Friction Stir Welding of Thin Aluminum Using Fixed Gap Bobbin Tools

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Abstract

Friction stir welding (FSW) of aluminum components using both fixed and variable gap bobbin tools has been demonstrated by several researchers, and reportedly these procedures were relatively easy to develop. However, in materials below approximately 6-mm thickness, weld initiation was reported to be difficult. Bobbin welds do not have an initial phase where the welding tool probe is plunged axially into the workpiece as is done in conventional FSW. Bobbin welds are typically started by driving onto the edge of the plate or from a pre-drilled hole with an initially slow travel speed until plastic deformation starts, followed by acceleration of the travel speed to the final steady state value. In thin materials, the two main problems are tearing of the workpiece edge, where a piece of material tears away and becomes lodged in the welding tool gap, or accumulation of a solid mass of material within the gap. Both of these conditions make weld initiation unlikely and typically require stopping the weld, cleaning the tool components, and discarding the components being welded. Based on many experiments with weld initiation in 5XXX and 6XXX aluminum extrusions using fixed-gap bobbin tools, welding tool designs and procedures have been developed that can permit welding in aluminum alloys as thin as 3-mm. It has been found that these welds require strict adherence to procedures, but upon doing so, reliable welding procedures can be developed.

Keywords: friction stir welding, bobbin, aluminum welding

Introduction

Fixed gap bobbin tools were considered very early in the development of FSW by researchers at The Welding Institute (TWI), based on the perceived benefit of internalizing the axial force on the welding tool and eliminating the welding fixture anvil. However, practical demonstration of the bobbin technique did not occur until other researchers introduced the variable-gap bobbin tool, combining a movable probe with shoulders designed with spiraled scrolls [1-4]. The first practical fixed-gap bobbin tool was based on the use of a tapered shoulder [5, 6], which made possible welds that accommodate variation in workpiece thickness by permitting variable embed of the shoulder into the workpiece, producing welds of variable width.

Starting in 2006, researchers at CTC began developing fixed-gap bobbin tools for welding thin aluminum structures for shipbuilding applications [7]. It was discovered early in the program that aluminum materials below about 6-mm thick were very difficult to weld based on problems associated with weld startup. Other researchers have acknowledged the difficulties associated with bobbin welding thin aluminum workpieces [3, 4]. These researchers reported problems with weld initiation which resulted in the welding tool essentially tearing a "coarse groove through the material". Experience at CTC produced the same effect, as shown in Figure 1.

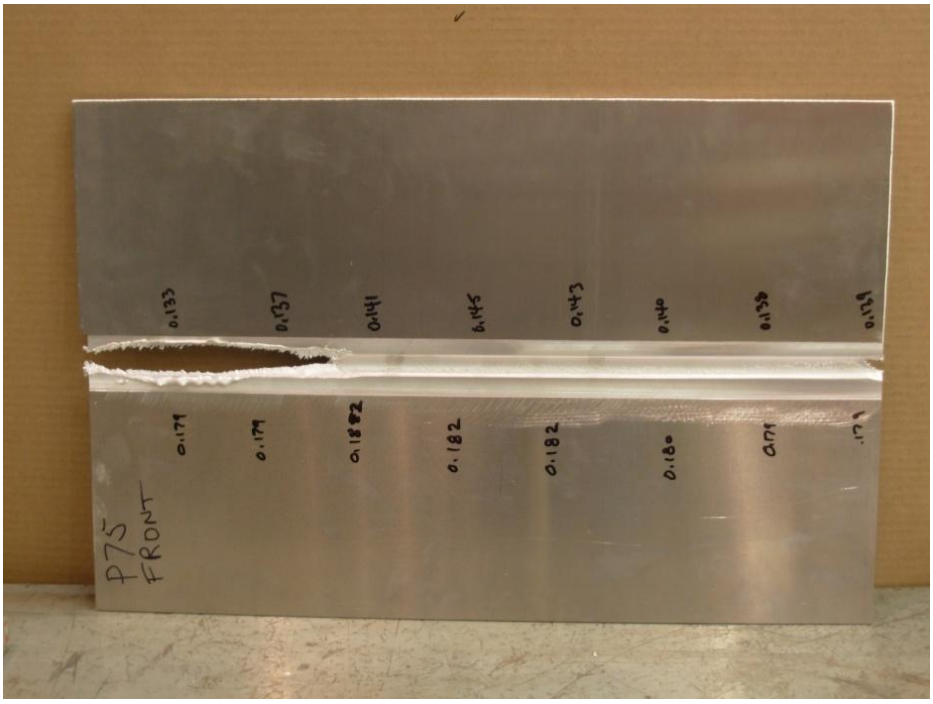

Figure 1. Delayed weld initiation, 4-mm 5083-H116 fixed-gap bobbin weld.

Extensive testing has isolated a number of welding tool design and welding procedure details that relate to the reliability of weld initiation in thin aluminum materials. All of the tests performed were done with fixed-gap bobbin tools, but it is likely that many of the observations and solutions will apply to both fixed and variable-gap bobbin FSW. This paper will describe weld initiation failure, and will present the main factors related to weld initiation reliability. Welding tool designs and welding machine operation parameters will then be presented, along with typical joint strength measurements for several alloys.

Weld Initiation Failure

Weld initiation failure came to be referred to as plugging, since it is characterized by a mass of workpiece material lodged within the gap between the shoulders of the bobbin tool, as shown in Figure 2. Two distinct types of weld initiation failure were identified during this study. The first type was referred to as tear-out plugging, where a discrete piece of the workpiece tears away and becomes lodged within the shoulder gap, which then prevents weld initiation, as shown schematically in Figure 3. The second type of weld initiation failure is referred to as an accumulation plug; where workpiece material appears to lodge at some small feature of the welding tool, then accumulate from that point to fill the shoulder gap. An example of this is shown in Figure 4 where the back-side shoulder has been removed. Other accumulation plugs appear to originate from a broader area, resulting in complete filling of the shoulder gap.

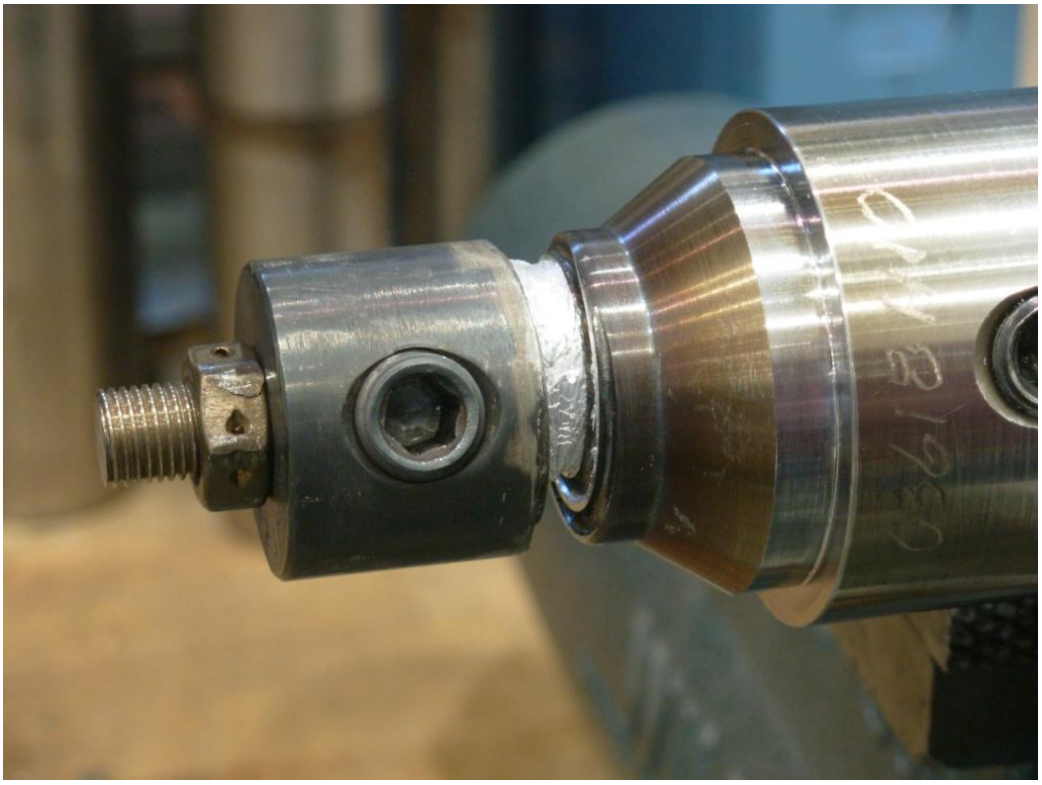

Figure 2. Plugged bobbin tool.

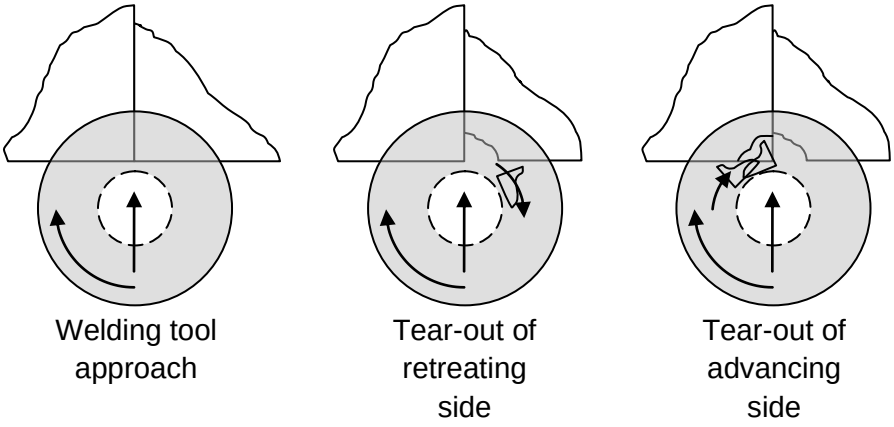

Figure 3. Initiation of a tear-out plug.

Figure 4. Example of an accumulation plug, with back-side shoulder removed to reveal workpiece material lodged in shoulder gap.

Weld Initiation Reliability

Many factors were identified to influence weld initiation reliability. These factors relate to welding tool design, welding parameters, and welding technique, as listed in Table 1. This section will discuss these factors as they relate to weld initiation.

Table 1. Factors Related to Weld Initiation Reliability.

Welding Tool Design Factors	Workpiece Factors	Welding Procedure Factors
Shoulder embed	Material product form	Initial travel speed
Stagnation points	Joint gap	Initial spindle speed
Counter-bore depth	Workpiece edge alignment	Welding tool surface condition
Counter-bore diameter	Heat-softened material in advance of pin	Fixture rigidity
Probe flat depth		Welding tool feature condition
Probe thread depth		
Probe/bore clearance		
Shoulder scroll depth		

All of the welds made in this study were performed on the Low-Cost FSW system (LC-FSW), shown in Figure 5. This system was developed by CTC in response to a need for low cost welding equipment capable of producing large, integrally stiffened panels for Navy shipbuilding applications. The LC-FSW system uses pneumatically and electrically actuated rollers to guide and drive workpiece materials through the machine during welding. The spindle is mounted beneath the workpiece in the bed of the machine, providing maximum

stability, and the system makes all welds using fixed-gap bobbin tools. Since workpiece materials are always presented to the spindle at the elevation of the table of rollers, any difference in thickness between the two workpieces being joined is biased to the upper side of the workpiece, while the side exposed to the spindle is always flush.

Figure 5. LC-FSW system, joining 63-in wide extrusions.

Welding Tool Design

Over the course of the development program, many different welding tool design variations were tested with the goal of improving startup reliability. For thin aluminum materials, two main designs emerged based on testing with 5xxx-series and 6xxx-series aluminum alloys. Certainly, other designs or design features are possible.

Welds were made in 4-mm thick and 5-mm thick 5083-H111 and 5083-H116, and in 5-mm thick 5454-H111 materials. The welding tool design that was ultimately adopted for thin 5xxx-series aluminum is shown in Figure 6. The spindle-side shoulder was essentially flat, with three interleaved, spiral scrolls which ran from the periphery of the shoulder to a central counter-bore. The counter bore was typically made with a depth equal to the scroll depth and a diameter that was developed in each case by trial and error. The probes had thread-shaped features interspersed with flats cut into the probe surface, and the thread features alternated between left-hand and right-hand orientation, which was shown to improve distortion and breakup of the residual oxide band. The back-side shoulder was tapered, with three spiraled scrolls and a counter-bore.

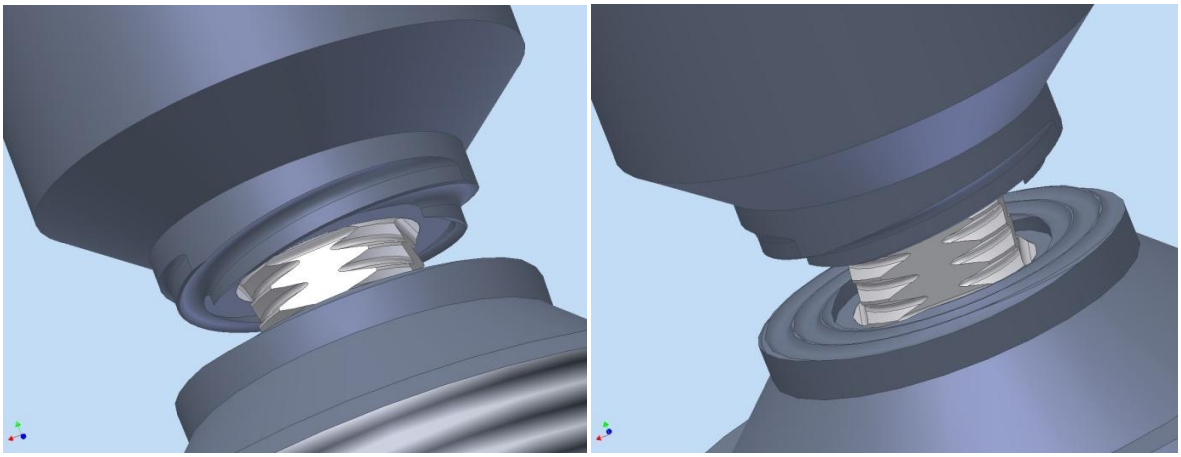

Figure 6. Fixed gap bobbin tool for thin 5xxx-series aluminum alloys, (left) view of back-side shoulder, (right) view of spindle-side shoulder.

A tool of similar description was developed for thin 6061-T6 extrusions, as shown in Figure 7. This tool had back-side shoulder and probe features that were generally the same as the tool for 5xxx alloys, but the spindle-side shoulder was flat and smooth. It was speculated that since 6061 rapidly softens with increasing temperature, the smooth spindle-side shoulder reduced torque during startup, thus contributing to improved startup reliability.

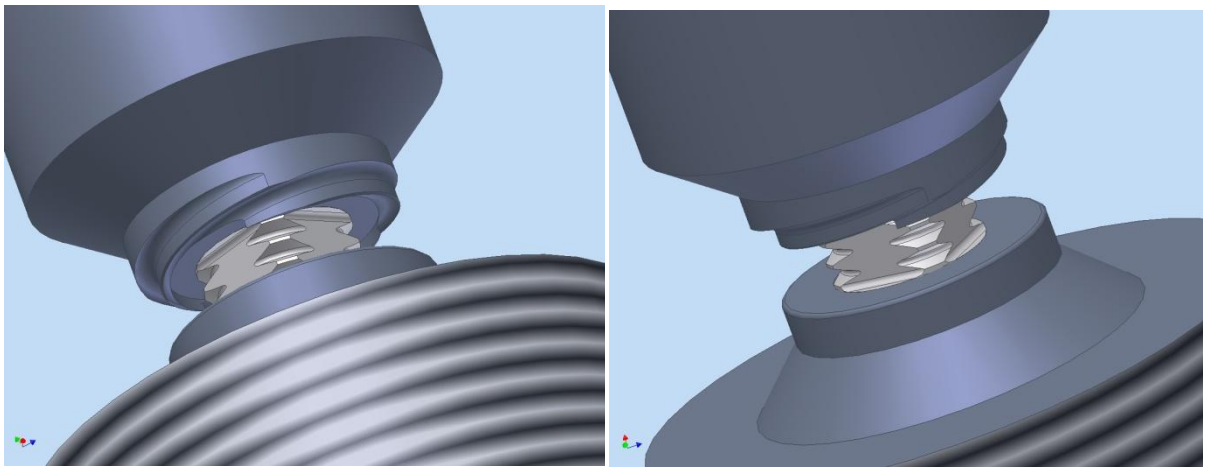

Figure 7. Fixed gap bobbin tool for thin 6061-T6 aluminum, (left) view of back side shoulder, (right) view of spindle side shoulder.

The main design features of fixed-gap bobbin tools for thin materials are shown schematically in Figure 8. In this figure, the dotted lines represent the hidden counter-bores and scroll features. As can be seen, the scroll pattern on the spindle-side shoulder is flat, since the welding system used aligned the workpiece faces exposed to this side. The shoulder is run essentially flush with the workpiece surface on the spindle-side. The scroll pattern on the back-side shoulder is tapered parallel to the general tool profile. Welding tool design parameters for specific materials are summarized in Table 2. For a welding system that aligns the workpiece faces adjacent to the back-side shoulder, the welding tool design may be reversed to place the flat shoulder profile on the back-side shoulder. It should be noted that at the bottom of Table 2, a welding tool assembly parameter, referred to as back-side embed, is specified. This refers to the amount that the back-side shoulder is embedded into the workpiece surface. The gap between the shoulders can be calculate as the welding

tool thickness, minus the shoulder embed. By setting the welding tool up in this way, if the spindle-side shoulder is maintained flush with the workpiece surface, the back-side shoulder will be embedded into the opposite surface by the correct amount.

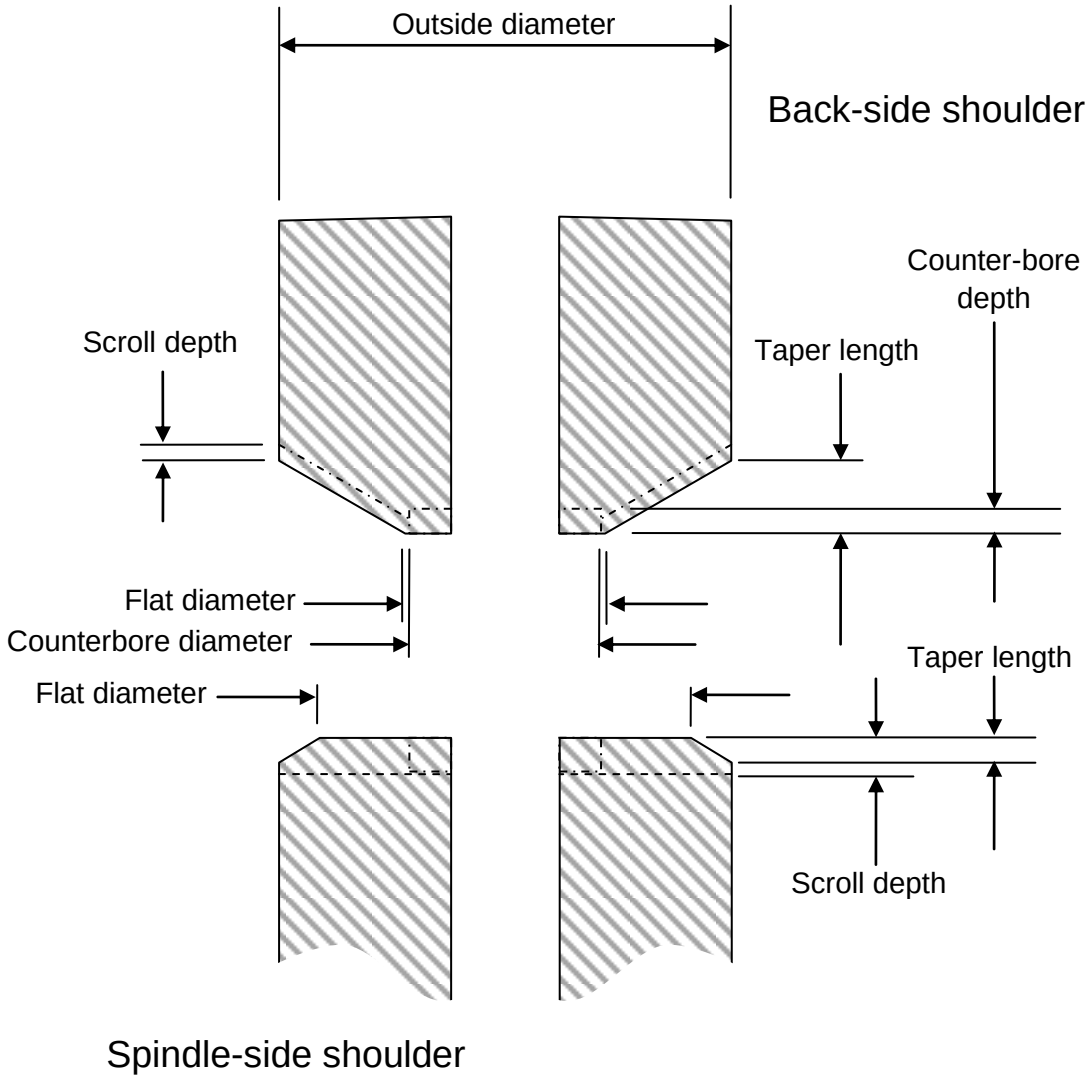

Figure 8. Schematic showing key fixed-gap bobbin tool design features.

Table 2. Welding Tool Design Parameters for Various Extruded Materials.

Parameter	3-mm 6061-T6	4-mm 6061-T6	5-mm 6061-T6	4-mm 5083-H111	5-mm 5083-H111 and 5454-H111
Spindle-side shoulder					
Outside diameter, mm	15.7	16.5	19.0	19.1	21.6
Flat diameter, mm	-	-	-	16.3	16.5
Scroll spacing, mm	-	-	-	1.5	1.5
Scroll width, mm	-	-	-	1.4	1.4
Scroll depth, mm	-	-	-	0.4	0.4
Number of spirals	-	-	-	3	3
Counter-bore dia., mm	-	-	-	11.4	12.7
Counter-bore depth, mm	-	-	-	0.8	0.75
Material	Viscount 44	Viscount 44	Viscount 44	Viscount 44	Viscount 44
Back-side shoulder					
Outside diameter, mm	16.2	16.3	16.3	16.3	16.3
Flat diameter, mm	13.5	13.7	13.7	13.7	13.7
Taper length, mm	0.8	1.3	1.3	1.3	1.3
Scroll spacing, mm	1.2	1.5	1.5	1.5	1.5
Scroll width, mm	1.6	1.6	1.6	1.6	1.6
Scroll depth, mm	0.4	1.2	1.2	1.2	1.2
Number of spirals	3	3	3	3	3
Counter-bore dia., mm	12.7	12.9	12.9	12.9	12.9
Counter-bore depth, mm	0.3	0.8	0.8	0.8	0.8
Material	Viscount 44	Viscount 44	Viscount 44	Viscount 44	Viscount 44
Probe					
Major Diameter, mm	7.9	9.5	9.5	9.5	11.4
Minor Diameter, mm	7.9	9.5	9.5	9.5	9.5
Number of flats	4	4	4	4	4
Number of threads	3	3	4	3	5
Depth of flats, mm	0.6	1.0	0.8	0.8	0.9
Thread pitch, threads/mm	0.74	0.74	0.85	0.85	0.89
Thread depth, mm	0.5	0.8	0.7	0.7	0.7
Length of flats, mm	2.9	4.4	5.0	5.0	4.5
Material	MP159	MP159	MP159	M4	M4
Assembly					
Back-side embed, mm	0.38	0.51	0.51	0.51	0.76

Each of the tool design features listed in Table 1 as being related to weld initiation are discussed below, followed by discussion of the workpiece and welding procedure factors.

Shoulder embed refers to the distance the back-side shoulder is embedded into the workpiece surface. This provides the needed tolerance to workpiece thickness variability.

This factor relates to startup reliability due to the tendency for deeper embed of the shoulder to tear the edge of the workpiece during weld startup, producing a tear-out plug. By reducing the shoulder embed, this tendency can be reduced. For thin materials, a shoulder embed on the order of 0.5-mm is typical, although each alloy has different settings.

Stagnation points are features or damage to the welding tool surface which may collect workpiece material, which then begins rotating with the welding tool. An example of such a stagnation point, in this case produced by probe flats extending into the bore in the back-side shoulder, is shown in Figure 9. Such features provide the initial attachment of a plug, which grows beyond the stagnation point to fill the gap between the shoulders, preventing weld initiation.

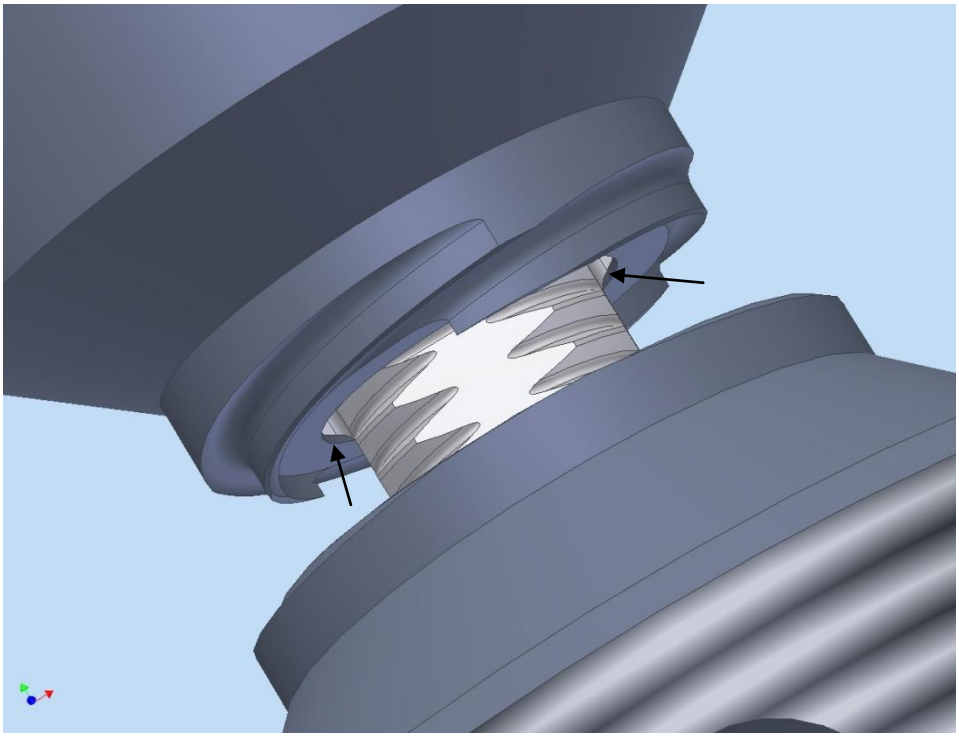

Figure 9. Illustration of stagnation points in bobbin tool design, in this case arising from probe features extending into the bore of the back-side shoulder.

Counter-bore depth, counter-bore diameter, probe flat depth, and probe thread depth all interact to produce a type of stagnation point, resulting from a variable-width flow path in the counter-bore region, shown in Figure 10. This “pinch point” in the counter-bore can initiate accumulation of workpiece material, but at the same time it provides needed drag on workpiece material to initiate welding, since when this restriction was eliminated in an experimental tool, weld initiation proved impossible. On the probe, the thread depth and flat depth can be used along with the counter-bore diameter and counter-bore depth to regulate this variable-width flow path to provide sufficient drag to initiate welding without pinching the flow so much as to produce stagnation or accumulation of workpiece material.

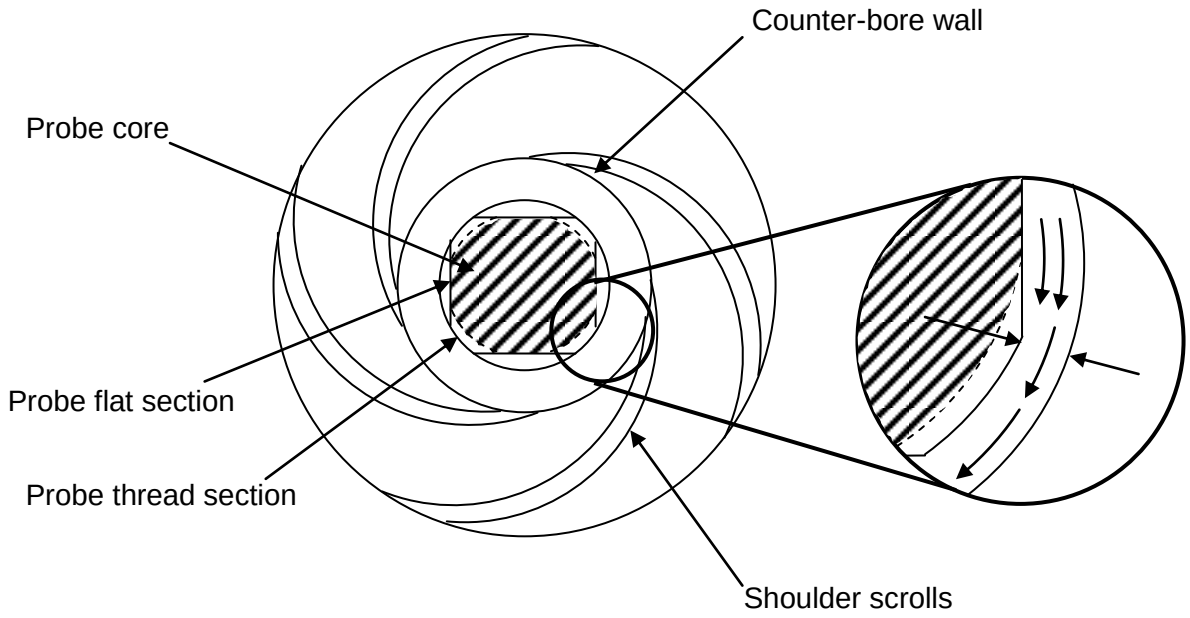

Figure 10. End view of shoulder features, with section of probe, showing variable flow area within counter-bore region.

Probe-to-bore clearance, if excessive, influences weld initiation by permitting “wobble” in the back-side shoulder. This can result in variation in the gap between the shoulders, as shown in Figure 11, causing the gap to cyclically pinch the edge of the workpiece, resulting in tear-out plugging. By maintaining a snug fit between the probe and the bore, smooth rotation of the probe and back-side shoulder ensures smooth rotation of these components, avoiding this source of plugging.

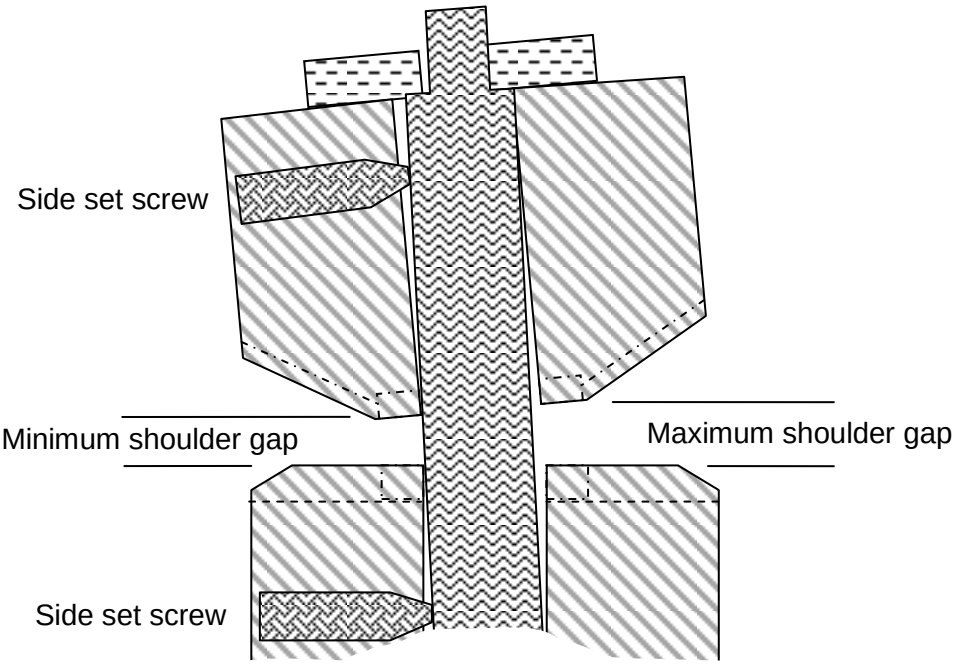

Figure 11. Probe/bore clearance leading to variation in shoulder gap (clearance exaggerated for effect).

Scroll depth relates principally to the formation of tear-out plugging, but plays an indirect role also in accumulation plugs. Aggressive scroll features increase cutting of the scroll into the workpiece surface, which can tear away the corner of the workpiece, lodging the fragment in the shoulder gap, as shown in Figure 3. This feature also plays an indirect role in accumulation, since it is related to the depth of the counter-bore, which plays a role in regulating the variable flow path there, as described earlier.

Workpiece Factors

Material product form refers to the method of producing the workpiece material, such as by extrusion, casting, rolling, or forging processes. The issue seems to come from the mechanical properties of the base metal, since compositional differences are restricted by the base metal specification. For example, a weld startup procedure developed for 5083-H116 plate was not successful in weld initiation in 5083-H111 extruded material. Although the two materials were of essentially the same composition, their mechanical properties were apparently sufficiently different to prevent transfer of the weld startup procedure from one material to the other.

Joint gap often resulted in weld initiation failure, possibly due to tear-out of the corner of a workpiece. This was a case where it was difficult to observe the root cause of the plugging, but it was often noted to cause a plug, by an unknown mechanism. When the joint was not closed at the start of the weld, it could be that the loss of mutual support between the two sides of the joint resulted in a higher probability of tear-out plugging.

Workpiece edge misalignment was also noted to often result in tear-out plugging, possibly by a similar mechanism to the suggestion given for joint gap. The protruding edge of one

workpiece is more vulnerable to tear out since it is not supported by the opposite workpiece, increasing the likelihood of weld initiation failure.

Heat-softened material in advance of the pin was found to cause accumulation plugging. A failed start-up attempt or aborted weld sequence dispersed enough heat in advance of the tool to soften the workpiece material locally, especially in the 6061 alloy welds, which made it nearly impossible to re-start the weld without cutting 50 to 75 mm of material away.

Welding Procedure Factors

Initial travel speed and initial spindle speed both played a critical role in weld initiation. If insufficient heat was generated on initial contact, the welding tool simply cut its way through the workpieces without initiating welding. If these parameters were too high, a form of accumulation plug resulted where there was not a single origin to the accumulation, but the plug seemed to grow from the probe features outward, completely filling the shoulder gap. A process of trial and error was required to find travel and spindle speed combinations that resulted in weld initiation. Startup parameters developed on this program are given in Table 3. It was interesting that, compared to the 5083 startup procedures, the initial spindle speed for 5454 extrusions was significantly higher, possibly due to the lower base metal yield strength, requiring higher relative speed to generate a similar initial energy input. Similarly, the 6061 extrusions required higher initial spindle speed, possibly due in part to the higher rate of softening with respect to temperature and in part to the higher thermal conductivity of this alloy, compared to 5083.

Table 3. Weld Startup Machine Parameters, Extruded Materials.

Alloy	Material Thickness (mm)	Initial Travel Speed (mm/min)	Initial Spindle Speed (rev/min)
5083-H111	4	46	600
5083-H111	5	46	500
5454-H111	5	61	900
6061-T6	3	44	1,400
6061-T6	4	43	800
6061-T6	5	43	800

All tools had 9.5-mm probe diameter except 3-mm 6061 tool, which had 8-mm probe.

Welding tool surface condition also played a critical role in weld initiation. It was found to be essential that the welding tool surfaces slide against the workpiece during weld initiation, so anything that promoted adhesion between the tool and the workpiece and resulted in accumulation of workpiece material prevented weld initiation. This was first noted on the current project when it was found that a welding procedure was developed for 5083 aluminum that would always successfully initiate a weld on the first attempt, but could never be successful on the second attempt. Initially, sodium hydroxide solution was used to clean the welding tool between experiments, essentially restoring them to the as-machined condition. Eventually it was found that brushing the tool with a brass bristle brush also worked. It was initially assumed that the brush was cleaning residual aluminum, but further analysis revealed that the brass brush was simply coating residual aluminum with a thin layer of brass, which apparently prevented cohesion between the tool and the workpiece during startup, preventing accumulation.

In the experiments that were performed with various thin aluminum alloys, it was found that any tool used to weld 6061-T6 could not be used to weld 5083 without cleaning in sodium hydroxide, even if the tool was brushed with a brass brush. The underlying cause was not studied in the course of this program. Welds in 5454 required cleaning in sodium hydroxide in all cases. Welds in 6061 and 5083 only required brushing with a brass brush.

Fixture rigidity, which includes rigidity of the welding head, the workpiece, and the fixture, influences tear-out plug formation, since the forces that develop as the tool initially contacts the workpiece can cause the welding tool to suddenly surge onto the workpiece, tearing out a corner of the workpiece. The scroll features on the two shoulders both pull workpiece material towards the probe, so as these scrolls enter the workpiece, if there is inadequate rigidity, they can suddenly and rapidly pull the welding tool forward, tearing the workpiece edge and lodging material within the gap between the shoulders, preventing weld initiation.

Welding tool feature condition refers to wear or damage to the scroll and thread features. This was first noted when steel bristle brushes were being used to clean welding tools between experiments. This initially worked as a means of removing residual aluminum from welding tool surfaces, but after several welds it was found that the tools became unreliable with respect to weld initiation. Inspection of the tool revealed that the steel bristle brush had rounded off the tool features, reducing their sharpness, which led to accumulation of aluminum and plugging. Switching to brass bristle brushes was intended to clean the tool without damaging it, which worked well, but for a different reason than was intended, as described earlier. Another welding tool feature condition of relevance is damage to a tool feature from impact, leaving a discontinuity on the tool surface which may promote stagnation of workpiece material.

Bobbin Welds in Thin Aluminum

Once reliable procedures were developed for initiating welds in the materials of interest in this study, welding parameters for making full-length welds were developed. The main welding parameters developed are presented in Table 4. The welding parameters for 4-mm and 5-mm 5083-H111 and 3-mm and 4-mm 6061-T1 were tested to confirm at least 0.75-mm joint gap could be tolerated without a significant reduction in transverse tensile strength. Representative average tensile properties for each alloy are presented in Table 5. As can be seen in the table, good tensile properties were achieved in the alloys studied, and the fixed-gap bobbin results compared favorably with conventional welds made in similar alloys. A representative macro section from a fixed-gap bobbin weld in 5-mm 5083-H111 aluminum is shown in Figure 12 as an example. As can be seen in the figure, the residual oxide band from the original faying surfaces was visible, but was highly distorted. For an optimized welding procedure, the residual oxide band typically did not initiate fracture in transverse tension testing.

Table 4. Main Segment Machine Parameters, Extruded Materials.

Alloy	Material Thickness (mm)	Travel Speed (mm/min)	Spindle Speed (rev/min)
5083-H111	4	762	360
5083-H111	5	635	360
5454-H111	5	508	490
6061-T6	3	2,540	1,100
6061-T6	4	2,032	800
6061-T6	5	2,032	700

Table 5. Average Transverse Tensile Properties, Extruded Materials

Alloy	Material Thickness (mm)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	50-mm Elongation (%)
5083-H111	4	294	167	15.8
5083-H111	5	301	168	13.4
5083-O*	5.9	298	141	-
5454-H111	5	228	123	14.7
6061-T6	3	215	157	6.0
6061-T6	4	225	163	7.3
6061-T6	5	210	143	7.4
6061-T6**	6.4	228	143	7.7

*Conventional FSW [8]
**Conventional FSW [9]

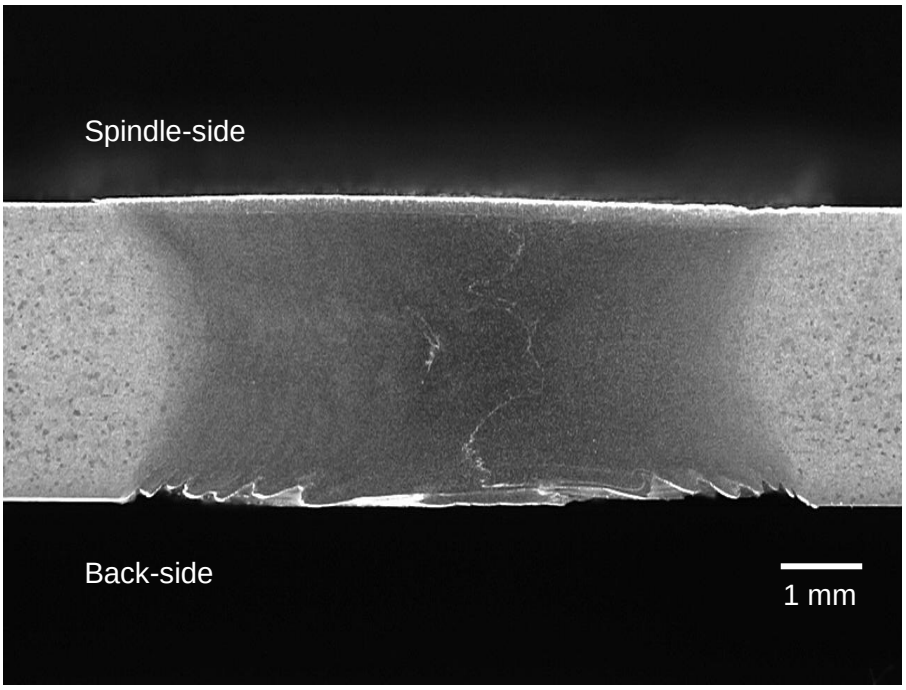

Figure 12. Representative macro section, 5-mm 5083-H111.

A typical weld startup and finish is shown in Figure 13. The arc of plastically deformed material in the startup came to be referred to as a “rooster tail”, and is produced by the smooth ejection of workpiece material as the welding tool enters the plate from the side. The weld end is produced when the welding tool is simply run off the edge of the workpiece. Other practitioners initiate bobbin welds from a hole drilled on the center of the joint, which is most convenient for circumferential welds.

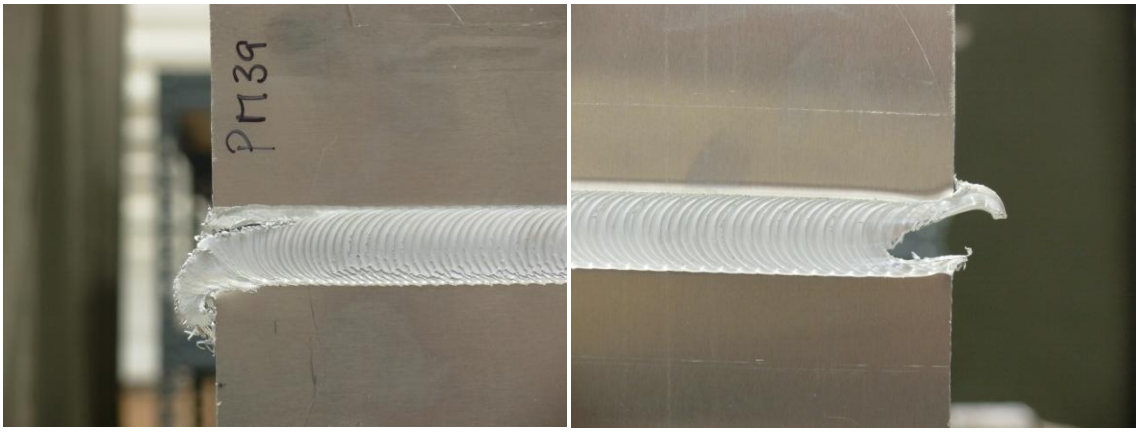

Figure 13. Typical weld start (left) and weld end (right), fixed-gap bobbin weld in 5-mm 5083-H116 plate.

An additional lesson was learned on this program with respect to making long welds using fixed-gap bobbin tools. Welding procedures were initially developed on a small welding system using workpieces that were approximately 1-m long. When the first procedure was used to make 6.1-m welds on the LC-FSW system, it was found that up to about 4.6-m of sound weld could be reliably produced in 5-mm 5083, at which point the weld would fail and workpiece material would become lodged in the gap between the tool shoulders. It was found, however, that if a blast of compressed air was directed at each of the shoulders during welding, the weld would weld as much as 12.2-m without incident. Apparently, the air blast resulted in stabilization of the welding tool temperature, avoiding over-heating and weld failure. With other materials, such as 3-mm 6061-T6 extrusions, the air blast was not needed, and in fact was itself associated with spontaneous weld failures. It is expected that this aspect of the welding procedure should be evaluated on a case-by-case basis in order to achieve a stable welding process that can produce long welds.

Fixed-gap bobbin tools were used to produce a number of large, integrally stiffened panels using the LC-FSW system, as shown in Figure 14. This demonstration was intended to confirm that large panels (6.1-m long by 3-m wide) could be produced on the system, and to evaluate the accuracy of the combined extrusion trimming and welding processes with respect to spacing of the stiffeners. The panel shown in the figure was produced with less than 2-mm true-position tolerance in stiffener spacing over the width of the panel, meeting end-user requirements. It was found that it was most important to avoid systematic bias in the trimming and welding processes in order to hold the required tolerances.

Figure 14. Welded panel, produced on LC-FSW system using fixed-gap bobbin tool, 5-mm 5083-H111.

Conclusions

Development of fixed-gap bobbin tools for welding thin aluminum extrusions led to identification of several factors related to weld initiation reliability. Any of these factors can lead to weld initiation failure, so strict adherence to welding procedure is crucial for successful application of this technique in a production environment. However, once procedures were developed, the tests performed indicate that welds with good cosmetic appearance, low distortion, and acceptable strength are possible. Based on this success, the operational advantages of fixed gap bobbin tools, including the elimination of applied force perpendicular to the plane of the workpiece, the elimination of defects related to incomplete weld penetration, and the possibility of implementing the LC-FSW system in a production application, are achievable.

Acknowledgements

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