**Friction Stir Welding and Processing III**
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# Friction Stir Welding of Aluminum Using a Tapered Shoulder Tool

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## Abstract

Since the time when friction stir welding (FSW) was invented by The Welding Institute (TWI) advancements in welding tool design have allowed the process to be operated at higher travel speeds, in thicker sections, and with more reliable quality. A new feature has been developed, referred to as the tapered shoulder, which allows FSW to be operated more easily and with simpler equipment. The tapered shoulder consists of a scrolled shoulder that is not generally flat but is tapered outward, i.e. convex, from the outside diameter to the pin. This scrolled cone can be embedded beneath the surface of the plate to any depth, with the width of the crown of the weld being variable depending on the depth of penetration. This tool design, patented by Concurrent Technologies Corporation (*CTC*), has implications for conventional welds, for welds in material with complex curvature, for thick-section pipe, and for self-reacting or "bobbin" welds using tools that have a fixed geometry. This paper describes the welding tool design and its use in different welding applications.

## Introduction

The patent filed by TWI for the basic process of friction stir welding disclosed a number of welding tool concepts, although some of these concepts were not practical for producing welds. Subsequent patent filings and disclosures through publications expanded and refined the publicly known information to include many of the tool features that are used today in FSW of aluminum and other materials. One concept put forward in the original patent filing by TWI is that of the bobbin tool [1]. The goal of this tool was to provide for a welding tool that had shoulders on both sides of the plate, connected by the pin that was fully contained inside the plate. This tool had either a flat or an outwardly tapered, smooth shoulder. However, it was found that the outwardly tapered shoulder profile did not actually work, since the shoulder simply displaced workpiece material in the form of flash, resulting in loss of joint thickness.

As the process was further developed TWI introduced the concept of the scroll shoulder [2]. This shoulder design was essentially flat with spiraled grooves cut into the surface. The spiral grooves acted to pull workpiece material toward the center of the tool, making it possible to perform welds without tilting the welding tool axis relative to the plane of the workpiece. This major advancement greatly simplified the welding process by eliminating a key welding variable (the tilt angle) and it simplified machine design, since it was no longer necessary to tilt the tool.

Using the flat, scrolled shoulder in combination with the proper pin profile design, the FSW process can generally be performed in a reliable, repeatable fashion. However, there are still several challenges for welding using these state-of-the-art tools. These challenges include joint mismatch, variation in workpiece thickness, bobbin applications, and welding of complex contours.

Welding plates of different thickness is a significant problem for the flat, scrolled shoulder, even for relatively minor mismatch in plate thickness. Typically it is necessary to drive the welding tool so the shoulder rides flush with the thinner of the two sides of the joint, causing the welding tool shoulder to expel material from the thicker side of the joint in the form of flash. This loss of material must then be mechanically removed after welding in order to have a generally smooth weld crown surface.

Variation in workpiece thickness, either by design or by workpiece variability, also causes a problem with fixed-pin welding tools that have a flat shoulder. Typically, the flat welding tool shoulder would be controlled to ride flush on the surface of the material. This causes the gap between the end of the pin and the anvil to change as a reflection of the change in the workpiece thickness. In order to ensure that the pin won't hit the anvil at any point along the length of the workpiece it is necessary to measure the thickness of the workpieces and set the pin length based on the thinnest section of the joint, usually about 0.25-mm shorter than the minimum thickness. However, the thickest portion of the joint cannot be more than about 0.75 mm thicker than the thinnest portion, otherwise there is the risk of producing a root defect due to incomplete penetration of the stir zone to the back of the plate. This situation effectively limits the allowable variation in workpiece thickness to about 0.75 mm to be certain of not hitting the anvil and not leaving an unwelded root. For many applications, commercially obtained aluminum plate is within this tolerance, but still there are applications where plate thickness variation is greater than 0.75 mm.

A self-reacting welding tool is a two-shoulder tool in which the top shoulder and the pin/back-side shoulder assembly are actuated axially relative to each other [3-7]. In contrast, a fixed-geometry bobbin welding tool has two shoulders that are connected by the pin and are fixed in relation to each other. Both types of tools allow welds to be made without the high plunge force that is required in conventional stir welds to keep the welding tool embedded in the plate, since the two shoulders effectively trap the workpiece between them. In spite of the inherent simplicity offered by the bobbin tool, it has never been practical when used with shoulders that have a flat profile, since a mechanism to control the gap between the shoulders is required to accommodate variation in workpiece thickness. Unfortunately, the need for this mechanism effectively excludes many welding machines from making this type of weld, since it is very difficult to retrofit an existing machine with the required hardware without replacing much of the welding head.

Welding of complex contours is sometimes difficult to accomplish with flat, scrolled shoulders, especially when the exact details of the surface contour are unknown due to variability or when the radius of curvature is small in relation to the material thickness. Since it is necessary to keep the welding tool from tilting forward in relation to the surface normal, it is generally necessary to weld with a slight backward tilt and know precisely the surface normal direction at all times during a weld. This can present a problem in cases of having uncertain workpiece shape, or in cases where there is a large amount of welding machine deflection.

A new tool design has been developed that greatly improves each of these difficulties associated with flat, scrolled shoulder welding tools [8]. This new tool design combines two features, previously suggested by TWI, in a way that produces a fundamental improvement in welding tool performance. This design is realized by making a shoulder that has an outward taper and combining this with a shoulder scroll cut into the surface, as shown in Figure 1. This tool operates on the principle that it is possible to weld with the shoulder at least partially embedded in the workpiece as long as the shoulder profile is tapered and has a scroll to prevent the loss of workpiece material in the form of flash, as shown in Figure 2. This tool can make sound welds with considerable variation in the depth of the embedded portion of the tool, thus allowing for variable shoulder penetration into the surface of the workpiece.

## Case Study 1 – Variable Depth Welding

One application for the tapered shoulder tool is where it may be desirable to change the penetration depth of the welding tool along the length of the weld, such as where there is variation in the workpiece thickness. The current state of the art in FSW of aluminum calls for making welds with a flat, scrolled shoulder, controlling the weld in such a way as to maintain constant plunge force. In this situation, the welding tool "floats" along the surface of the plate, producing a consistent weld crown profile, as shown in Figure 3. However, if the workpiece thickness increases by more than about 0.75 mm, there is the possibility of forming root defects from incomplete stir zone penetration. Alternatively, the current state of the art tool can be operated in position control mode, maintaining a constant gap between the pin end and the anvil, but this runs the risk of forming excessive flash in thicker portions of the work or surface defects in thin portions of the work. The tapered shoulder welding tool can be used to eliminate the possibility of root defects in this situation by allowing the weld to be made in position control mode with constant pin end gap, and allowing the tapered shoulder to accommodate the variation in surface level. The shoulder of the welding tool is simply designed to leave a portion of the taper exposed above the workpiece during welding, as shown in Figure 3, so as the workpiece thickness increases the contact point on the taper moves outward. This results in a wider weld crown, but a sound weld with minimal flash is still produced.

An increase in shoulder penetration also results in changes in the weld forces. To demonstrate this, welds were made in nominally 25.4-mm thick 5083-H116, 2519-T87, and 6061-T6 aluminum alloys and 2195-T8 aluminum-copper-lithium alloy using a tapered shoulder tool. The chemical composition limits for these alloys are listed in Table 1. The welding tool design and weld parameters are shown in Table 2. It should be noted that on this particular tool the outward taper of the shoulder was only about 1-mm, although greater shoulder tapers have also been successfully demonstrated. For each material, a weld was made by incrementally increasing the plunge depth from an initial value, which would have produced a theoretical shoulder width of about 23-mm, to a final depth that would have resulted in approximately the full shoulder width of 36 mm. The results from the weld in 5083-H116 are presented in Figure 4, as an example. In this chart the initial plunge depth was used as a basis for comparison in computing the relative plunge depth for other depths. A laser displacement sensor was used to give accurate depth change data that excluded welding machine and fixture deflection. As can be seen in the figure, the forces generally increased with increasing shoulder depth. Table 3 shows the slope of the force change with respect to plunge depth for the four alloys studied. The plunge force and spindle torque were most affected by increases in plunge depth, while the longitudinal and transverse forces were only slightly affected. The transverse force actually decreased with increasing plunge depth for alloys 6061 and 2195, which could have been related to the fact that these alloys showed the highest increase in torque, and thereby heat generation, with respect to plunge depth.

The weld crown width was measured for each weld and plotted as a function of relative plunge depth, as shown in Figure 5. The weld crown width was seen to increase with increasing plunge depth, consistent with the shoulder geometry, and was approximately equal in the case of the 2195 and 2219 welds. The 5083 had a wider crown width, presumably due to the significant difference in material properties between the solution-strengthened 5083 and the precipitation strengthened 2195 and 2219.

Weld tensile properties were measured for welds made in 25-mm thick 2519 aluminum plate using flat, 1-mm tapered, and 2-mm tapered shoulder welding tools using a spindle speed of 275 rev/min. Each weld was cut to produce 5 tensile specimens. Figure 6 shows the mean values for each weld. The tensile results were not significantly different between the welds made at the same travel speed, indicating that the use of the tapered shoulder was not detrimental to the strength of the joints.

## Case Study 2 – Bobbin Welding

The tapered shoulder is an enabling technology to make a practical fixed geometry bobbin tool. Previously, it was necessary to actuate the back shoulder relative to the front shoulder in order to ensure correct spacing between the shoulders and provide adequate axial force to make a sound weld. This requires that the welding machine be equipped with a special mechanism to actuate the back shoulder axially relative to the front shoulder, making this type of weld impractical for most users. By making both the front and back shoulders with an outwardly tapered and scrolled profile, it is possible to fix the gap between the shoulders such that the average plate thickness contacts the tapered shoulders at some point as shown in Figure 7. As long as the variation in plate thickness doesn't cause the plate surface to contact the shoulder outside of the taper, on the shank of the welding tool or on the pin surface, then a sound weld can be produced. Correct pin design is also required, but no special pin design is required for the tapered shoulder tool compared to a flat shoulder tool.

Welds were made to demonstrate the use of the fixed-gap bobbin tool for welding 25.4-mm 6061-T6 aluminum plate. The welding tool design parameters and weld operating parameters are shown in Table 4. The macrograph on the left side of Figure 8 shows the symmetric stir zone appearance relative to the workpiece central plane that is typical of bobbin and self-reacted welds. On the right in this figure is an example of a bead-on-plate weld that was made to demonstrate the fixed-gap tool. On this weld the tool was started off of the plate to the right, driven onto the plate moving from right to left, curved around to cross a segment of the weld, then exited the plate by proceeding upward. The plate shown is as-welded, with no significant flash produced. The forces measured during welding are shown in Table 4.

## Case Study 3 – Pipe Welding

The welding of thick-wall, small diameter pipe can present a special problem for flat or cupped shoulder tools due to the tight curvature and the need to contain softened metal around the pin. Typically, in order to accomplish a weld in thick-wall, small diameter pipe using a flat or cupped shoulder it is necessary to "over-plunge" the tool in order to get adequate containment of workpiece material around the pin. This often results in the production of excessive flash and loss of section thickness, reducing the load carrying capacity of the joint. In addition, this can make it very difficult to perform welds in load-control mode, since a portion of the leading edge of the shoulder is necessarily embedded in the plate surface.

However, the tapered shoulder tool can provide adequate containment of the softened material around the pin without over-plunging the tool and without tilting the tool axis relative to the surface normal, as shown in Figure 9. As long as the surface of the taper contacts the surface of the pipe, the scrolls act to pull the workpiece material inward, preventing the formation of excessive flash. Although this type of tool does produce some undercut on the advancing side of the shoulder, the undercut is less than would normally be expected from a flat or cupped shoulder tool that is over-plunged.

## Conclusions

The evolution of welding tool designs for aluminum alloys has led to the possibility of making welds in thicker materials, at higher travel speeds, and with more reliable quality. The development of the outwardly tapered shoulder profile further advances the state of welding tool technology, making it practical to use fixed-geometry bobbin welding tools on relatively simple welding machines. Welds can also be made with this type of tool in situations where there is excessive mismatch and in applications for welding thick wall, small diameter pipe. By outwardly extending the shoulder surface and employing a spiral scroll, this tool design fundamentally changes the interaction of the shoulder with the workpiece surface, resulting in a tool that can be applied in new ways.

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Table 1. Specified chemical composition ranges for aluminum alloys 2519, 5083, 6061, and 2195.

| Alloy | Chemical Compositions, wt. % | | | | | | | | | | | Impurities, % | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cu | Mn | Mg | Fe | Si | Zn | Ti | Cr | Zr | V | Ag | Al | Each | Tot. |
| 2519 [9] | 5.30-6.40 | 0.10-0.50 | 0.05-0.40 | 0-0.30 | 0-0.25 | 0-0.10 | 0.02-0.10 | - | 0.10-0.25 | 0.05-0.15 | - | Bal. | 0-0.05 | 0-0.15 |
| 5083 [10] | 0-0.10 | 0.40-1.00 | 4.0-4.9 | 0-0.40 | 0-0.40 | 0-0.25 | 0-0.15 | 0.05-0.25 | - | - | - | | | |
| 6061 [11] | 0.15-0.40 | 0-0.15 | 0.80-1.20 | 0-0.70 | 0.40-0.80 | 0-0.25 | 0-0.15 | 0.04-0.35 | - | - | - | | | |
| 2195 [12] | 3.70-4.30 | 0-0.25 | 0.25-0.80 | 0-0.15 | 0-0.12 | 0-0.25 | 0-0.10 | - | 0.08-0.16 | - | 0.25-0.60 | | | |

Table 2. Tool design and weld parameters for welds in 1-in 5083, 2519, 6061, and 2195.

| | |
|---|---|
| Shoulder Diameter, mm | 35.6 |
| Outward Taper Length, mm | 1.02 |
| Scroll Depth, mm | 1.3 |
| Scroll Pitch, mm | 3.3 |
| Scroll Width, mm | 2.5 |
| Nominal Pin Length, mm | 24.1 |
| Pin Maximum Diameter, mm | 15.2 |
| Thread Pitch, mm | 1.41 |
| Number of Flats | 3 |
| Alloy 5083-H116 | |
| Spindle Speed, rev/min | 250 |
| Travel Speed, mm/min | 127 |
| Alloy 2519-T87 | |
| Spindle Speed, rev/min | 275 |
| Travel Speed, mm/min | 102 |
| Alloy 6061-T6 | |
| Spindle Speed, rev/min | 250 |
| Travel Speed, mm/min | 127 |
| Alloy 2195-T8 | |
| Spindle Speed, rev/min | 170 |
| Travel Speed, mm/min | 102 |

Table 3. Mean change in force per unit plunge depth for tapered shoulder tool during FSW of four aluminum alloys.

| Statistic | Change in Forces with Respect to Tool Depth | | | |
|---|---|---|---|---|
| | 5083-H116 | 2519-T87 | 6061-T6 | 2195-T8 |
| Plunge Force, kN/mm | 17.6 | 24.8 | 14.0 | 21.4 |
| Longitudinal Force, kN/mm | 8.6 | 12.6 | 0.1 | 7.9 |
| Transverse Force, kN/mm | 1.5 | 3.15 | -2.5 | -3.5 |
| Spindle Torque, N-m/mm | 38.8 | 57.6 | 78.6 | 90.3 |

Table 4. Tool design and weld parameters for fixed-geometry bobbin welds in 25.4-mm 6061-T6 aluminum.

| | |
|---|---|
| Shoulder Diameter, mm[1] | 35.6 |
| Outward Taper Length, mm | 1.02 |
| Scroll Depth, mm | 1.3 |
| Scroll Pitch, mm | 3.3 |
| Scroll Width, mm | 2.5 |
| Thread Pitch, mm | 1.41 |
| Number of Flats | 3 |
| Alloy 6061-T6 | |
| Spindle Speed, rev/min | 280 |
| Travel Speed, mm/min | 127 |
| Plunge Force, kN | 1.1 |
| Longitudinal Force, kN | 7.3 |
| Transverse Force, kN | 11.5 |
| Spindle Torque, N-m | 364.7 |

[1]Shoulder parameters apply to front and back shoulders.

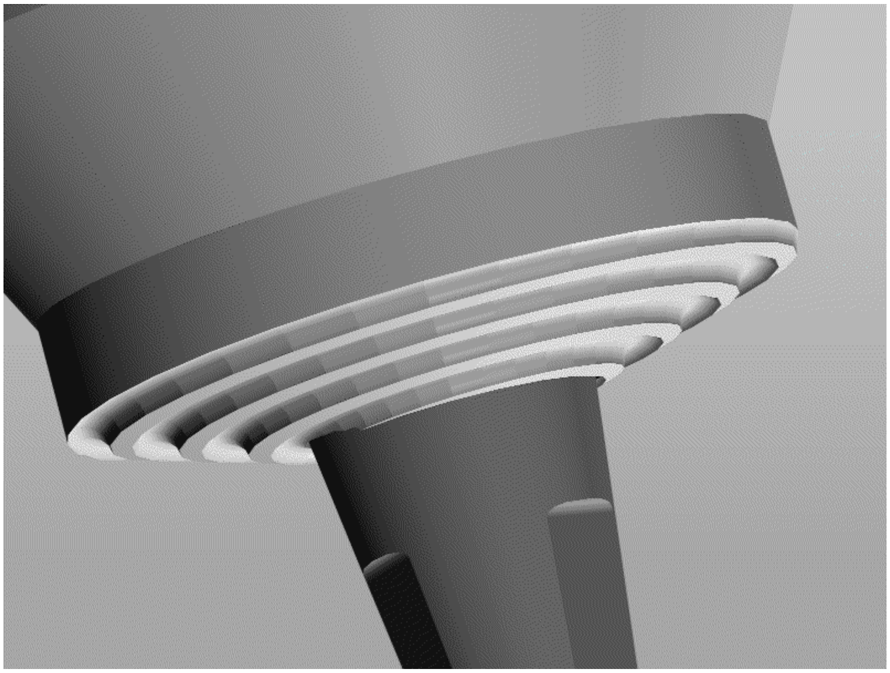

Figure 1. Tapered Shoulder Welding Tool

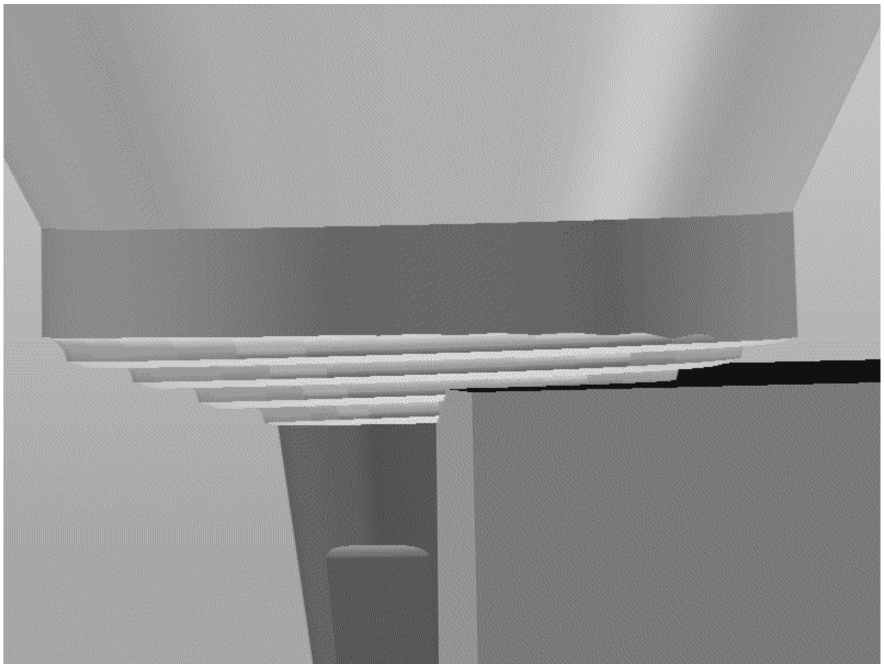

Figure 2. Tapered shoulder tool embedded in a workpiece,
(workpiece cut away for clarity).

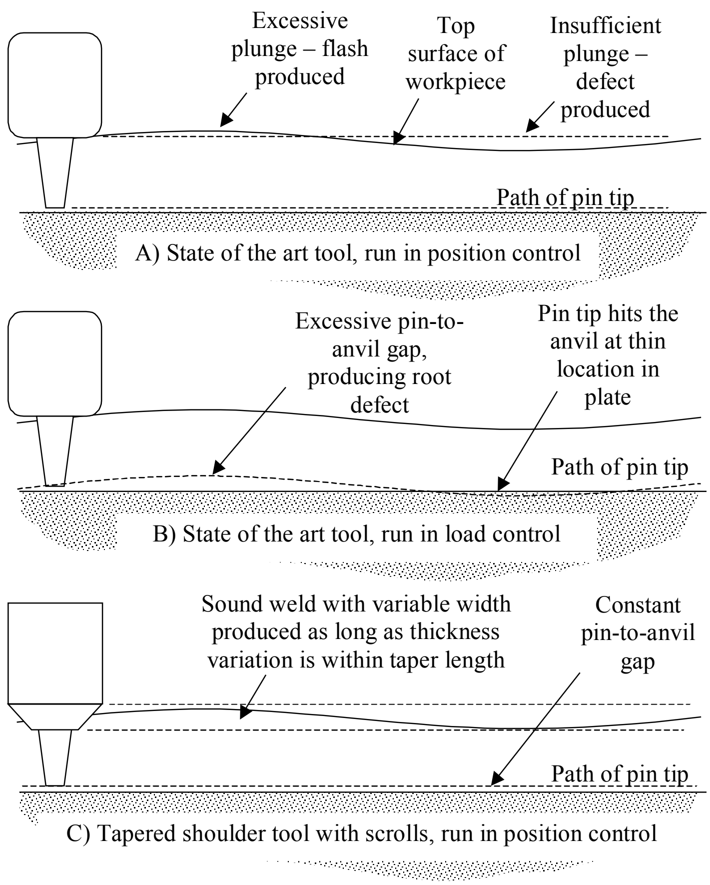


Figure 3. Strategies for welding workpiece that has variation in thickness.

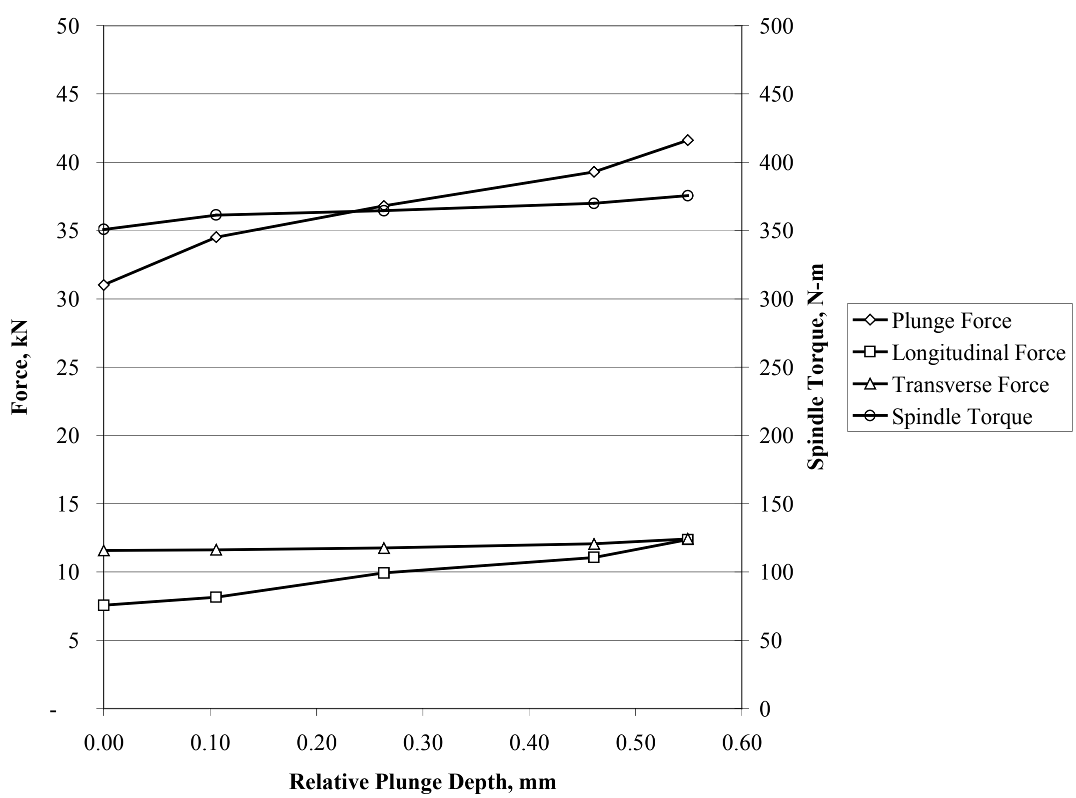


Figure 4. Weld forces as a function of relative plunge depth for 25.4-mm plate of Al alloy 5083-H116.

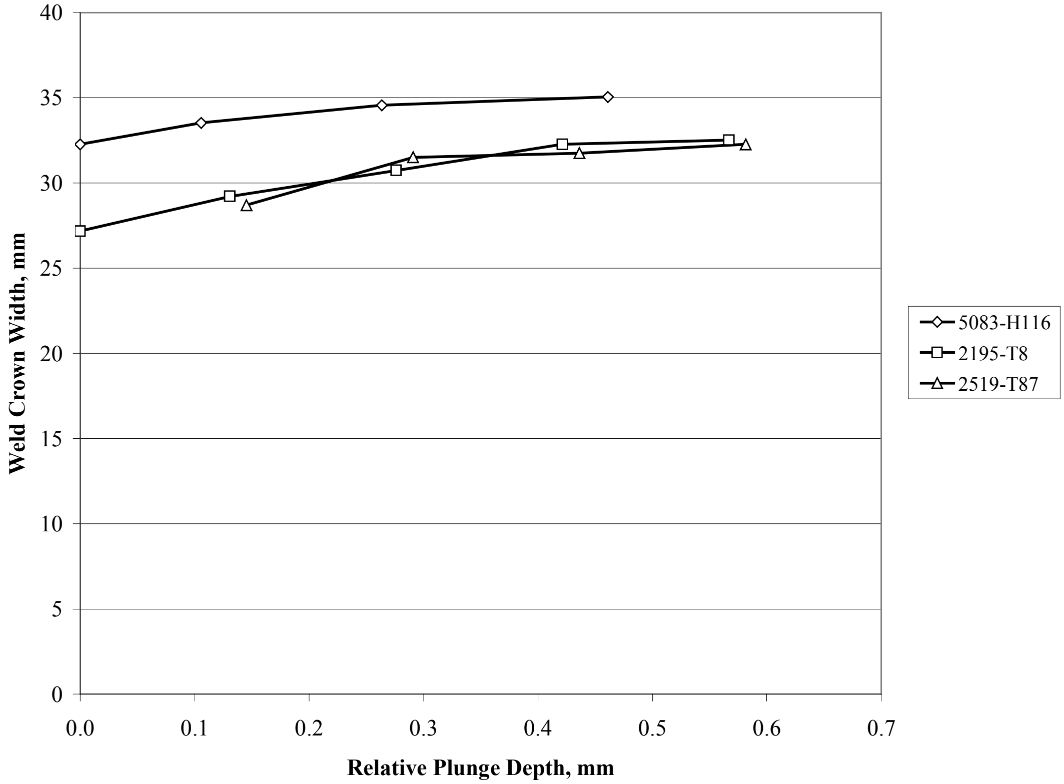


Figure 5. Weld crown width as a function of relative plunge depth for three aluminum alloys.

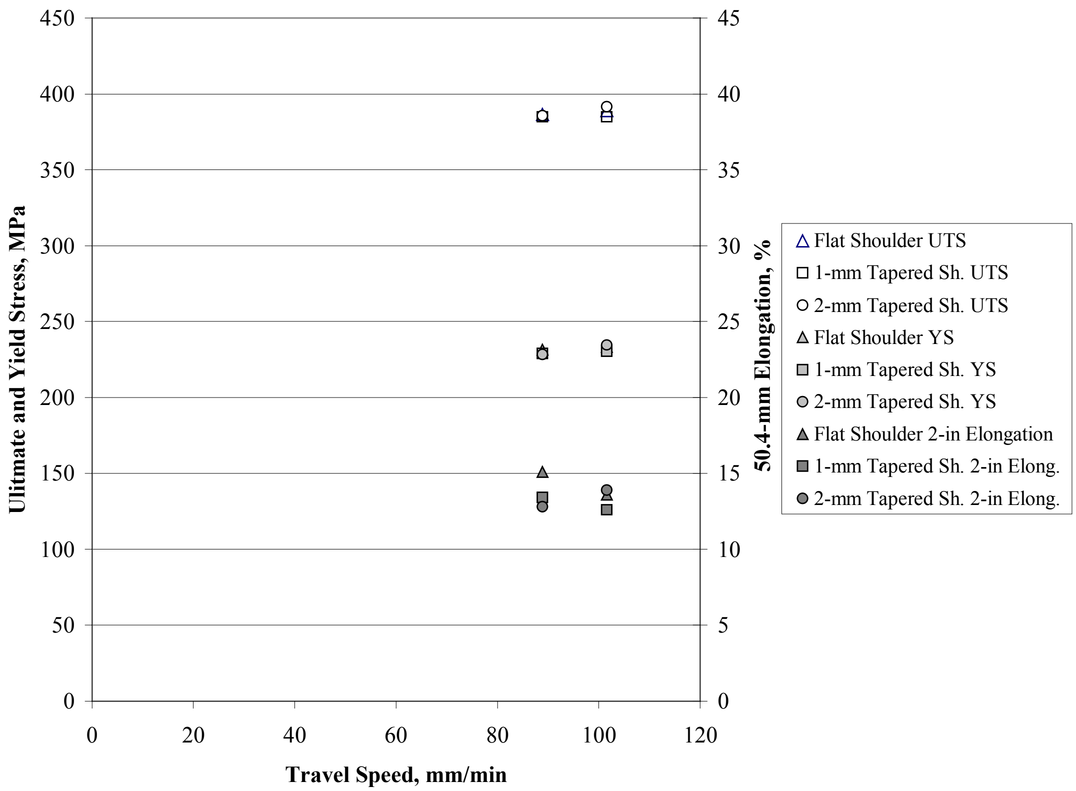


Figure 6. Tensile properties from flat, 1-mm tapered and 2-mm tapered shoulders, friction stir welds in 25-mm 2519-T87 aluminum plate.

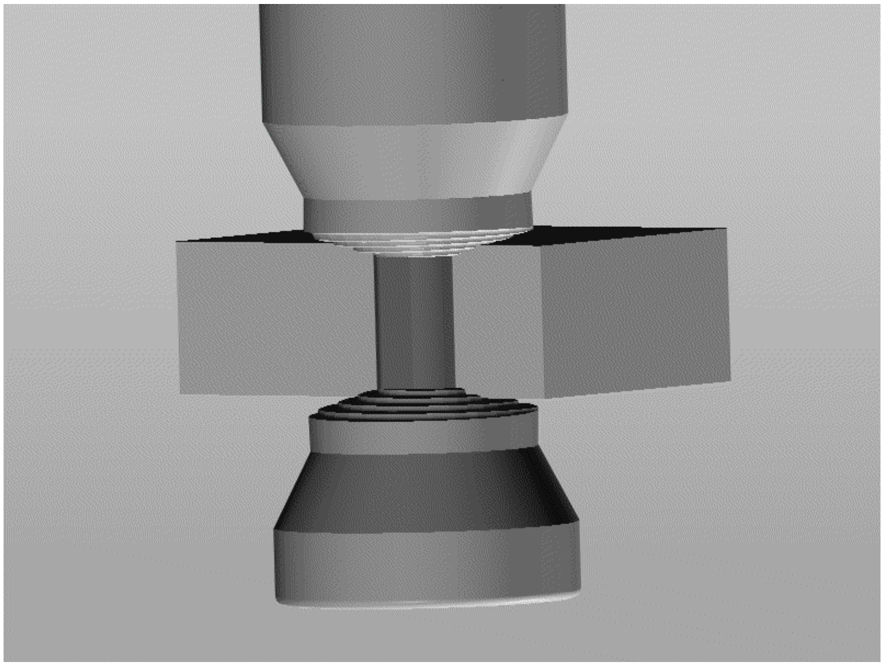

Figure 7. Fixed-geometry bobbin tool using tapered shoulder profile (workpiece cut away for clarity).

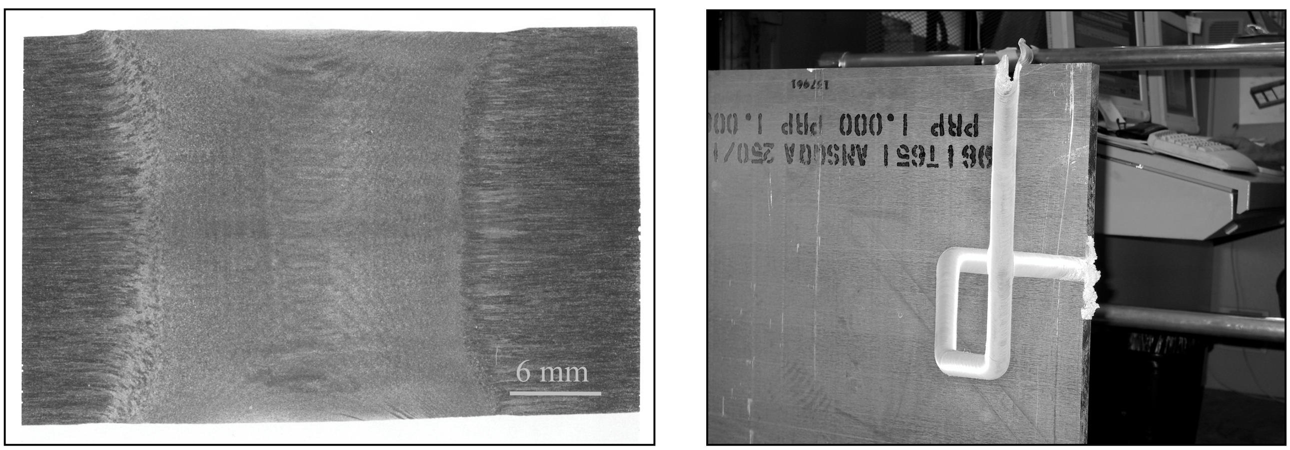


Figure 8. (left) Macrograph from bobbin tool weld in 25.4-mm 6061-T6, (right) bead-on-plate bobbin weld in 25.4-mm 6061-T6.  Note entry of bobbin tool from side of plate.

Figure 9. Tapered shoulder tool used to weld thick-wall aluminum pipe.