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Research Article

INFLUENCE OF PROCESS AND TOOL PARAMETERS ON FRICTION STIR WELDING – OVER VIEW

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ABSTRACT
This paper gives the review of basic concepts of Friction Stir Welding, Applications and advantages of FSW, role of tool materials and tool design, contribution of welding process parameters and mode of metal transfer for producing a better weld. Further the extensive application of Friction Stir welding on magnesium and Aluminium alloys.

Keywords: *Friction Stir Welding, Tool Materials, Process Parameters, Weld Micro Structure*

INTRODUCTION

FRICTION STIR WELDING (FSW) was invented in 1991 by The Welding Institute (TWI) of UK. It is a solid–state joining technique, and was applied initially to aluminium alloys (Thomas *et al.*, 1991). The advantage of FSW is no melting occurs as conventional fusion joining techniques. So at lower temperatures the FSW process is performed than the conventional welding. Other than this, FSW allows avoiding many of the environmental and safety issues associated with conventional welding methods (Mehta *et al.*, 2011). The FSW technique was initially developed for Al-alloys, it also has great potential for welding of Mg-, Cu-, Ti-, Al-alloy matrix composites, lead, some steels, stainless steels, thermoplastics and different material combinations, particularly those with close melting temperatures and similar behaviour such as hot workability. However, cost effective stirring tools are needed for welding some of these materials such as metal matrix composites (MMCs) and those with high melting temperatures, i.e. steels and Ti-alloys (Yin *et al.*, 2010; Rai *et al.*, 2011).

FSW Process

The working principle of Friction Stir Welding process is shown in Fig1. To perform the welding process the FSW process utilizes a rotating tool. The tool can be described as having three parts. The main part of the rotating tool is the pin (probe) which provides the stirring and heating of the work piece by both frictional heating and to a larger extent the shearing of the work piece. Pin is submerged into the work piece (material to be welded).The shoulder is the other main part of the tool which is in contact with the work piece and also provides some frictional heating and contributes to the shearing of the work piece. Shoulder also provides the necessary pressure to the welded material. The tool also has a larger shank that extends away from the work piece and allows for the Friction Stir Welding Machine to firmly grip and rotate the tool. The tool is typically placed at an angle with respect to the work piece (tilted 0° – 3° about the y-axis) such that the leading edge of the shoulder is slightly above the work piece, and the rear of the shoulder is slightly below the surface of the work piece. The part of the shoulder that is below the surface is known as the heel, and the amount of plunge experienced is called the heel plunge depth. The tool performs three primary functions, that is, heating of the work piece, movement of material to produce the joint, and containment the hot metal below the tool shoulder. In FSW, rotating shouldered tool plunges into the joining point of plates and the heat is developed from the friction between the welding tool (including the shoulder and the probe) and the welded material, which causes the welded material to soften at a temperature less than its melting point. The tool shoulder restricts softened material below the shoulder is further leads to movement of material from the front of the pin to the back of the pin by the rotational and transverse movements of tool. It is expected that this process will produce a weld with less residual stress and distortion as compared to the fusion welding methods, since no melting of the material occurs during the welding (Fujii *et al.*, 2006).

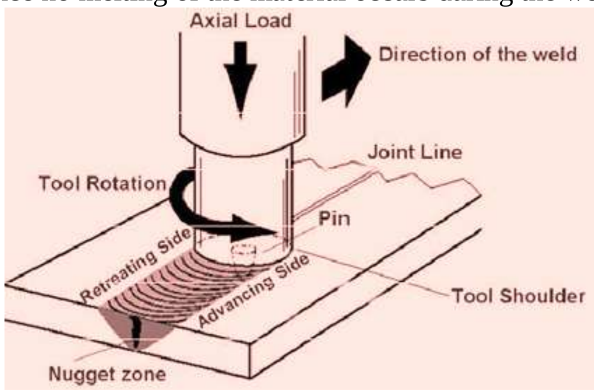

Figure 1: FSW process (Shrikant and Shete, 2013)

There are several terms used in FSW that help identify which part of the weld and tool are being discussed. When talking about the welding direction, this simply refers to the movement toward the unwelded material. More simply, it is the direction the pin appears to move relative to the backing anvil. The advancing and retreating sides of the weld can be defined by placing a tangential vector on the tool. The side of the tool in which the vector is in the same direction as that of the welding direction is called the advancing side, the side in which the vector is in the opposite direction is the retreating side. The nugget is the part of the weld that actually contains the sheared material. This is the zone that the tool affects mechanically and thermally. In some instances there are tools with more intricate designs including those with fixed shoulders (to eliminate the heat input by the shoulder), threads and/or flutes on the pin, non-axis symmetric pin design to increase stirring and shoulder features such as scrolls.

FSW Process Parameters

As in fusion welding, the feed rate is an important part of the process. When discussing the feed rate, it is common to use the term "welding speed" or "traverse rate" to describe the translational speed of the tool. The term "Tool Rotation Speed" is used to classify the angular velocity (typically in rpm) of the tool. The direction of the tool is defined by looking down the tool towards the work piece, using the terminology "clockwise" and "counter (anti) clockwise." The Forces present in FSW are also an important parameter for the process. The force parallel with the axis of tool rotation (z component) is defined as the "down force." The force acting in parallel with the welding direction (x component) is known as the "traversing force", and the force perpendicular to this (y component) is known as the "side force" (Richard and Philip, 2003).

The welding (traverse) speed, the tool rotational speed (rotation rate), the vertical pressure on the tool (axial pressure), the tilt angle of the tool, ratio of D/d and the tool design are the main independent variables used to control the FSW process. These variables determine the peak temperature, x-direction force, torque and the power features of the process. Peak temperature significantly rises with the increase in tool rotational speed and axial pressure, and decreases slightly with increasing traverse speed. The torque depends on parameters such as the applied vertical pressure, tool design, the tilt angle, local shear stress at the tool/work piece interface, the friction co efficient and the extend of slip between the tool and the work piece. The welding traverse speed (v_{trans}), the tool rotational speed (ω), the downward force (F), the tilt angle of the tool and the tool design are the main variables usually used to control the FSW process (Mehta *et al.*, 2011). The rotation of the tool results in stirring of material around the tool probe while the translation of the tool moves the stirred material from the front to the back of the probe. Axial pressure on the tool also affects the quality of the weld. It means that very high pressures lead to overheating and thinning of the joint, whereas very low pressures lead to insufficient heating and voids.

The tilt angle of the tool, measured with respect to the work piece surface, is also an important parameter, especially to help producing welds with "smooth" tool shoulders (Rowe and Wayne, 2006). As mentioned before, tool design influences heat generation, plastic flow, the power required to perform FSW and the uniformity of the welded joint. Generally, two tool surfaces are needed to perform the heating and joining processes in FSW. The shoulder surface is the area where the majority of the heat by friction is generated. This is valid for relatively thin plates; otherwise the probe surface is the area where the majority of the heat is generated. Fig.2 presents a schematic example of an FSW tool with conical shoulder and threaded probe. In this case, the conical tool shoulder helps to establish a pressure under the shoulder, but also operates as an escape volume for the material displaced by the probe due to the plunge action. As the probe tip must not penetrate the work piece or damage the backing plate, in all tool designs the probe height is limited by the work piece thickness (Ákos Meilinger and ImreTörök, 2013).

Weld Microstructure

FSW involves complex interactions between simultaneous thermo mechanical processes. These interactions affect the heating and cooling rates, plastic deformation and flow, dynamic recrystallization phenomena and the mechanical integrity of the joint (Diogo and Pedro; Nandan *et al.*, 2008) The thermo mechanical process involved under the tool results in different microstructural regions (see Fig. 2). Some microstructural regions are common to all forms of welding; while others are exclusive of FSW (Diogo and Pedro; Guerdoux, 2007). The stir zone (also called nugget) is a region of deeply deformed material that corresponds approximately to the location of the probe during welding. The grains within the nugget are often an order of magnitude smaller than the grains in the base material. The thermo mechanically affected zone (TMAZ) occurs on either side of the stir zone. The strain and temperature levels attained are lower and the effect of welding on the material microstructure is negligible. The heat affected zone (HAZ) is common to all welding processes. This region is subjected to a thermal cycle but it is not deformed during welding.

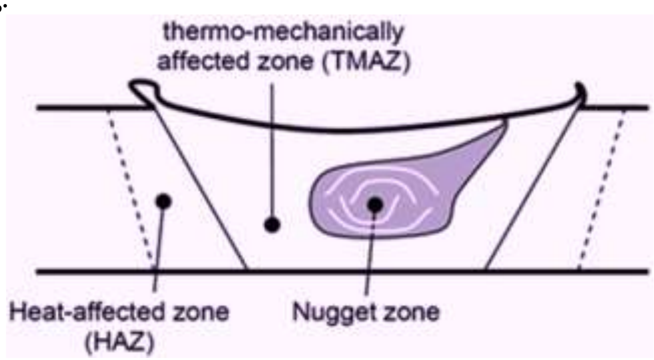

Figure 2: Different microstructural regions in a transverse cross section of FSW (Diogo and Pedro; Guerdoux, 2007).

V-THE FUNCTION OF TOOL

The friction stirring tool consists of a pin, or probe, and a shoulder. Contact of the pin with the work piece creates frictional and deformational heating and softens the work piece material; contacting the shoulder to the work piece increases the work piece heating, expands the zone of softened material, and constrains the deformed material (Rajiv and Murray, 2007). Figure 3 shows the most important tool parts (ÁkosMeilinger and ImreTörök, 2013).

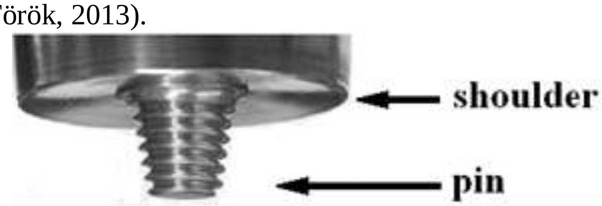

Figure 3: Parts of friction stir welding tool (ÁkosMeilinger and ImreTörök, 2013)

Important effects to the tool during welding are abrasive wear, high temperature and dynamic effects. Therefore, the good tool materials have the following properties are good wear resistance, high temperature strength, temper resistance, good toughness. So as we can see there are two important fields of friction stir welding tool design are tool material and geometry (Rajiv and Murray, 2007; ÁkosMeilinger and ImreTörök, 2013).

Selection of Tool Material

Weld quality and tool wear are two important considerations in the selection of tool material, the properties of which may affect the weld quality by influencing heat generation and dissipation. The weld microstructure may also be affected as a result of interaction with eroded tool material. Apart from the potentially undesirable effects on the weld microstructure, significant tool wear increases the processing cost of FSW.

Table 1: Tool materials to use depending on the base material:

Tool Materials	Characteristics
Hot-work tool steels	The most commonly used material, easy availability and machinability, thermal fatigue resistance, wear resistance, especially for aluminium and copper.
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 (typically 600 – 800 °C).
Refractory metals (W, Mo):	High temperature strength, strongest alloys between 1000 – 1500 °C, expensive, difficult machining, brittle because of powder processing.
Tungsten-base alloys	Good strength, high operational temperature, high cost (W-Re)
Carbide particle reinforced metal composites (WC, WC-Co, TiC)	superior wear resistance, reasonable fracture toughness
Steels with polycrystalline cubic boron nitride (PCBN) coating	High operational temperature, excellent wears resistance, low fracture toughness, expensive tool (Rajiv and Murray, 2007).

Table 2: Most commonly used tool materials for different base materials and thicknesses (ÁkosMeilinger and ImreTörök, 2013)

Alloys to be welded	Thickness (mm)	Tool material
Titanium alloys	3-10	W-alloys
Magnesium alloys	3-10	Tool steel , WC Composite
Aluminium Alloys	3-50	Tool steels,Co-Wc Composite
Copper alloys	3-50	Ni-alloys-alloys, PCBN, Tool steels
Stain less steels	3-10	W-alloys,PCBN
Low-alloy steels	3-10	WC composite, PCBN
Nickel alloys	3-10	PCBN

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The severe heating of the tool during FSW, significant wear may result if the tool material has low yield strength at high temperatures. Stresses experienced by the tool are dependent on the strength of the work piece at high temperatures common under the FSW conditions. Temperatures in the work piece depend on the material properties of tool, such as thermal conductivity, for a given work piece and processing parameters. The coefficient of thermal expansion may affect the thermal stresses in the tool. Other factors that may influence tool material selection are hardness, ductility and reactivity with the work piece material. The tool hardness is important in mitigating surface erosion due to interaction with particulate matter in the work piece. Tool degradation may be exaggerated if the tool material and work piece react to form undesirable phases.

Friction stirring is a thermo mechanical deformation process where the tool temperature approaches the solidus temperature of base metal. 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 fractures (Rajiv and Murray, 2007). The following characteristics have to be considered for material choice: ambient and elevated temperature strength, elevated temperature stability, wears resistance, tool reactivity, fracture toughness, coefficient of thermal expansion, machinability.

Tool Geometry

Tool geometry has a great influence on resulting mechanical properties of the weld (Sun *et al.*, 2009; Cao and Jahazi, 2011). It provides in-situ heating, stirs base material, and thus creates weld. There has been variety of tool shapes used. FSW can be performed with tool of a simple geometry (Figure 4) yet having good mechanical properties (Sun *et al.*, 2009). Advanced tool design (Figure 6) provides intensified material flow in the stirred zone and better weld quality (Atharifar *et al.*, 2009).

Figure 4 and Figure 5 provide basic overview on the basic and advanced types of FSW tools.

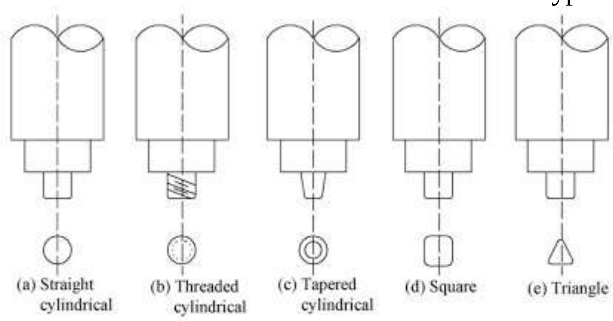
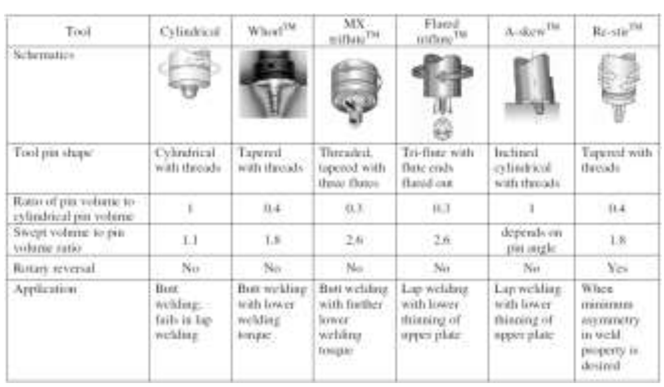


Figure 4: Basic FSW tool pin profiles



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

Figure 5: Various tool designs from The Welding Institute (Nandan *et al.*, 2008)

Experiments performed by Elangovan on tools with simple geometry (Sun *et al.*, 2009) showed remarkable influence on mechanical properties of the weld as illustrated in the Figure 6 (Sun *et al.*, 2009).

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The best results were produced using tool with square cross-section pin that assured best stirring of the material in the weld area.

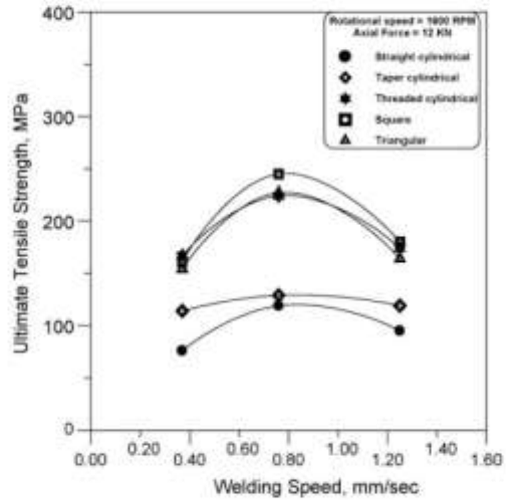

Figure 6: Dependency of material properties on welding speed and tool shape (Sun *et al.*, 2009)

The Figure 6 shows that the mechanical properties of the weld strongly depend on the volume of material stirred by the tool. The more material the tool stirs, comparing to its volume, the better the quality of the joint. This is also the reason why tool producers try to create specially tapered and threaded tools to raise the ratio (Atharifar *et al.*, 2009).

Welding Speed and Tool Rotational Speed

These two parameters of the welding process are the most important ones and determine overall mechanical properties of the welds. A comprehensive study investigating dependency of mechanical properties of the weld on the welding and rotational speed was done by Elangovan *et al.*, (Sun *et al.*, 2009; Chowdhury *et al.*, 2010). Figures below show the obtained results.

Dependency of Mechanical Properties on Welding Speed

Figure 7 and Figure 8 show the dependency of mechanical properties on welding speed as measured by Elangovan *et al.*, (Sun *et al.*, 2009)

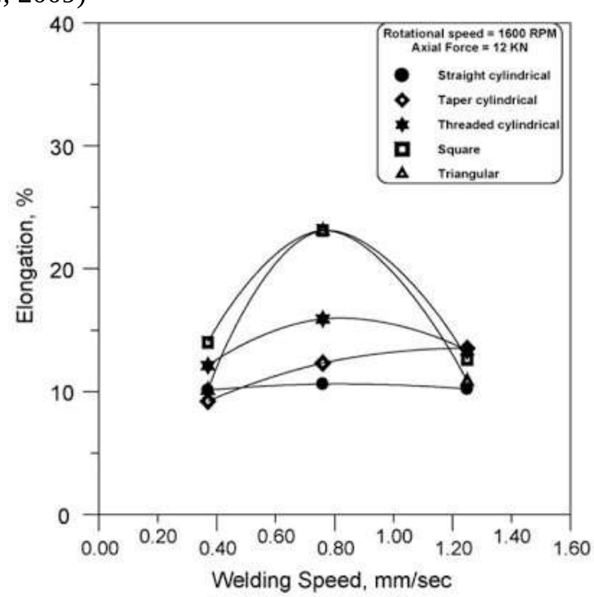

Figure 7: Dependency of elongation on welding speed and tool shape (Sun *et al.*, 2009)

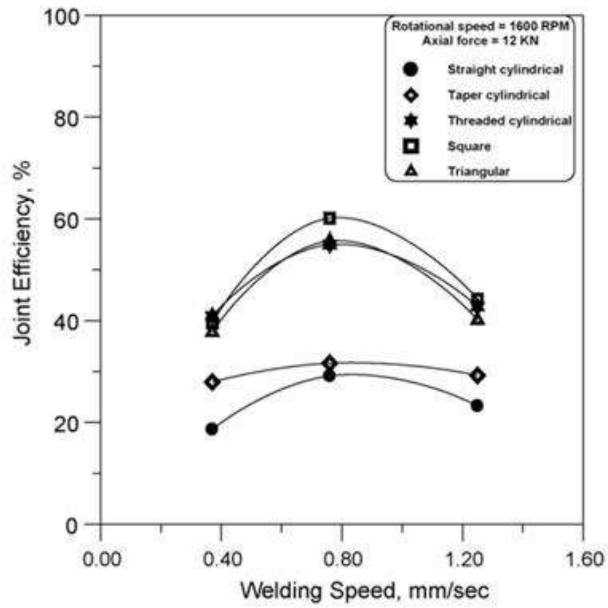

Figure 8: Dependency of elongation on welding speed and tool shape (Sun *et al.*, 2009)

Even though the number of different welding speed measurements is quite low, we can expect that there always is an optimal welding speed for the given material, rotational speed and tool shape. Optimal welding speed in the cases shown on the figures above does not strongly depend on the tool shape and optimal value of the welding speed for the given other parameters considering elongation and joint efficiency lies between 0.8 and 1 $mm.s^{-1}$.

Dependency of Mechanical Properties on Rotational Speed

Figure 9 and Figure 10 show the dependency as measured by Elangovan *et al.*, (Chowdhury *et al.*, 2010).

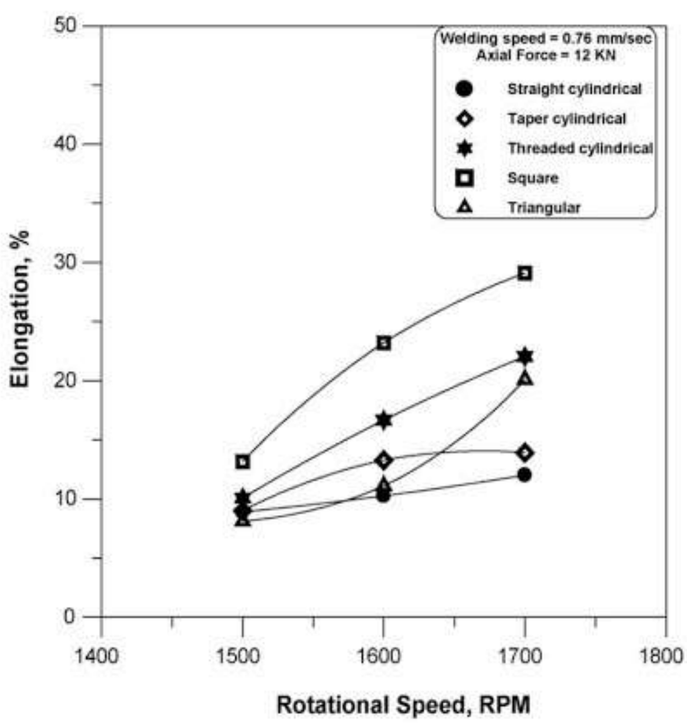

Figure 9: Dependency of elongation on rotational speed and tool shape (Chowdhury *et al.*, 2010)

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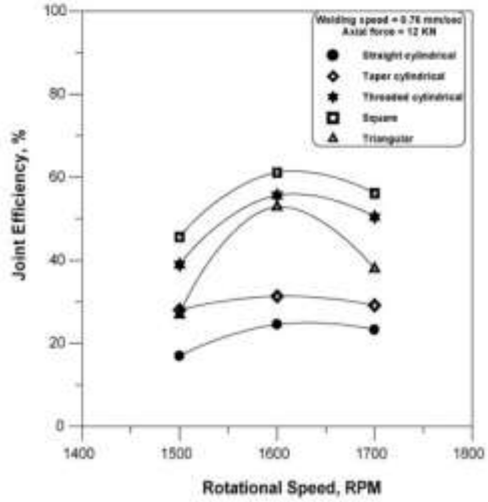

Figure 10: Dependency of joint efficiency on rotational speed and tool shape (Chowdhury *et al.*, 2010)

In this case, the dependency of the value of elongation and joint efficiency on the tool shape is more significant than their dependency on rotational speed.
The joint efficiency graph in Figure 10 exhibits a peak around the rotational speed value of 1600 min-1, whereas elongation values grow with raising rotational speed throughout the measured range. The author does not specify aging time of the welds, so it is possible that higher values of elongation are caused by higher weld temperature at higher rotational speed of the tool. This could have lead to creation of unstable microstructure with higher elongation and would return to the metastable state with lower elongation and higher joint efficiency after aging.
Each of the friction tool parts (pin and shoulder) has a different function. Therefore, the best tool design may consist of the shoulder and pin constructed with different materials. The work piece and tool materials, joint configuration (butt or lap, plate or extrusion), tool parameters (tool rotation and travel speeds), and the user's own experiences and preferences are factors to consider when selecting the shoulder and pin designs. Very important factor of the tool design that the material flow has adequate direction and quantity during welding. Generally, the greater volume of material to stir better weld quality is obtained, but it has strong correlation with other technological parameters (rotational speed, welding speed). Horizontal material flow certainly occur during welding, but if some oxide occurs on the base material surface, the vertical material flow will be very significant and this is especially true at lap joint welding. If vertical flow doesn't occur during welding, the surface oxide will remains in the joint line and remains the creation of the joint. Figure 11.a shows the horizontal material flow, figure 11.b shows the vertical material flow around the tool: (ÁkosMeilinger and ImreTörök, 2013).

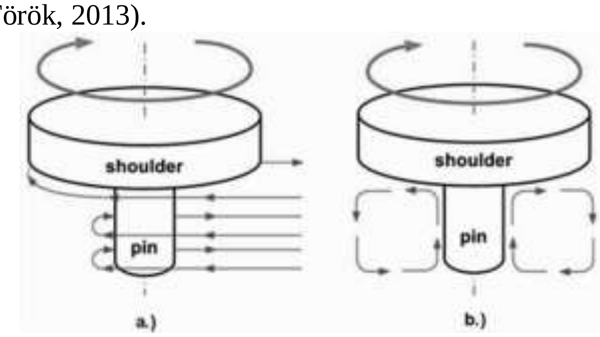

Figure 11: a.) Horizontal material flow, b.) Vertical material flow

Design of Tool Shoulders

Tool shoulders are designed to produce heat to the surface and subsurface regions of the work piece. The tool shoulder produces a majority of the deformational and frictional heating in thin sheet, while the pin produces a majority of the heating in thick work pieces. So one of the most important parameter of the shoulder is the diameter because it has significant effect to the amount of frictional heat. Figure 11 shows the relation between the shoulder diameter and peak temperature at different rotational speed during aluminium welding (Mehta *et al*., 2011):

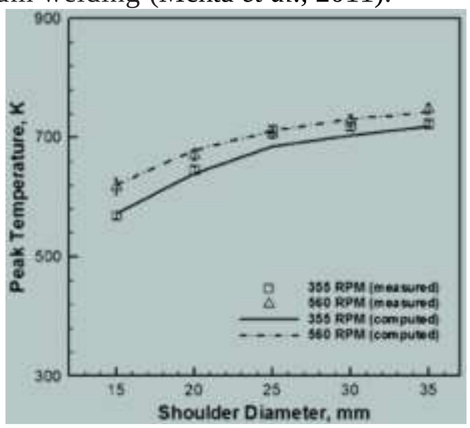

Figure 12: The effect of shoulder diameter to the peak temperature (Mehta *et al*., 2011)

Greater shoulder diameter increases the pressure force and the weld shape changes which degreases the mechanical properties of welds. So the choice of shoulder diameter requires consideration. Besides this the shoulder shape is very dominant too:

Concave Shoulder (Figure 3): It was the first shoulder design, commonly referred to as the standard-type shoulder. Concave shoulders produce quality friction stir welds, and the simple design is easily machined. 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. This material serves as the start of a reservoir for the forging action of the 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 workpiece away from the direction of travel (Rajiv and Murray, 2007; ÁkosMeilinger and ImreTörök, 2013).

Convex Shoulder (Figure 13): The tool with a convex shoulder was unsuccessful, be-cause the convex shape pushed material away from the pin. Convex shoulder 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. This shoulder design allows for a larger flexibility in the contact area between the shoulder and work piece, improves the joint mismatch tolerance, increases the ease of joining different thickness work pieces, and improves the ability to weld complex curvatures (Rajiv and Murray, 2007; ÁkosMeilinger and ImreTörök, 2013).

Figure 13: Convex and scrolled shoulder of FSW

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 (Figure 14.) 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 (Rajiv and Murray, 2007; ÁkosMeilinger and ImreTörök, 2013).

Figure 14: Different shoulder features
a. scrolled, b. knurled, c. ridged, d. grooved, e. concentric circles

Design of Tool Pins
Friction stirring pins produce deformational and frictional heating to the joint surfaces. 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. Commonly used pin designs are as follows:
Round-bottom Cylindrical Pin (Figure 7a): 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. It was claimed that as the dome radius decreased, a higher probability of poor-quality weld was encountered, especially directly below the pin. Machining a radius at the bottom of the threads will increase tool life by eliminating stress concentrations at the root of the threads (Rajiv and Murray, 2007; Rowe and Wayne, 2006).
Flat Bottom Cylindrical Pin (Figure 14b): The friction velocity of a rotating cylinder increases from zero at the centre 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. The lowest point of the flat bottom pin tilted to a small angle to the normal axis is the edge of the pin, where the velocity is the highest.
Truncated Cone Pin (Figure 3): Cylindrical pins were found to be sufficient for aluminium plate up to 12mm thick, but researchers wanted to friction stir weld thicker plates at faster travel speeds. 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 the base of the cone, where it is the strongest (Atharifar *et al.,* 2009). After the described basic pin geometries the developments of tools were continuing and appeared unusual pin geometries.
MX Tri Flute Pin (Figure 14c): It contains three flutes cut in to 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 (Rajiv and Murray, 2007; Rowe and Wayne, 2006). It can be used advantageously to welding thick-section aluminium alloys.
A Skew^{TM} (Figure 14d): The effect of this pin geometry is similar than MX tri flute. It increases travel speed, improves the tensile properties of the weld, and reduces the weld symmetry (Tracy, 2005).
Tri vex Pin (Figure14e): It produced an 18 to 25% reduction of traversing forces and a 12% reduction in forging (normal) forces in comparison to an MX tri flute pin of comparable dimensions (Rowe and Wayne, 2006; Ákos Meilinger and ImreTörök, 2013).
Thread Less Pins (Figure 14f): These are useful in specific FSW applications where thread features would not survive without fracture or severe wear.

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Table 3: Tool materials, geometries and welding variables used for FSW of sever Al magnesium alloys*

Work piece material	Tool material	Tool shape and size	Operating parameters	Remarks	Reference
AZ31Mg, 1.5 mm thick	H13steel	SD: 10mm; PD: 4mm; PL: 1.8mm; PS: SCT, 3Fwith M4 threads	1000 3000 rev/min; dwell time: 1,4s; plunge rate: 0–10 mm/s; FSSW		Sun *et al.*, (2009)
					Yin *et al.*, (2010)
AZ31 Mg, 1.5 mm	H13steel, 46-48 HRC	SD: 10mm; PD: 4mm; PL: 1.8 mm; PS: SCT, and threaded and Unthreaded 3F	1000–3000 rev/min; dwell time: 1s; plunge rate: 2.5mm/s; FSSW	Welds with 3F/threaded superior to those with SCT Joint efficiencies: 74–83%	Chowdhury *et al.*, (2010)
					Padmanaban and Balasubramanian (2009)
AZ31B-H24 Mg alloy, 2mm	Mild steel, stainless steel, armour steel, high carbon steel, high speed steel	PD: 3.175mm; PL: 1.65mm; PS: SC, LHT, RHT	1000–2000 Rev/min; 300–1800mm/min		Cao and Jahazi (2011)
AZ31B Mg alloy, 6mm		SD: 15, 18, 21 mm; PS: SC, TC, SCT, triangular and square; PL: 5.7mm; PD: 6mm	1600rev/min; 40mm/min; 0^0 tilt	Joint efficiencies: 48.8–96.7%	Rai *et al.*, (2011)
AZ31B-H24Mg alloy, 2mm	H13steel	SD: 19mm; PL: 2–3.5mm; PD: 6.35mm	1200mm/min; 500–2000rev/min	Joint efficiencies: up to 62%	

**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: three flats; FSSW: friction stirs spot welding. Joint efficiency is the ratio of the tensile strength of the joint to that of the base metal.*

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 (Rowe and Wayne, 2006).

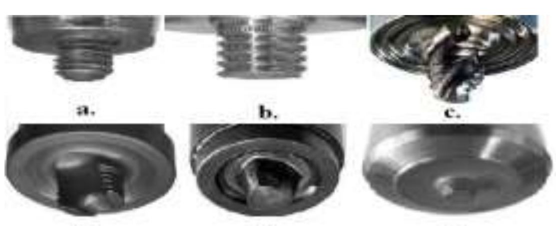

Figure 15: Different pin geometries

a) Round-bottom, b). Flat-bottom, c). MX triflute, d). A-skew TM, e). Trivex f). Thread les

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Table 4: Tool materials, geometries and welding variables used for FSW of several aluminium alloys*

Work piece material	Tool material	Tool shape and size	Operating parameters	Remarks	Reference
6111-T4 Al alloy, 0.9 mm thick	H13 steel	SS: flat with scroll; SD: 10 mm; PL: 0–1.6 mm PS: Tri flute, Tri vex	2000 rev/ min; dwell time: 2.5 s; plunge rate: 2.5 mm/ s; FSSW	Better quality with pin less tool	Rai *et al.*, (2011) Lorrain *et al.*, (2010)
7075-T7351, 6.35 mm 7075-T7351; 6.35 mm, 16 mm	1. MP159; 2. Dievar tool steel; 3. MP159 pin, H13 shoulder	PS: threaded	394 and 457 rev/ min; 300–540 mm /min21 190–457 rev/ min21; 0.3–1.4 mm/ rev21	Weld UTS: 470–488 MPa Surface scaling and voiding problems	Bakavos and Prangnell (2009) Colegrove and Shercliff (2004)
Al alloys, 5 mm		SS: concave; SD: 15 mm; PS: SC, SCT, triangular; PL: 4.7 mm, 6 mm	600–1500 rev/ min; 25–1000 mm/ min; 3° tilt	Peak joint efficiencies: 70–100%	Fujii *et al.*, (2006) Kumar *et al.*, (2008)
7020-T6 Al alloy, 4 mm 6082-T6 Al, 1.5 mm	Steel	SD: 10–20 mm, flat; PD: 3–8 mm; PL: 4.2 mm; PS: frustum and SC SS: scroll, cavity, fillet; PD: 1.7 mm; PS: SC; PL: 1.2 mm	1400 rev/ min21; 80 mm/ min 1810 rev/ min21; 460 mm/ min21; 2° tilt	Peak joint efficiency: 92% Joint efficiencies: ~76%	Scialpi *et al.*, (2007) Sorensen and Stahl (2007) Atharifar *et al.*, (2009)
6061-T6 Al, 9.5 mm and 12.7 mm 6061-T6 Al, 6.3 mm	H13 steel	SD: 25.4 mm; PD: 5.2–7.6 mm; PL: 1.8–7.1 mm SS: concave; SD: 26 mm; PD: 5.6 mm; PL: 5.9 mm; PS: SCT	650 rev/ min; 150 or 200 mm/ min; 3u tilt 286–1150 rev/ min; 30–210 mm/ min		Badarinarayan *et al.*, (2009) Rodriguez *et al.*, (2005) Lorrain *et al.*, (2010)
5754 Al, 1.32 mm	H13 steel	SS: concave, convex, flat; SD: 12 mm; PD: 5 mm; PL: 1.6 mm	1500 rev/ min; dwell Time: 2 s; plunge rate: 20 mm/ min; FSSW		
A319 and A413 Al alloy, 6 mm	Tool steel	PD: 6 mm	1000 rev/ min; 120 mm min21	No property de gradation in weld metal	
7020-T6 Al, 4 mm	High carbon steel	SS: concave; SD: 13 mm; PS: SC, TC3F; PL: 3.19 mm: PD: 5 mm	300–1620 rev/ min21; 100–900 mm /min21; 2.5° tilt		

Joints

The different types of joints were welded by FSW like butt joint, lap joint and fillet joint and the other type of joints are square butt, edge butt, T butt joint, lap joint, multiple lap joint, T lap joint, and fillet joint .The most widely used type of joints is butt joint and lap joint. Now the research is going on different types of joint of plates to increase the mechanical properties of a weld.

Joint Configuration

FSW allows the use of virtually any joint configuration as we know them from traditional fusion welding. The only limitation is the tool shoulder, which makes fillet joints more problematic than flat ones (Guerdoux, 2007). Typical FSW joints are shown (Figure 16).

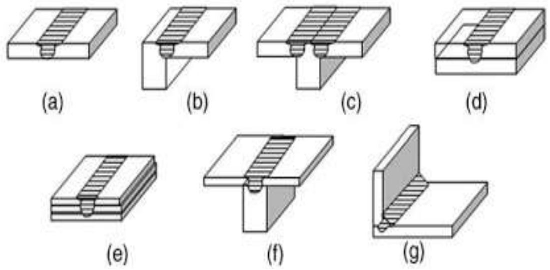

Figure 16: Joint configurations for friction stir welding: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint, and (g) fillet joint.

The most commonly used types of joint are the butt joints, in particular, square butt joint.

Machinery Used

FSW is not demanding in regard of machinery requirements. There is no special welding machine necessary and utilisation of standard workshop equipment such as milling machines is possible. Although specialised machines provide higher levels of productivity especially in the respect to the ease of gripping work pieces, welding speed (maximum speed around 2 $m.min^{-1}$ for standard FSW machines) and also number of welding heads allowing to work on multiple parts of the work piece at the same time.

Most of the currently used machinery is tailor made for the customers by several specialised producers that provide wide range of machine parameters suitable to customer needs.

Welding Forces

Welding forces are important for choosing appropriate machinery and tool design. Hattingh *et al.*, studied forces applied to variety of tools during friction stir welding (Cao and Jahazi, 2011). At welding speed of 150 mm/min and spindle speed 500 rpm the maximum radial forces never exceeded 6 kN. Maximal axial force varied from 4 to 14 kN for different tools. The axial, also called vertical down force, is crucial for creation of sound weld, as it assures proper contact of the tool with welded work pieces and together with rotational speed induces release of frictional heat from the tool shoulder which is the main source of heat for the weld (Guerdoux, 2007).

CONCLUSION

In conclusion, overviews of friction stir welding Cost effective and long life tools are available for the FSW of aluminium and other soft alloys. They are needed but not currently available for the commercial application of FSW to high strength materials. Tool material properties such as strength, fracture toughness, hardness, thermal conductivity and thermal expansion coefficient affect the weld quality, tool wear and performance. Reactivity of tool material with oxygen from the atmosphere and with the work piece is also an important consideration. Further developments in FSW tool materials are required to address the problem of high tool cost with low tool life during welding of harder alloys. Heat generation rate and plastic flow in the work piece are affected by the shape and size of the tool shoulder and pin. Although the tool design affects weld proper-ties, defects and the forces on the tool, they are currently designed empirically by trial and error. Work on the systematic design of tools using scientific principles is just beginning. Examples of recent studies include calculation of flow fields for different tool geometries and the calculation of tool shoulder dimensions based on the tool's grip of the plasticised material. The pin cross-sectional geometry and surface features such as threads influence the heat generation rates, axial forces on the tool and material flow. Tool wear, deformation and failure are also much more prominent in the tool pin compared with the tool shoulder. The axial, longitudinal and lateral forces on the tool can be calculated as functions of process parameters, or evaluated from the measured data. Estimation of the load bearing ability of the tool pin is needed considering the maximum stresses in the tool pin due to combined effects of bending and torsion. There is a need for concerted research efforts towards development of cost effective durable tools for commercial application of FSW to hard engineering alloys.

Shoulder: the 1 - 2° tilting angle of the tool is usually quite normal, but it results too wide weld, thickness reduction and greater downward force which increase the tool wear. Therefore the concave shoulder design is unnecessary. However the heat input is very important which is not always ensured by the convex shape. Accordingly we used a simple shoulder, which is neither concave nor convex, but a simple flat surface.

Pin: we decided for truncated cone pin because it is a long standing shape and fewer imperfections appear than in case of use of unusual pin geometries of welding of aluminium alloys. The usage of thread is not advantageous because it can cause aluminium-oxide stirring from the surface to the weld, stronger wear of the shapes which affects to the reproduction. The simple pin shape is also not favourable because it cannot produce enough heat input on the whole thickness of aluminium alloys. The solution was little-used pin geometry, the staged shape. Adequate heat came inside the weld with this pin geometry so the root was sufficient. We used a great radius on the pin end because the flat-bottom can cause material congestion during welding. In the other hand the radius results narrower root and eliminates the absence of tilting angle. An important factor is the choice of the pin length. The welding will not be successful if the pin length is equal to the base material thickness. The pin can touch the support plate or it can cause material congestion so the shoulder doesn't touch the surface and doesn't create heat. We choose with 0, 3 mm shorter pin length than the base material thickness. With this length the shoulder touched the surface and the root was good.

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