Effect of Pin tool Shape on Metal Flow During Friction Stir Welding

J.C. McClure, E. Coronado, S. Aloor, B. Nowak, L.M. Murr, A.C. Nunes, Jr.*

Metallurgical and Materials Engineering Department
University of Texas El Paso
* NASA, Marshall Space Flight Center, Huntsville, AL

Abstract

It has been shown that metal moves behind the rotating Friction Stir Pin Tool in two separate currents or streams. One current, mostly on the advancing side, enters a zone of material that rotates with the pin tool for one or more revolutions and eventually is abandoned behind the pin tool in crescent-shaped pieces. The other current, largely on the retreating side of the pin tool is moved by a wiping process to the back of the pin tool and fills in between the pieces of the rotational zone that have been shed by the rotational zone. This process was studied by using a faying surface copper trace to clarify the metal flow. Welds were made with pin tools having various thread pitches. Decreasing the thread pitch causes the large scale top-to-bottom flow to break up into multiple vortices along the pin and an unthreaded pin tool provides insufficient vertical motion for there to be a stable rotational zone and flow of material via the rotational zone is not possible leading to porosity on the advancing side of the weld.

Introduction

Friction Stir Welding (FSW) is a solid state welding process patented by The Welding Institute[1] in 1991. A rotating pin tool is passed along a butt weld seam literally stirring the faying surface of the weld together. Typically, the diameter of the pin tool is equal to the thickness of the parts to be welded and its length is slightly shorter than the thickness of the part. The pin tool is capped by a larger diameter shoulder necessary to prevent weld metal from rising around the tool which would result in a plowing, not a welding, operation. Weld metal is sheared below the shoulder as well as around the pin. The pin and shoulder jointly produce a pattern of metal flow around the tool that generates heat and reduces the stresses at which the metal flows.

Various pin tool shapes are used but most are threaded and rotated during welding in such a direction that the threads push weld metal down the pin tool away from the shoulder. Typical rotational velocities are several hundred revolutions per minute and welding speed is comparable to fusion welding speeds. Aluminum has been most successfully welded by FSW, but Magnesium alloys[2], Titanium, and metal matrix composites[3] have also been welded. Although butt joints are the most common application of FSW, lap welds have been made with efficiencies higher than obtained by fusion welds.[4]

Since no melting takes place during FSW [5,6] the question of how solid material flows from the front of the pin tool to the rear during weld is of both theoretical and practical interest for pin tool designers. There have been previous studies of this flow. Steel balls[7] and thin aluminum sheets of a different alloy than the work piece,[8] have been imbedded along the faying surfaces of welds. The location of the tracers after welding was determined either by X-ray radiography or serially etching. From the final position of the tracers, it was difficult to determine their path during welding but it is clear that material moves in a complicated three dimensional pattern. In some cases material seems to have been "stirred" multiple times around the pin tool and in other cases it seems to flow around one side of the rotating pin tool.

There has been extensive pin tool development for higher joint efficiency and longer life[9], but there seems to be very little published on how these different pin tools actually change the flow pattern of metal. This paper will show metal flow results based on pin tools frozen in place during welding. A faying surface copper foil has been used as a tracer, and pin tools with threads of various pitches were studied.

Experimental

Experiments were performed on 0.25-inch (6mm) thick 6061-T6 aluminum. The pin tools were 0.25-inch (6mm) diameter with SAE threads cut to pitches of 14, 20, 32, and 40 per inch. A pin tool with no threads was also used. The pin tools were O-1 tool steel hardened to R_C=50. The shoulder diameter was 0.75-inch (18mm). Lead angle was 1^o and a typical plunge depth was 0.020-inch measured at the back of the shoulder. Unless otherwise noted, rotational and translational speeds were 650 rpm and 2mm/sec (4.7in/min).

A thin (0.0045-inch, 0.01cm) copper foil served as a tracer. The tracer was placed along the faying surfaces before the weld metal parts were clamped to the anvil. After a few inches of weld, the process was abruptly stopped by turning off the power and applying a manual break. The heavily loaded pin tool stops very quickly and becomes frozen into the work piece. Samples were cut either parallel or perpendicular to the axis of the pin tool and were polished and etched with Keller's reagent. Typical etching times were 120 seconds.

Vickers microhardness measurements were made at various places in the weld zone using a 100-gram load.

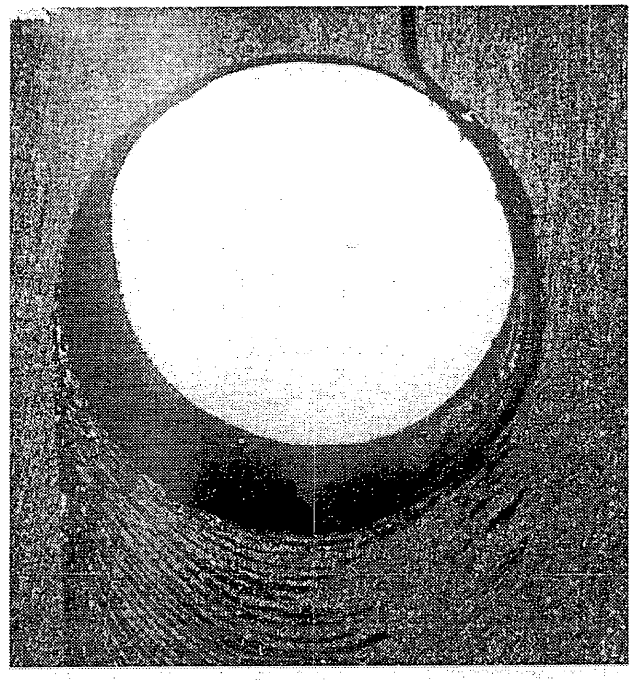


Figure 1 Round feature is frozen pin tool sectioned perpendicular to its axis. Dark rotational zone surrounds the nib. Note faying surface copper tracer at top of picture that bends round the pin tool and breaks up into pieces that are scattered throughout the rotational zone. Advancing side is on left and weld was proceeding upwards in picture.

Fig. 1 shows a section through the frozen pin tool near the mid thickness. The copper foil tracer can be seen at the top of the figure bending around (in the direction of rotation) the dark etching rotational zone that surrounds the pin tool. The copper foil is broken into small pieces at the edge of the rotational zone and small (10-30μm) pieces of the copper are seen throughout the rotational zone. The fact that copper can only enter the rotational zone at the front of the weld while copper particles are seen throughout the rotational zone indicates that the rotational zone rotates with the pin tool and that material near the front of the weld is incorporated within this zone during one or more revolutions of the pin tool.

Fig. 2 shows copper particles from the advancing side of the rotational zone. To correctly indicate flow in a system such as FSW, the tracer should 1) have a total volume small compared to the volume of material moved so that the properties of the work piece are not effected and 2) the dimensions of the particles should be small compared to other relevant dimensions of the flow. In a solid state system such as FSW, the drag forces on the particles are large compared to buoyancy forces so density differences between the copper and aluminum are not significant for determining flow, but, for example, stresses should not be calculated from the size or shape of the particles because the yield stress of copper and aluminum are quite different.

Behind the pin tool in Fig. 1 are crescent shaped bands of dark etching material that are pieces of the rotational zone that are shed by the moving pin tool. Between these features is seen light material that that was rotated around the pin tool but never entered the rotational zone.

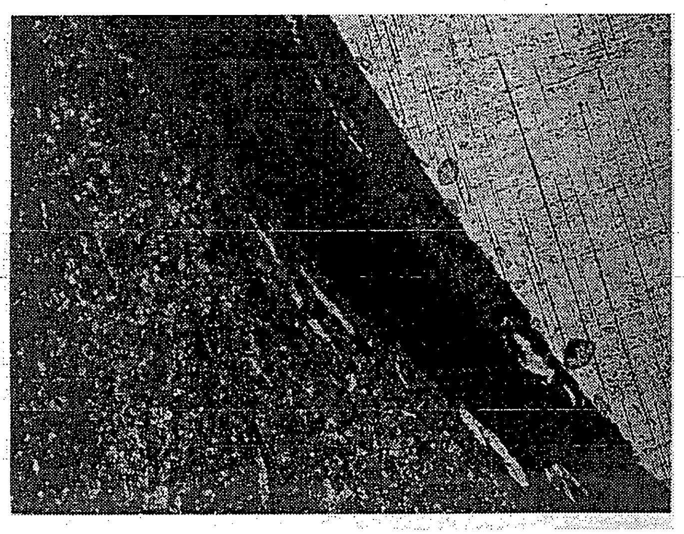


Fig. 2 Small copper particles seen on advancing side of rotational zone. Similar particles are seen throughout the rotational zone.

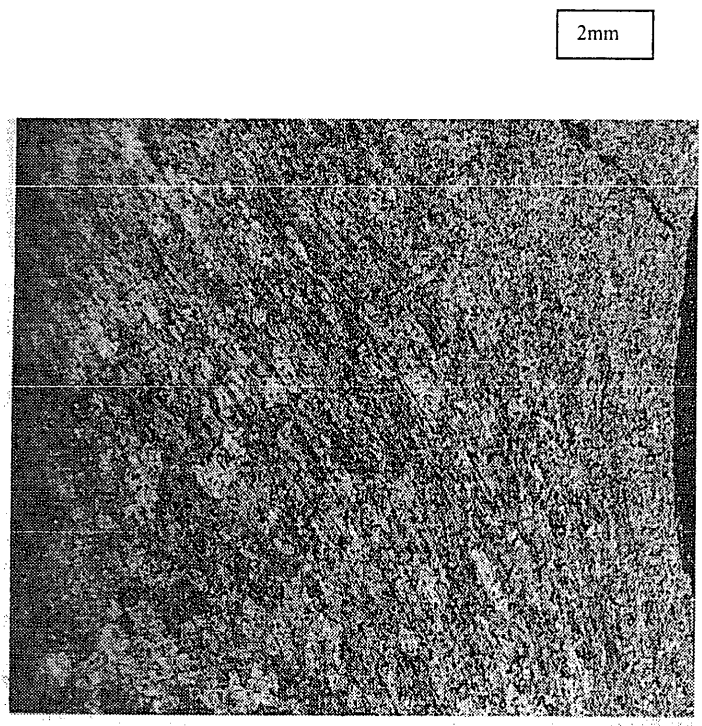


Fig. 3 Microstructure on retreating side of weld showing elongated grains of material being wiped around nib and carried to the back of the weld.

Fig. 3 shows elongated grains from the retreating side of the pin tool that are being moved from to back and becomes these light regions. Copper tracer particles are found throughout the dark features in the wake of the pin tool (just as they are found throughout the rotational zone) but never found in the white material. This indicates that the white material that was rotated around the pin tool (but did not enter the rotational zone) comes only from the retreating side ahead of the pin tool.

The light material in the wake of the weld has similar grain size to the dark features but has a typical Vicker's hardness of 60 compared to hardness of the dark material of 68. The rotational zone (which was in contact with the hot pin tool for several minutes after the weld was stopped and was partially annealed by it) had a hardness of approximately 70.

Welds made on a sample with alloy 2195 on the top of the work piece against the shoulder, and 6061 on the bottom against the anvil have shown [10,11] that material flows vertically within the rotational zone in the wash of the threads. Near the threads, material is moved downward and to conserve volume it must move upward near the outside of the rotational zone. Thus, motion in the rotational zone follows a vortex flow both around the pin tool and vertically downward and then upward.

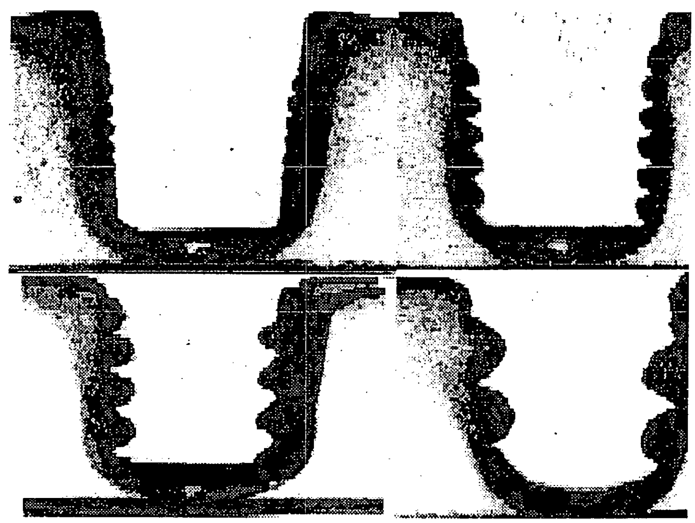


Figure 4 Cross sections of pin tools frozen in place. Top left to bottom right the pin tools 42, 32, 20, and 14 threads per inch. Advancing sides are on right. Note that a dark etching rotational zone is present for all nibs, but Fig. 5 shows that the 14 threads/inch pin tool did not produce a rotational zone with large vertical motion from top to bottom of the weld.

Fig. 4 shows cross sectional views of frozen pin tools having 14, 20, 32, and 42 threads per inch.. The included angles in the threads are the same so the depth of the threads varies. Welds were made at 650rpm and 2mm/sec. (4.7in/min) weld speed. The rotational zone can be seen for all pin tools and porosity free welds were made with all pin tools except the 14 threads per inch tool which had a small pore on the advancing side near the top. Note that in the root of the threads on the 14 threads/inch tool, (seen in Fig. 5) there is an apparent circular motion with large pieces of copper tracer present indicating that the copper does not undergo the same shear forces that the other pin tools produce.

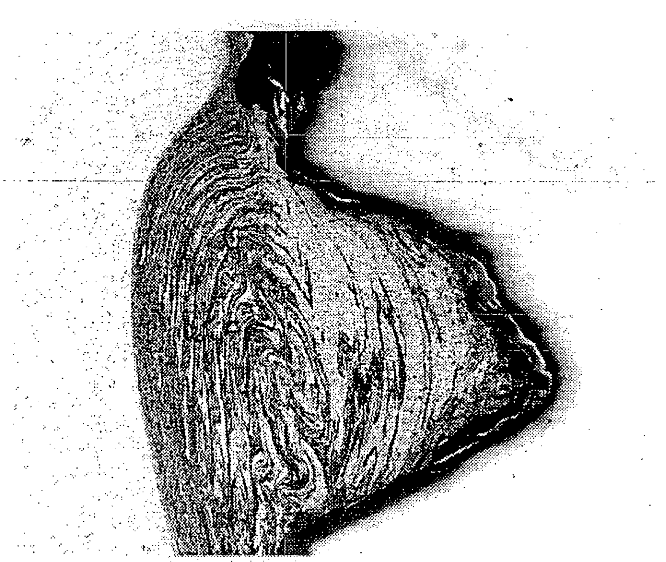
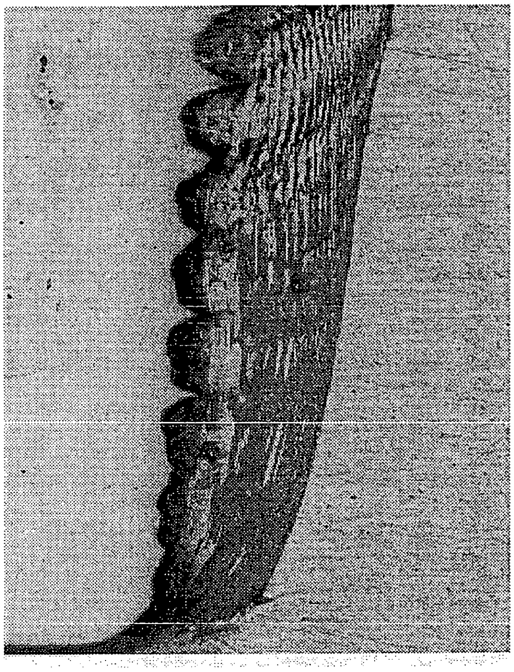


Figure 5 Material in the root of the 14thread/inch pin tool showing rotation of material within the root of the

thread rather than large scale vertical motion. Arrow indicates copper smeared between pin tool and weld metal.

It appears that this weld schedule with this s pin tool does not produce the same large scale top to bottom motion as the tools with shallower more numerous threads. Hardness profiles across the welds for all nibs were similar indicating the different nibs did not produce large differences in heating.



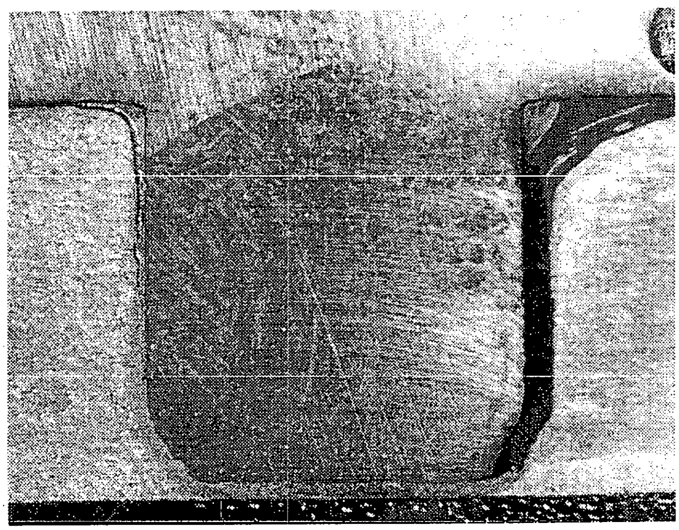


Figure 7 Cross section of unthreaded nib frozen during weld. Advancing side is on right. Note complete absence of rotational zone around pin tool and copper tracer (note arrow) smeared along pin tool rather than broken into pieces.

Fig. 7 shows a cross section of an unthreaded pin tool frozen in place. Welds made with such a pin tool typically show voids on the advancing side. We note an absence of rotational zone and large pieces of copper against the pin tool. There seems to have been no vertical motion of material which is apparently necessary to stabilize the rotational zone and to provide sufficient deformation of material to obtain a sound weld.

Conclusions

1) Material from the advancing side of the weld is transported behind the pin tool via a rotational region of material that rotates with the pin tool. This material may travel once or more around the pin tool while moving up and down in a vortex motion under the influence of the threads.

2) This vortex motion stabilizes the rotational motion A combination of pin tool and weld schedule that produces a poorly developed rotational zone or no rotational zone at all, make poor quality welds.

Fig. 6 Detail of material in the root of the 40 thread/inch pin tool. Note vertical motion of material as contrasted with Fig. 5.

Acknowledgements

The support of the National Aeronautics and Space Administration MURED program is gratefully acknowledged.

---

[1] W.M. Thomas, *et al., Friction Stir Butt Welding*. International Patent Application No. PCT/GB92102203 and Great Britain Patent Application No. 9125978.8

[2] Esparza, J. A., Davis, W.C., E.A. Trillo, Murr, L.E., "Friction Stir Welding of Magnesium Alloy AZ3B" , under review, *Material Science Letters.*

[3] Prado. R.A., Murr, L.E., Shindo, D.J., McClure, J.C., "Friction Stir Welding: A Study of Tool Wear Variation in Aluminum Alloy 6061+20% Al_2O", Friction Stir Welding and processing, Edited by K.V. Jata, M.W. Mahoney, R.S. Mishra, Semiatin, S.L., and D.P. Field, TMS, 2001, p. 105-116.

[4] Cederqvist, I., Reynolds, A.P. "Factors Affecting the Properties of Friction Stir Welded Aluminum Lap Joints", Welding Journal, Vol. 80, No. 12, 2001, p. 287-s to 287-s.

[5] Tang, W., Guo, X,., McClure, J.C., et al. "Heat Input and Temperature Distribution of Friction Stir Welds", *J. of Materials Processing and Manufacturing Science*, Vol. 7, No. 2, 1999, p. 162-172.

[6] McClure, J.C., Tang, W., Murr, L.E., Guo, X., "A Thermal Model of Friction Stir Welding", *Proceedings of the 5th International Trends in Welding Conference*, Georgia, June, 1998, p. 590-595

[7] Coligan, K., "Material Flow Behavior during Friction Stir Welding of Aluminum", *Welding Journal*, July 1999, 229s-237s.

[8] Reynolds, A., Seidel, R.U., Simonsen, M. "Visualization of Material Flow in an Autogeneous Friction Stir Weld.", *Proceedings 1st International symposium on Friction Stir Welding.*

[9] Kallee, W.F., "Friction Stir Welding--How to Weld Aluminum Without Melting It.", http://www.twi.co.uk/j

[10] Guerra, M., McClure, J.C., Murr, L.M, *et al.* "Material Flow during Friction Stir Welding", *Proceedings Friction Stir Welding and Processing*, Editor K.V. Jata, M.W. Mahoney, R.S. Mishra, TMS (The Minerals, Metals and Materials Society), 2001

[11] Guerra, M. R., *Material Transport During Friction Stir Welding*, M.S. Thesis, University of Texas El Paso, 2001.