSW of several metal matrix composites [4]

Working material	Tool material	Tool shape	Dimensions
6061-T6 Al+20%Al2O3	AISI oil hardened Tool steel (62 HRC)	PS: SCT	SD: 19 mm; PD: 6.3mm
Al 359+20%SiC	AISI oil hardened tool steel (62 HRC)	PS: SCT	SD: 19 mm; PD: 6.3 mm PL: 3.6mm
Al–10 wt-%TiB2	High C high Cr steel (60–62 HRC)	PS: SSq, TSq,SOct, TOct, SHex, THex	SD: 16 mm;
Al–15 wt-% Mg2Si	H13 steel	PS: TCT	SD: 18 mm; PL: 5.7mm
AA 6061– (3–7)%TiC	High C, high Cr steel	PS: SSq,TSq, SHex, THex, TOct	

SS: shoulder shape; SD: shoulder diameter; PL: pin length; PD: pin diameter; PS: pin shape; SCT: straight circular threaded; TCT: tapered circular threaded; SSq: square; TSq: tapered square; SHex: hexagonal; THex: tapered hexagonal; TOct: tapered octagonal; PD_t: pin diameter at the top (larger diameter) for tapered pin; PD_b: pin diameter at the bottom (smaller diameter) for tapered pin

Table 6 Tool materials, geometries and welding variables used for FSW of several titanium and its alloys [4]

Working Material	Tool material	Tool shape	Dimensions
cp-Ti,3mm	pcBN	SS: concave; PS: tapered at 450 and truncated	SD:15mm;PL:1.7mm; PDt:5.1mm
Ti,3 mm	1.Hss;2.WC pin, HSS shoulder;3. WC pin, W shoulder	PS:SC	PD:5mm;PL:2.85mm; SD:18mm
Ti-6Al-4V,3-12 mm	W-La alloy	PS: tapered	SD:19-32mm; PL:2.8-13.3mm
Ti,2 mm	WC-Co		SD:15mm;PL:2mm;PD:6mm
Ti metal 21S	W alloy	Proprietary	
Ti,5.6 mm	Sintered TiC		
Ti-6Al-4V	W-3 wt-%Re		SD:11mm;PL:1.8mm: PDt:6mm;PDb:4mm
Ti-5111 plate	W alloy		PL:12.7mm;PDt:25.4; PDb:9.5mm
Ti-15V-3Cr-3Al-3Sn	Mo based alloy	SS: convex	SD:15mm;PDt:5.1mm ;PDb:3mm

SD: shoulder diameter; PD: pin diameter; PL: pin length; PD_t: pin diameter at the top (larger diameter) for tapered pin; PD_b: pin diameter at the bottom (smaller diameter) for tapered pin; PS: pin shape; SS: shoulder shape; SC: straight circular; BM: base metal.

7. CONCLUDING REMARKS

Tool is the heart of FSW process. A proper tool with geometry and design definitely will have impact on the working materials. In this paper we mainly focused on tool. Proper tool selection, tool material, geometry and design has been reviewed from different researchers in order to know which geometry and tool material is accommodate for particular work materials and details are tabulated. Joining of thicker section higher strength aluminium alloys such as the 7xxx series still provide considerable challenges for FSW tool design. The tool design can be improved through the practical implementation of some fundamental concepts. These concepts can be further fine tuned by computer based stress analysis of the complex tool geometry.

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