Friction Stir Welding: Tool Material and Geometry

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Abstract -- **The Friction stir welding is a dynamically developing version of pressure welding processes by which High-quality welds can be created. The mixing the material flow conditions specifically affect the quality of the weld, so the Tool geometry is very important. Tool design and selection of process variables are critical issues in the usage of FSW process. The Development of cost effective and durable tools, which lead to structurally sound welds, is still awaited. Material selection and design intensely affect the performance of the tools. Here we reviewed several important aspects of FSW tools such as tool material selection & its importance, geometry and load bearing ability and process economics for applications in this article.**

Keywords: *Friction Stir Welding; Tool Material; Tool Geometry; Rotational Speed.*

I. INTRODUCTION

FRICTION stir welding is a solid state joining process using a rotating tool moving along the joint interface, generating heat and resulting in a re-circulating plasticized material flow near the tool surface. This plasticized material is subjected to extrusion by the tool probe rotational and linear movements leading to the formation of stir zone. This stir zone formation is affected by the material flow behavior under the action of rotating tool. It was developed in England by The Welding Institute (TWI) in 1991 [1]. The friction stirring tool consists of a pin, or probe, and a shoulder as shown in Fig.1. Contact of the pin with 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. Naturally, there are important effects to the tool during welding: abrasive wear, high temperature and dynamic effects. Therefore, the good tool materials have the following properties: good wear resistance, high temperature strength, temper resistance, and good toughness.

So there are two important aspects of friction stir welding tool design: tool material and geometry [2]. Most important Challenges of Friction Stir Welding are application of high temperature materials, Tool material selection, Development of Tool Materials, Tool design and Complex geometries and dissimilar materials.

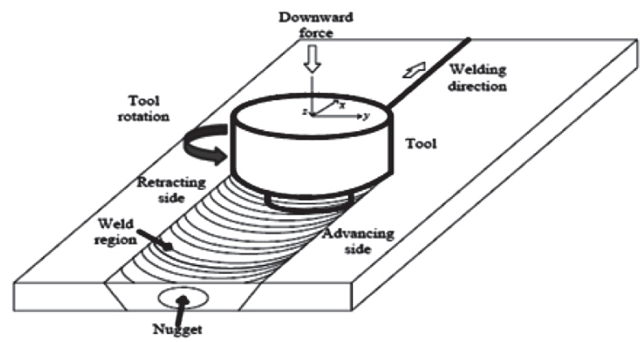

Figure 1. Schematic drawing of friction stir welding.

II. INFLUENCE OF TOOL MATERIAL AND GEOMETRY ON WELD QUALITY

The tool of FSW is composed of two parts: a tool body and a probe. The tool technology is the heart of friction stir welding process. The tool shape determines the heating, plastic flow and forging pattern of the plastic weld metal. The tool shape determines the weld size, welding speed and tool strength. The tool material determines the rate of friction heating, tool strength and working temperature, the latter ultimately determines which materials can be friction stir welded [3]. Two different tool pin geometries (square and hexagonal) and three different process variables, i.e. rotational speeds and welding speeds were selected for the experimental investigation of AA6101-T6 alloy. It was observed that square pin profile gave better weld quality than the other profile. Besides, the electrical conductivity of the material was maintained up to 95% of the base metal after welding. Arora et al [4] proposed and tested a criterion for the design of a tool shoulder diameter (considered three Shoulder diameters 15, 18, & 21mm) based on the principle of maximum utilization of supplied torque for traction.

The optimum tool shoulder diameter computed from this principle using a numerical heat transfer and material flow model resulted in best weld metal strength in independent tests and peak temperatures that are well within the commonly encountered range. The optimum shoulder diameter of 18 mm at 1200 rpm has resulted in superior tensile properties in independent tests. Elangovan and Balasubramanian [5] have also reported that the tool with an 18 mm shoulder diameter provided the best weld joint strength at a rotational speed of 1200 rpm, as shown in Table 1.

TABLE I- THE MECHANICAL PROPERTIES OF WELDS MADE USING A CYLINDRICAL PIN PROFILE [4]

Diameter (mm)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
15	110.5	131.7
18	130.3	161.7
21	94.0	120.0

TABLE II - WELDING TEMPERATURE RANGE OF VARIOUS ALLOYS [5]

Alloy Group	Temperature Range, ^{0}C
Aluminium alloys	440 to 550
Magnesium alloys	250 to 350
Copper alloys	600 to 900
Carbon and Low alloy steels	650 to 800
Titanium alloys	700 to 950
Stainless steel	600 to 875

TABLE III - TOOL MATERIALS USED IN FSW FOR SOFT ALLOYS [5]

Tool Material	Work Piece Material
Mild Steel	Magnesium alloys
High Carbon Steel	Magnesium alloys
Stainless Steel	Magnesium alloys
Armour Steel	Magnesium alloys
AISI Oil hardened Tool Steel	Aluminium matrix composite materials
AISI 4140	Dissimilar Materials
Tool Steel	Aluminium alloys, Dissimilar Materials
High Speed Steel	Magnesium alloys
SKD 61 Tool Steel	Dissimilar Materials
H13 Steel	Magnesium alloys
High Carbon High Chromium Steel	Magnesium alloys, Aluminium matrix composite materials, Dissimilar Materials

Materials such as aluminium or magnesium alloys, and aluminium matrix composites (AMCs) are commonly welded using steel tools. Steel tools have also been used for the joining of dissimilar materials in both lap and butt configurations. Tool wear during welding of metal matrix composites is greater when compared with welding of soft alloys due to the presence of hard, abrasive phases in the composites. Total wear was found to increase with rotational speed and decrease at lower traverse speed, which suggests that process parameters can be adjusted to increase tool life [6]. Lakshman Rao et al [7] highlight the role of tool geometry in their investigation, because tool geometry plays a major role in FSW. Proper selection of a tool material and shape of the pin reduces number of trials and tooling cost. In addition this study also highlights the wear effect due to friction between sliding surfaces. The effect of Friction Stir Welding process parameters on the mechanical properties of the AA 2014-T6 alloy joints produced by friction stir welding have been discussed by Vagh and Pandya [8]. Effects of tool design, tool rotation speed & tool travels speed on mechanical properties have been analysed using Taguchi orthogonal array design of experiments technique. There are three different tool rotation speeds (1000, 1400 & 2000 rpm) and three different tool traverse speeds (14, 20, 28 mm/min). For each combination of tool rotation speeds and tool traverse speeds three different types of tool pin profiles (threaded cylindrical pin, Stepped pin and Threaded cone pin) have been used. The study indicates that Tool design is the main process parameter that has the highest statistical influence on mechanical properties.

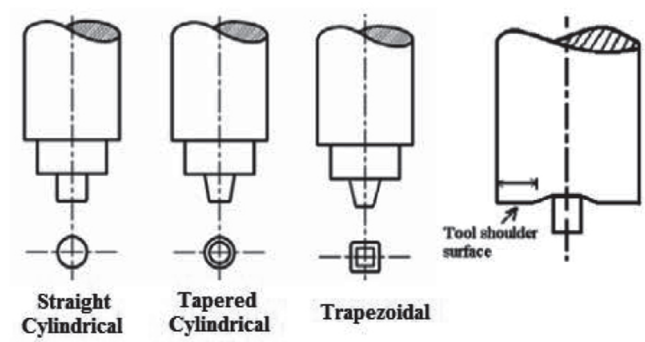

Figure 2. Different FSW tool geometries used in the experiment [8].

Prasanna et al [10] studied the effect of four different tool pin profiles on mechanical properties of AA 6061 aluminum alloy. Four different profiles have been used to fabricate the butt joints by keeping constant process parameters of tool rotational speed 1200rpm, welding speed 14mm/min and an axial force 7kN. Different heat treatment methods like annealing, normalizing and quenching have been applied on the joints and evaluation of the mechanical properties like tensile strength, percentage of elongation, hardness and microstructure in the friction stirring formation zone are evaluated. Of the four tool profiles, the maximum tensile strength and % of elongation of 210 MPa and 20.9 respectively was observed on Hexagonal pin profile tool with annealing process. The tensile strength and percent of elongation of the hexagonal tool profile with annealing process has reached about 90 % and 80 % respectively of the parent metal. Lee et al [11] welded Al–Mg alloy with low carbon steel in lap joint configuration using tool steel as tool material without its excessive wear by placing the softer Al–Mg alloy on top of the steel plate and avoiding direct contact of the tool with the steel plate. Tungsten based alloys have also been used for the welding of both low and high melting point alloys [12]. For example, Edwards and

Ramulu [13] used a W–La alloy tool to study FSW of Ti–6Al–4V alloy. Tools made of a tungsten alloy Densimet (composition not reported) were used by Yadava et al [14] to weld AA 6111-T4 aluminium alloy. Table 4 shows properties of tool materials. over which the torque is applied increases with shoulder diameter. As a result, the product of these two components shows the trend indicated in the Fig.3. The sliding torque, increases continuously with increasing shoulder diameter due to the larger contact area. With the increase in shoulder diameter the total torque increases continuously even when the sticking torque decreases for large shoulder diameters.

TABLE 4 - PROPERTIES OF COMMON TOOL MATERIALS *[11]*

	Co-efficient of Thermal Expansion/ $10^{-6}K^{-1}$	Thermal conductivity/ $Wm^{-1} K^{-1}$	Yield strength/ MPa	Hardness/ HV	Remarks
pcBN	4.6-4.9 [15]	100-250 [15]	-	2600-3500	High hardness, high temperature strength, susceptible to crack, wear may be enhanced by chemical reactions with Ti, high cost
Cp-W	~4.6 at 20-1000C [18]	167 at 20uC [18]	~100 at 1000C [16]	360-500 [18]	high temperature strength, low toughness at room temperature, less strength than W alloys
W-25 wt.%Re	-	55-65 [16]	~500-800 at 1000C [16]	-	Higher strength than W, tougher and easier to machine than ceramics
WC	4.9-5.1 [15]	95 [15]	-	1300-1600 [15]	High temperature strength, high hardness, wear due to oxidation at high temperatures, addition of Cr_3C_2 prevents oxidation
TiC	8.31 [19]	5-31[19]	20000[19]	2800-3400 [19]	High hardness, high temperature strength, susceptible to crack
4340 Steel	11.2-14.3 [15]	48 [15]	-	280 [15]	Low thermal conductivity, high temperature strength is not very high, possible alloying with Ti
Si_3N_4	3.9 at 20C 6.7 at 1000C [21]	20-70 [20]	-	1580	High hardness, high temperature strength, susceptible to crack, decomposes at high temperatures

Tool geometry

Tool geometry affects the heat generation rate, traverse force, torque and the thermo-mechanical environment experienced by the tool. The flow of plasticised material in the workpiece is affected by the tool geometry as well as the linear and rotational motion of the tool. Important factors are shoulder diameter, shoulder surface angle, pin geometry including its shape and size, and the nature of tool surfaces [12]. It was also observed from the previous data that the friction stir weld tool geometry has a significant effect on the weldment reinforcement, micro hardness, and weld strength.

Shoulder diameter

In order to determine the optimum tool geometry, the two components of the torque are plotted in Fig. 4 for various shoulder diameters. As the shoulder diameter increases, the sticking torque, increases, reaches a maximum and then decreases [4]. This behavior, which shows that two main factors affect the value of the sticking torque. First, the strength of the material, shear stress decreases with increasing temperature due to an increase in the shoulder diameter. Second, the area

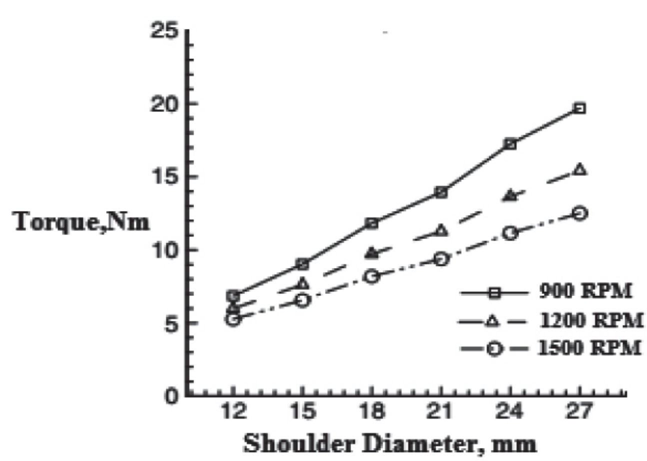

Figure 3. Total torque required during FSW of AA6061 as a function of the tool shoulder diameter for rotational speeds of 900, 1200 & 1500 rpm [3].

Pin (probe) geometry

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 [3].

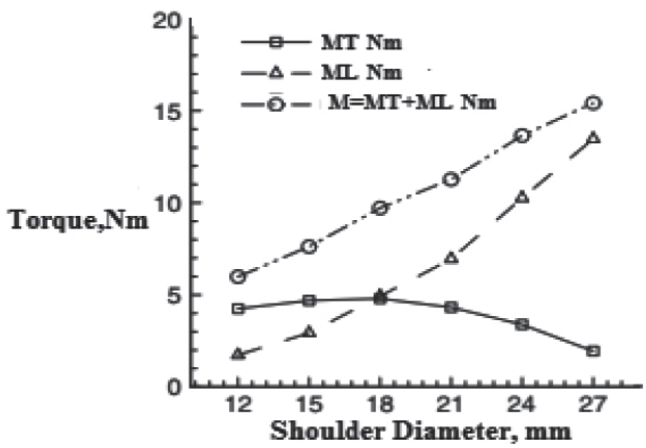

Figure 4. The computed values of sticking, sliding and total torque for various shoulder diameters at 1200rpm [3].

Tool cost

While the energy cost for the FSW of aluminium alloys is significantly lower than that for the fusion welding processes [25] the process is not cost effective for the FSW of hard alloys. Tools made of pcBN are often used for the welding of hard materials. However, pcBN is expensive due to high temperatures and pressures required in its manufacture [12]. Santella et al [22] did an approximate cost benefit analysis for FSW with a pcBN tool versus resistance spot welding (RSW) of DP 780 steel. The equipment and utility costs for FSSW were assumed to be 90 and 30% respectively of the costs in RSW; however, they did not report the dollar amounts of these costs. They further assumed that a typical RSW tool tip lasts 5000 welds and costs $0.65 per tip [12]. Considering the costs involved with equipment, utility and the tool, they estimated that in order for the FSSW to be cost competitive with respect to RSW, each FSSW tool, costing ~$100, needs to make 26 000 spot welds. Since the cost of each pcBN tool was significantly greater than $100 and typical tool life was between 500 and 1000 welds, they suggested lowering tool costs as an important need. Feng et al [24] produced over 100 friction stir spot welds on dual phase steel (ultimate tensile strength 600 MPa) and martensitic steel (ultimate tensile strength 1310 MPa) without noticeable degradation of the pcBN tool. The costs of Si_3N_4 and TiB_2 tools were less than 25% of the cost of pcBN tools [22]. Tools of W–Re or W–La alloys are relatively less expensive than that of pcBN tool but suffer considerably more wear compared with super abrasives due to their relatively lower high temperature strength and hardness [12]. Mohanty et al [9] investigated the effects of different friction stir welding tool geometries on mechanical strength and the microstructure properties of aluminum alloy welds. Three distinct tool geometries with different types of shoulder and tool probe profiles were used in the investigation according to the design matrix.

The effects of each tool shoulder and probe geometry on the weld was evaluated.

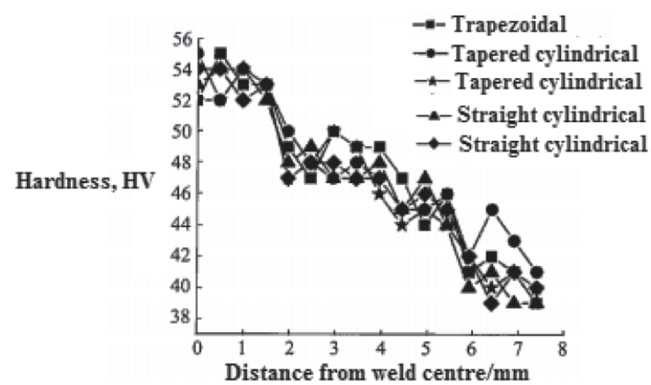

Figure 5. Micro hardness profile for various tool geometry [8].

The micro hardness of weld nugget TMAZ obtained with different tool profiles is shown in Fig. 5. It is observed that the weld nugget exhibits a higher micro hardness compared to the thermo-mechanically affected zone (TMAZ) and the base metal [9].

III. CONCLUDING REMARKS

The joints of different tool pin profiles like straight cylindrical, Taper cylindrical, triangular, square, trepezoidal and hexagonal tool etc., with different rotational speeds, weld speeds and axial force were reviewed in this paper. The following important conclusions were made: Based on the literature survey, Tool shoulder-to-pin diameter ratios play an important role in stir zone development. The diameter of the pin is equal to the thickness of the parts to be welded and its length is slightly shorter than the thickness of the part. Tool material properties such as strength, fracture toughness, hardness, thermal conductivity and thermal expansion coefficient affect the weld quality, tool wear and performance. Heat generation rate and plastic flow in the workpiece are affected by the shape and size of the tool shoulder and pin. Although the tool design affects weld properties, defects and the forces on the tool. 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. There is a need for concerted research efforts towards development of cost effective durable tools for commercial application of FSW to hard engineering alloys.

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