THE IMPORTANCE OF FRICTION STIR WELDING TOOL

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Abstract
The friction stir welding is a dynamically developing version of pressure welding processes. It was developed in England by The Welding Institute (TWI) in 1991. High-quality weld can be created by this process with e. g. a milling machine because using same movement conditions but the tool is different. Basically other tool design is needed because the goal isn’t the material removing but the material mixing and heating by frictional heat. The tool must be meet several important requirements. On the one hand in the course of mixing the material flow conditions specifically affect the quality of the weld, so the tool geometry is very important. On the other hand significant dynamic stress occurs with high heat load and abrasive wear depending on the material. The tool has evolved reasonably in point of geometry, material and coating in the past two decades. I would like to show the importance of tools of friction stir welding in this article.

Keywords: friction stir welding, FSW tool

1. Introduction

Friction stir welding (FSW) is a solid-state process, which means that the objects are joined without melting of base metals. This opens up whole new areas in welding technology. In FSW, a cylindrical shouldered tool with a profiled pin is rotated and plunged into the joint area between two pieces of sheet or plate material. The parts have to be securely clamped to prevent the joint faces from being forced apart. Frictional heat between the wear resistant welding tool and the workpieces causes the latter to soften without reaching melting point, allowing the tool to traverse along the weld line. The plasticized material, transferred to the trailing edge of the tool pin, is forged through intimate contact with the tool shoulder and pin profile. On cooling, a solid phase bond is created between the workpieces [1]. Friction stir welding can be used to join aluminium sheets and plates without filler wire or shielding gas. Material thicknesses ranging from 0.5 to 65 mm can be welded from one side at full penetration, without porosity or internal voids. In terms of materials, the focus has traditionally been on non-ferrous alloys, but recent advances have challenged this assumption, enabling FSW to be applied to a broad range of materials. It has been proven successful on numerous of alloys and materials, including high-strength steels, stainless steel and titanium.

Figure 1. shows the process principle:
2. The function of tool

The friction stirring tool consists of a pin, or probe, and a shoulder. 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 [2]. Figure 2 shows the most important tool parts.

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,
- good toughness.

So as we can see there are two important fields of friction stir welding tool design: tool material and geometry.
2.1. Tool material

Friction stirring is a thermomechanical 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 worse, fractures [2]. The following characteristics have to be considered for material choice:

- ambient and elevated temperature strength,
- elevated temperature stability,
- wear resistance,
- tool reactivity,
- fracture toughness,
- coefficient of thermal expansion,
- machinability.

There are several tool materials to use depending on the base material:

- 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)
- steels with polycrystalline cubic boron nitride (PCBN) coating: high operational temperature, excellent wear resistance, low fracture toughness, expensive tool [2].

Table 1 shows the most commonly used tool materials for different base materials and thicknesses:

<table>
<thead>
<tr>
<th>Alloys to be welded</th>
<th>Thickness (mm)</th>
<th>Tool material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium alloys</td>
<td>3 – 50</td>
<td>Tool steels, Co-WC composite</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>3 – 10</td>
<td>Tool steel, WC composite</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>3 – 50</td>
<td>Ni-alloys, W-alloys, PCBN, Tool steels</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>3 – 10</td>
<td>W-alloys</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>3 – 10</td>
<td>PCBN, W-alloys</td>
</tr>
<tr>
<td>Low-alloy steels</td>
<td>3 – 10</td>
<td>WC composite, PCBN</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>3 - 10</td>
<td>PCBN</td>
</tr>
</tbody>
</table>
2.2. Tool geometry

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 workpiece 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 3.a shows the horizontal material flow, figure 3. b shows the vertical material flow around the tool:

2.2.1 Design of tool shoulders

Tool shoulders are designed to produce heat to the surface and subsurface regions of the workpiece. 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 workpieces. 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 4. shows the relation between the shoulder diameter and peak temperature at different rotational speed during aluminium welding[3]:

Figure 2. a.) Horizontal material flow, b.) vertical material flow
Greater shoulder diameter increases the pressure force and the weld shape changes which degrades 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 2.):** 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 [2].

- **convex shoulder (Figure 5.):** the tool with a convex shoulder were unsuccessful, because 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 inward the pin. This shoulder design allows for a larger flexibility in the contact area between the shoulder and workpiece, improves the joint mismatch tolerance, increases the ease of joining different thickness workpieces, and improves the ability to weld complex curvatures [2].
shoulder features: The FSW tool shoulders can also contain features to increase the amount of material deformation produced by the shoulder, resulting in increased workpiece mixing and higher-quality friction stir welds. These features can consist of scrolls, ridges or knurling, grooves, and concentric circles (Figure 6.) 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 [2].

Figure 6. Different shoulder features
a. scrolled, b. knurled, c. ridged, d. grooved, e. concentric circles

2.2.2 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 workpiece, 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 7.a.): 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 [4].

• flat-bottom cylindrical pin (Figure 7.b.): 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
The importance of friction stir welding tool 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 2):** Cylindrical pins were found to be sufficient for aluminum plate up to 12 mm 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 at the base of the cone, where it is the strongest [2].

After the described basic pin geometries the development of tools were continuing and appeared unusual pin geometries:

- **MX triflute pin (Figure 7.c.):** 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 [4]. It can be used advantageously to welding thick-section aluminium alloys.

- **A-skew™ (Figure 7.d):** 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].

- **Trivex pin (Figure 7.e.):** 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 [2].

- **Threadless pins (Figure 7.f.):** These are useful in specific FSW applications where thread features would not survive without fracture or severe wear. 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 [4].
- **retractable pin**: The retractable pin tool consisted of an actuated pin within a rotating shoulder to allow pin length adjustment during welding. The normal operational mode for these tools was to retract the pin at a prescribed rate as the tool traversed forward. This allowed the closure of the exit hole in circumferential friction stir welds [4]. Figure 8 shows the operation of retractable pin:

![Figure 8. Operation of retractable pin](image)

- **pin for lap joint**: The lap joint interface (and corresponding surface oxides) resides in a horizontal layer that is more difficult to break up than the vertical interface encountered in butt joints. Cylindrical pin butt joint tools were used in the first friction stir lap welding attempts. These tools produced uplift adjacent to the friction stir zone and thinning of the upper sheet. Interface uplift is produced by vertical flow adjacent to the pin, which sharply moves the joint interface upward [4].

- **bobbin tools**: Bobbin tools consist of two shoulders, one on the top surface and one on the bottom surface of the workpiece, connected by a pin fully contained within the workpiece. The bobbin tool works by placing the bottom or reacting scrolled shoulder onto the end of a retractable pin. This is typically done by first drilling a hole through the workpiece, inserting the threaded pin, and securing the second shoulder to the pin. During FSW, the bottom shoulder is drawn toward the top shoulder until the desired force is reached. Because the two shoulders are reacting together to form the friction stir weld, the bobbin tool is also known as the self-reacting tool. The primary advantages of bobbin tools include ease of fixturing, the elimination of incomplete root penetration, and increased tool travel speeds due to heating from both shoulders. Figure 9 shows a typical bobbin tool:
3. Results of our experiments

We carried out experiments to optimize the technological parameters of aluminium alloys welding at the University of Miskolc, at the Department of Mechanical Engineering. The test-piece was a pure aluminium sheet of 6 mm thickness. The tool which we used was slightly different from the usually applied and previously described ones because of the following considerations:

- **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 less 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 favorable because it can not produce enough heat input on the whole thickness of aluminium alloys. The solution was a 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.

The Figure 10 shows this tool and the weld made with it:
The tool was made from a hot-work tool steel (material number: 1.2567) which maintains the mechanical properties at higher working temperatures as well.

The weld examinations certified that tool geometry is adequate for this task because the mechanical properties of welds were better than the same of other welds made by different tool geometries.

4. Summary

Numerous factors must be considered for designing the tool of friction stir welding, so it is a fairly complicated task. Because the tool has significant load, designers must pay attention to material, surface quality and geometry of tools. In addition technological parameters have significant effect on the tool and its life, so it is important to create conformity among them. Since 1991, the tool geometry has evolved appreciably and the tool material has had better and better properties. But the evolution is not ended; further improvements are needed in this field. There is a growing demand on weld materials with high melting temperature, high strength and hardening, and the key is the tool design and the tool itself.

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6. References