WELDING RESEARCH

SUPPLEMENT TO THE *WELDING JOURNAL*, JULY 1999
Sponsored by the American Welding Society and the Welding Research Council

Material Flow Behavior during Friction Stir Welding of Aluminum

Tracers embedded in the weld path and a "stop action" technique give insight into the movement of material during friction stir welding

BY K. COLLIGAN

ABSTRACT. Friction stir welding (FSW) is a new technique for joining aluminum alloys. Invented in 1991 at The Welding Institute (Ref. 1), this technique results in low distortion and high joint strength compared with other techniques, and is capable of joining all aluminum alloys. To date, the majority of research has concentrated on developing the tools and procedures for making reliable welds in a variety of alloys, on characterizing the properties of welds and on developing design allowables (Refs. 2–7). However, very little is known about material flow behavior during welding. The purpose of the current study is to document the movement of material during friction stir welding as a means of developing a conceptual model of the deformation process. In this paper, two new techniques for visualizing material flow patterns in friction stir welds are presented. Based on measured results in welds of 6061 and 7075 aluminum, material movement within friction stir welds is by either simple extrusion or chaotic mixing, depending on where within the weld zone the material originates. These results impact the development of welding procedures and suggest ways to model the process for predicting welding tool performance.

Introduction

Friction stir welding is a new welding technique for aluminum alloys invented by The Welding Institute, Cambridge, U.K., in 1991 (Ref. 1). This technique uses a nonconsumable steel welding tool to generate frictional heating at the point of welding and to induce gross plastic deformation of workpiece material while the material is in a solid phase, resulting in complex mixing across the joint. A detailed account of the process has been provided by others (Refs. 1, 3, 7). Although friction stir welding can be used to join a number of materials, the primary research and industrial interest has been to join aluminum alloys. Defect-free welds with good mechanical properties have been made in a wide variety of aluminum alloys, even those previously thought to be "unweldable," in thicknesses from less than 1 mm to more than 35 mm. In addition, friction stir welds can be accomplished in any position. Clearly, friction stir welding is a valuable new technique for butt and lap joint welding aluminum alloys.

Of importance to this work, and subsequent interpretation of results, is the FSW tool design and how it interacts with the workpiece. The steel tool is comprised of a shank, shoulder and pin, as shown in Fig. 1. The welding tool is rotated along its longitudinal axis in a conventional milling machine and the workpiece material is firmly held in place in a fixture. The shoulder is pressed against the surface of the metal generating frictional heat while containing the softened weld metal. The pin causes some additional heating and extensive plastic flow in the workpiece material on either side of the butt joint. As can be seen in Fig. 1, the pin is equipped with a screw thread. This thread was found to assist in ensuring that the plastically deformed workpiece material is fully delivered around the pin, resulting in a void-free weld. To achieve full closure of the root, it is necessary for the pin to pass very close to the backplate, since only a limited amount of plastic deformation occurs below the pin, and then only very close to the pin surface.

A typical butt joint welding sequence proceeds as follows:

The workpiece material, with square mating edges, is fixtured on a rigid backplate. The fixturing prevents the plates from spreading or lifting during welding, and holds the material at a slight angle relative to the axis of the welding tool. The welding tool, fixed in its holder, is spun to the correct spindle speed and is slowly plunged into the workpiece material until the shoulder of the welding tool forcibly contacts the upper surface of the material and the pin is a short distance from the backplate. At this point the welding tool is forcibly traversed along the butt joint, which continues until the end of the weld is reached. The welding

KEY WORDS

Friction Stir Welding
Aluminum Alloys
6061 and 7075
Material Flow
Weld Tool
Friction Heating
Plastic Deformation

At the time this paper was written, K. COLLIGAN was with The Boeing Co., Seattle, Wash. He is currently with Lockheed Martin Manned Space Systems, New Orleans, La.

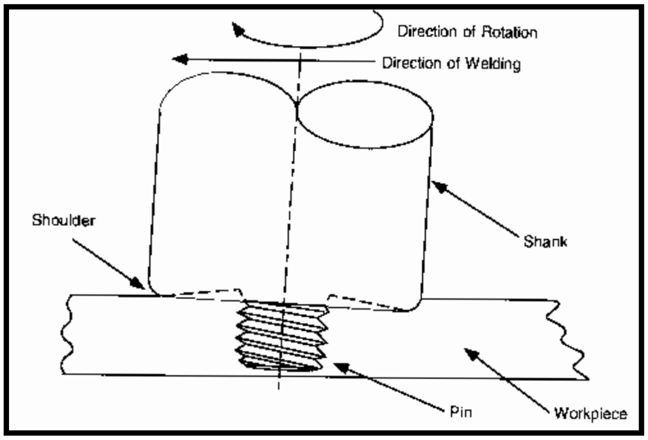

Fig. 1 — Schematic of friction stir welding tool (Refs. 1, 4, 8, 9). The tool is composed of a steel shaft with a pin and shoulder on one end and a shank on the opposite end, which is mounted to the spindle of a milling machine.

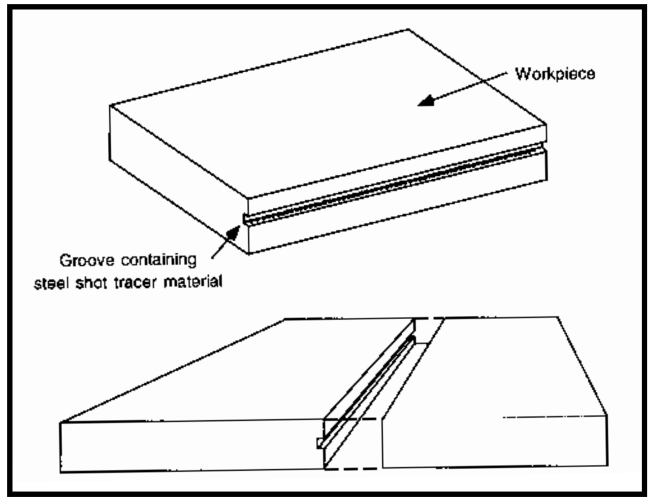

Fig. 2 — The tracer line technique employs a continuous line of 0.38-mm steel shot tracer material sprinkled into a small rectangular groove machined in the butting edge of a plate.

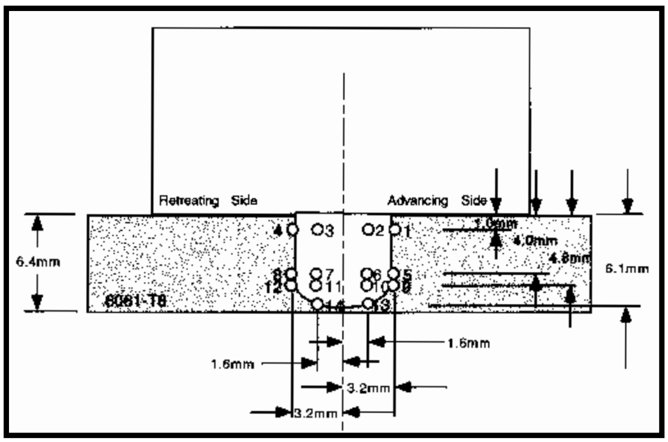

Fig. 3 — Tracer line positions for the 6.4-mm 6061-T6 plate. The groove containing the steel shot tracer material was oriented at various positions relative to the welding tool pin and at various depths in the workpiece plate, as shown in this schematic.

tool is then retracted, generally while the spindle continues to turn. Once the tool is completely retracted, the spindle is stopped, and the welded plate can be removed from the fixture. It should be noted that when the tool is retracted the pin of the welding tool leaves a hole in the workpiece at the end of the weld.

Experimental Procedures

Steel Shot Tracer Technique

To better visualize the flow of material around the welding tool, two new techniques were used. First, small steel balls (0.38 mm diameter) were used as a tracer material embedded at different positions within butt joint welds of 6.4-mm-thick 6061-T6 and 7075-T6 plate. A weld was run along the length of the "seeded" butt joint and stopped at a point along the tracer pattern. By stopping the forward motion of the welding tool while it is still in the seeded material, the steel shot distribution around the welding tool is preserved in the end of the weld, revealing the path that the tracer material took in traveling around the welding tool. Each weld was subsequently radiographed to reveal the distribution of the tracer material as it transitioned from its original position, around the welding tool and into the welded joint.

A number of techniques for embedding the steel tracer material were evaluated in preparation for the detailed experimental work in this study. However, the most effective method of embedding the tracer material involved machining a small groove, 0.75 mm high by 0.3 mm deep, along the butting edge of a plate of 6.4-mm aluminum and filling the groove with steel balls, as shown in Fig. 2. Prior to welding, the plates are forced together to imbed the 0.38-mm balls into the 0.3-mm groove. This technique results in a horizontal line of steel shot arranged at any desired position within the weld by making the groove at different depths and by orienting the butt joint at different lateral positions relative to the path of the welding tool. The initial tracer line locations are shown in Fig. 3 for the 6061 and in Fig. 4 for the 7075. Inspection of the weld by radiography then revealed the line of tracer material in advance of the welding tool, as the material was deforming around the tool, and after passage of the welding tool.

The second technique used in this study involved ending friction stir welds by suddenly stopping the forward motion of the welding tool and simultaneously retracting the tool at a rate that caused the welding tool pin to unscrew itself from the weld, leaving the material within the threads of the pin intact and still attached to the keyhole. By sectioning the keyhole at the end of a weld that was made using this "stop action" technique, one can study the flow of material in the region immediately within the threads of the welding tool. This technique requires the use of a numerically controlled (NC) milling machine.

The welds in 6061 were made on a three-axis NC milling machine equipped with a special fixture for friction stir welding. The use of the NC mill allowed the stop action technique used on the 6061 alloy. Due to the higher forces required to weld 7075, it was necessary to use a different FSW system for those welds. Unfortunately, this equipment was not capable of performing the stop action motion at the end of the weld; therefore, the tracer dispersal patterns in the region immediately around the welding tool are not valid representations of the path taken by the steel shot for the 7075 as it traveled around the pin.

Welding Procedures

The welding parameters and details of the welding tool geometry are restricted from publication by agreement with the

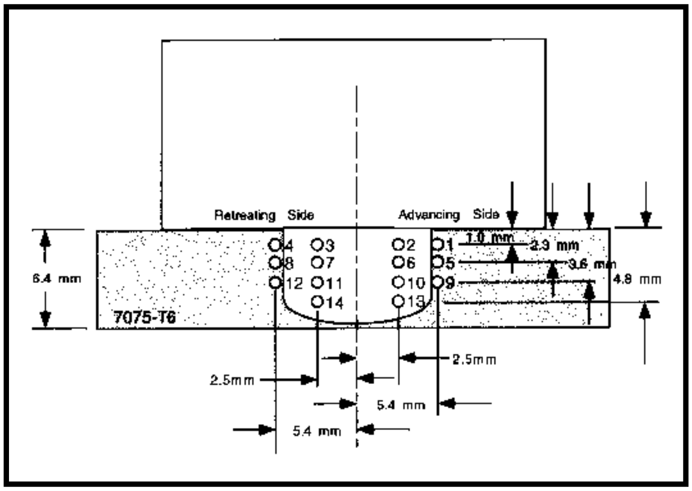

Fig. 4 — Tracer line positions for the 6.4-mm 7075-T6 plate. The groove containing the steel shot tracer material was oriented at various positions relative to the welding tool pin and at various depths in the workpiece plate, as shown in this schematic.

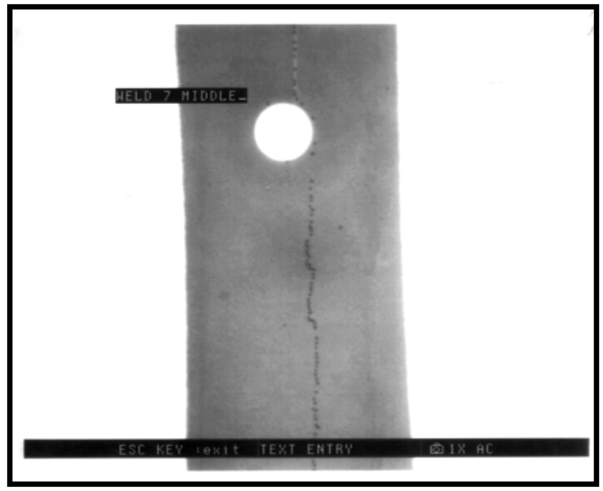

Fig. 5 — The plan view radiograph of 6061 tracer position 7 weld, its position defined in Fig. 3, shows the unwelded tracer material at the top of the figure, as it flows around the welding tool pin, and as it is dispersed within the weld. The outline of the welding tool shoulder can just be seen. The hole left by the extracted welding tool pin is clearly visible.

companies that funded industrial development of FSW at The Welding Institute (TWI). However, it can be said that the welding tool pin had a threaded surface, as shown schematically in Fig. 1, and the weld travel speed can be in excess of 30 cm/min. For reference, some public domain information about the details of welding tool geometry and attitude during welding is available (Ref. 8). It should be noted that different welding tools and parameters were used for the welds made in the 6061 alloy and the 7075 alloy; however, it is expected that the small differences between the welding tools used does not preclude comparison of the results obtained.

Results

Steel Shot Tracer Results

Before presenting the results, it is necessary first to discuss the convention used for referring to locations within friction stir welds. Since friction stir welds are asymmetrical, it is necessary to accurately convey which side is intended when referring to specific locations within a weld with respect to the tool rotation and feed directions. The following convention will be used in the discussions to follow. The side of the welding tool where the motion of the surface of the welding tool is in the same direction as the feed direction is referred to as the *advancing side*. The opposite side, where the motion of the surface of the welding tool opposes the feed direction, is referred to as the *retreating side*. A terminology convention that is also used (Ref. 10) refers to the advancing and retreating

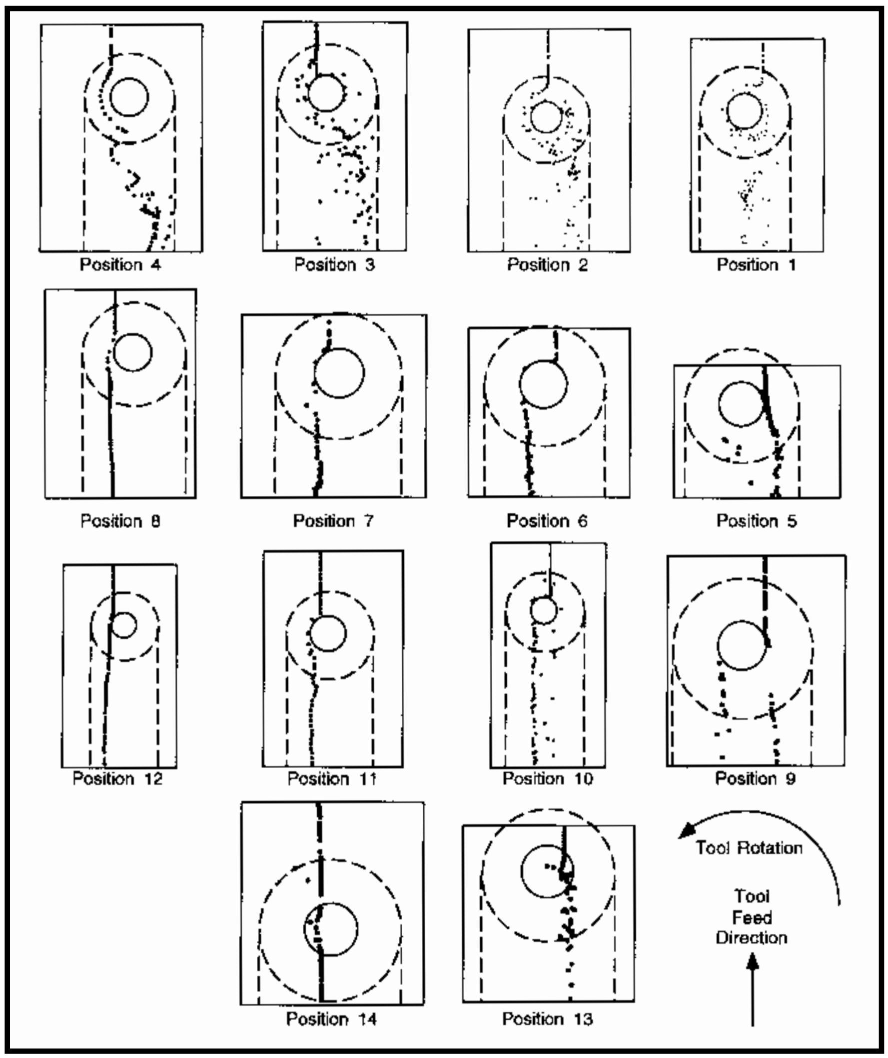

Fig. 6 — Drawings generated from each of the plan view radiographs for the 6061 welds are shown here. The positions are defined relative to the welding tool path in Fig. 3.

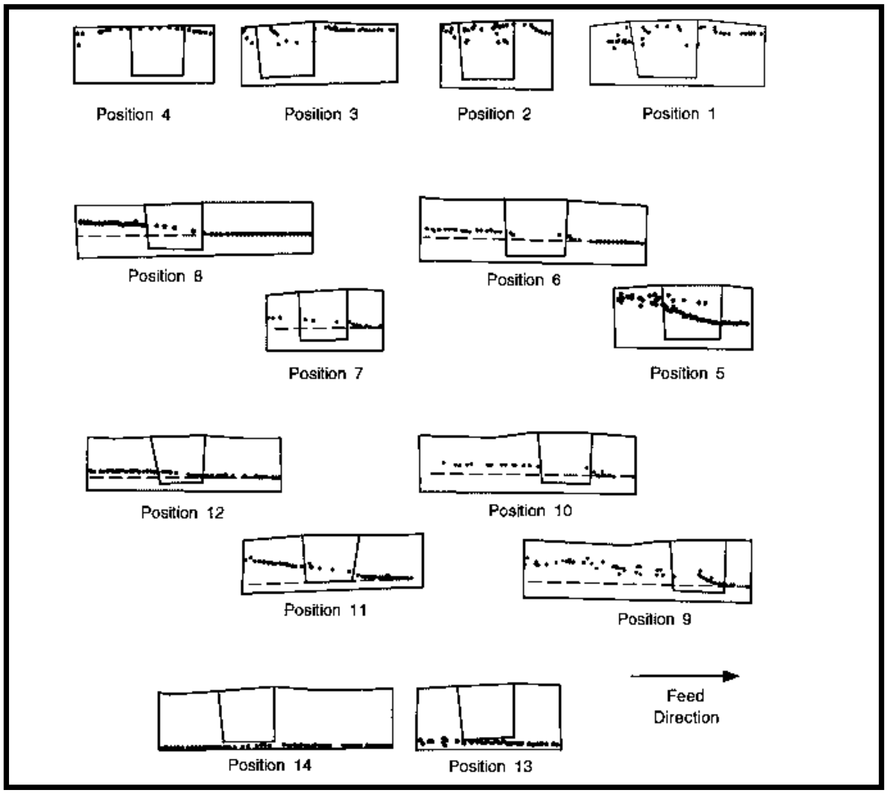

Fig. 7 — Drawings generated from each of the side view radiographs for the 6061 welds are shown here.

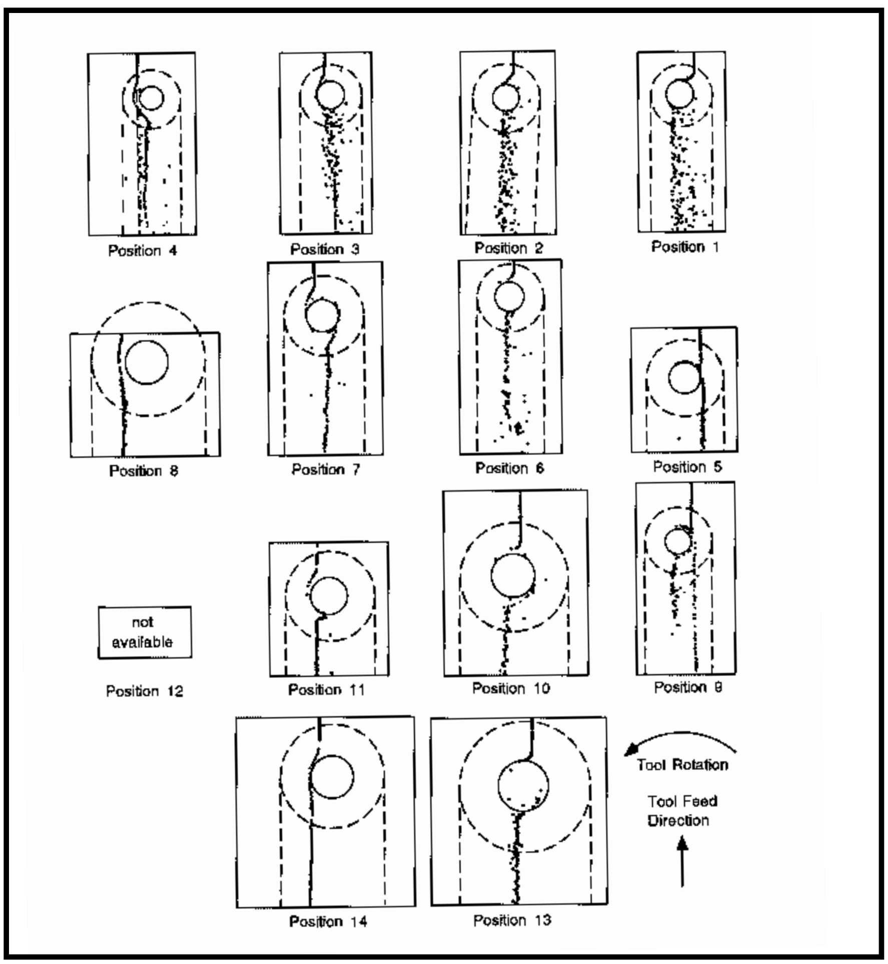

Fig. 8 — Drawings generated from each of the plan view radiographs for the 7075 welds are shown here. The positions are defined relative to the welding tool dimensions in Fig. 4.

sides as the shear side and the flow side, but since this convention makes assumptions about the material flow, the more generic terminology will be used here.

Another convention used here is to refer to tool movement in indicating the feed direction, as opposed to workpiece movement. Also, the welding tool rotation direction used in the welds made in 7075 was clockwise when viewed from above; however, the diagrams of tracer dispersal patterns were reversed in order to make them appear the same as the diagrams from the 6061 alloy, which had a counterclockwise tool rotation.

The tracer line technique produced a comprehensive depiction of material movement in friction stir welds. A typical radiograph is shown in Fig. 5. This sample was taken from 6061 alloy, tracer line position 7 as defined in the layout in Fig. 3. This plan view shows the weld keyhole, the steel shot in advance of the keyhole (in the upper portion of the figure) and the reoriented steel shot behind the keyhole (in the lower portion of the figure). Figure 6 shows the plan views of all of the 6061 tracer line radiographs, Fig. 7 shows the side views from the same specimens, Fig. 8 shows the plan views from the 7075 radiographs and Fig. 9 shows the side views from the same specimens. The "stop action" technique was used when welding the 6061 specimens, but not with the 7075 specimens.

Results shown in Figs. 6 and 7 confirm some conclusions drawn from conventional metallographic FSW cross sections and also introduce new information in the development of a comprehensive material flow description. Referring to Fig. 6, one can immediately observe different material movement patterns in different parts of the weld. In positions 1 through 3, lines of steel shot originate near the upper surface of the plate. The tracer material in these positions is brought around the pin on the retreating side and scattered behind the pin, the final resting place being biased toward the advancing side, but the material is otherwise randomly scattered. It is evident from Fig. 7 that this tracer material also rises slightly in front of the pin and is then driven down to a final depth that is deeper than the original level.

The pattern of movement of tracer material in position 2 is representative of that seen in each of the first three positions. In position 2 a nearly continuous line of tracer material in front of the welding tool is lifted and brought counterclockwise around the pin as it enters the weld zone. Both motions take place well in advance of the pin, as can be seen by viewing both the plan view and side view in Figs. 6 and 7. The appearance of tracer material on the advancing side of the pin implies that some of the tracer material may make at least one full rotation around the pin as it is being driven down into the weld. This observation is repeated in position 3, where a number of steel shot are seen on the advancing side, very close to the pin. It appears that in position 2 the steel shot is driven from an initial depth of 1 mm to a maximum observed depth of about 2 mm, or 30% of the plate thickness.

Position 4 appears to fundamentally differ from the first three positions. The material is not significantly propelled downward into the weld and the tracer material is not chaotically scattered behind the pin. The tracer material in this position appears to be dragged behind the pin by the rotation of the shoulder and is deposited behind the shoulder within about 1 mm of the upper surface of the weld, near its initial depth.

In position 5, tracer material is significantly lifted as it passes the pin and is slightly pushed away from the weld zone. A small amount of tracer material is deposited outside of the general trend of the rest of the tracer material. Referring to the plan view of position 5, a small cluster of tracer material was deposited toward the back of the shoulder on the retreating side. Despite this exception, a large majority of the tracer material is pushed away from the pin and lifted as the pin passes. A very similar trend is followed in position 9, originating at the same lateral position as 5 but just below it in the weld. As can be seen in the plan and side views, about half of the tracer material is lifted and pushed away from the pin but the balance of the material, a larger percentage in this position than in the previous one, is deposited on the retreating side of the pin. In both positions 5 and 9, the material deposited on the retreating side is left at the same depth in the weld as that on the advancing side.

Similar tracer deposition patterns are found in positions 6 through 8 and 10 through 12. Generally, tracer material from these welds was brought around the retreating side of the pin, while being simultaneously lifted to a higher position within the weld. The tracer material was typically deposited adjacent to the retreating flank of the pin, or slightly behind this side of the pin.

In positions 13 and 14 the steel shot passes under the pin and does not signif-

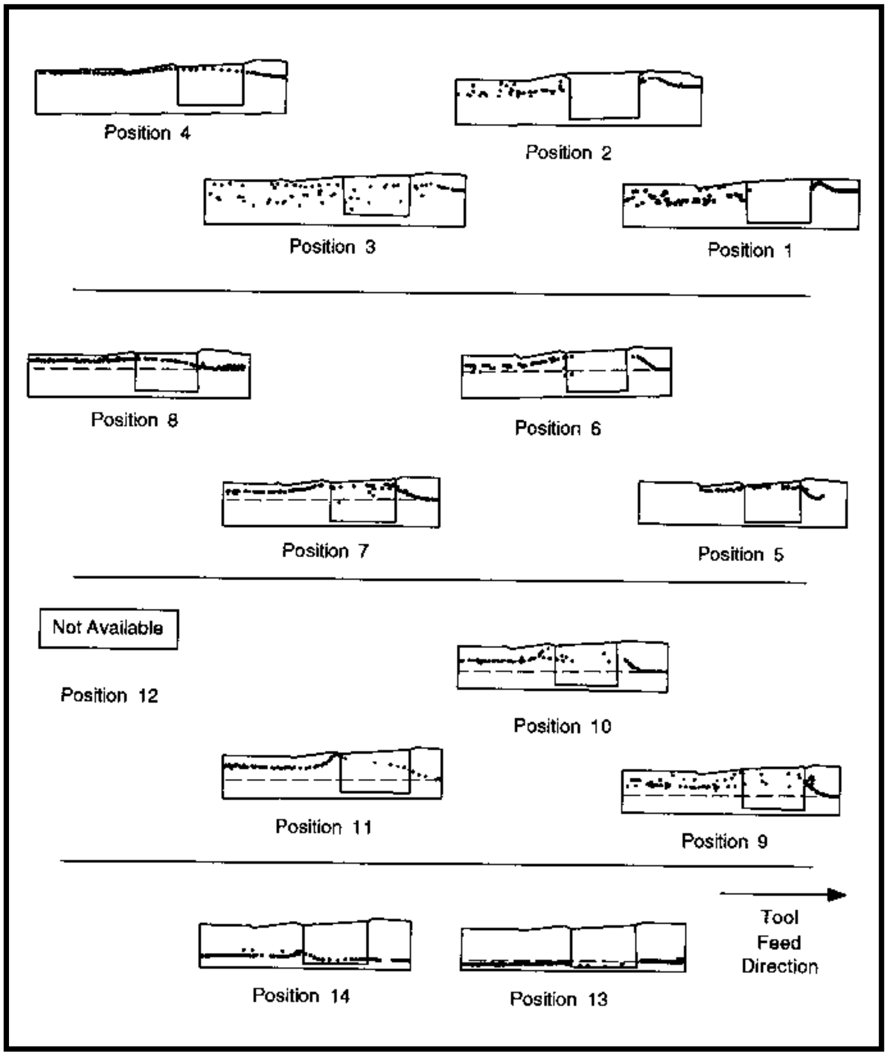

Fig. 9 — Drawings generated from each of the side view radiographs for the 7075 welds are shown here.

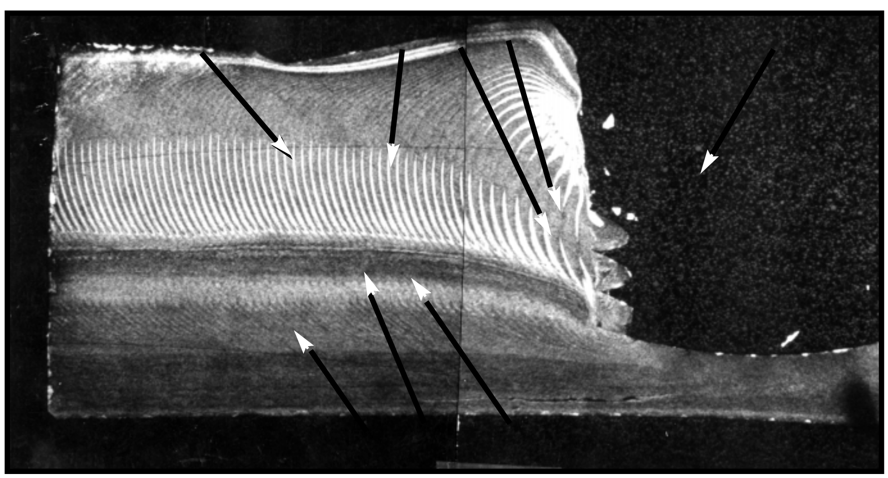

Fig. 10 — In this 6.4-mm 6061 specimen the "stop action" technique was used to capture material flow patterns during welding near the welding tool pin and shoulder. A — Initial butting surface intersection with section plane; B — material filling thread space; C — filled thread space in front of pin; D — void behind upper portion of pin; E — filled thread space behind pin; F — material flowing upward behind pin; G — material extruded under pin; H — material extruded under shoulder.

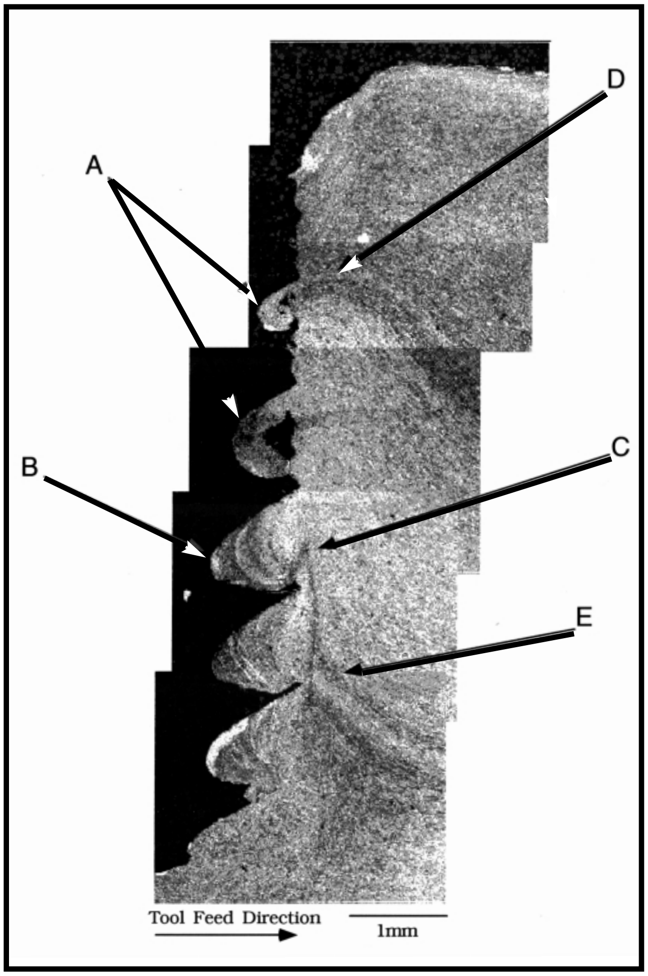

Fig. 11 — View of the 6.4-mm 6061 "stop action" keyhole trailing edge longitudinal section. A — Partially filled threads; B — fully filled threads; C — dark band; D — downward distortion of material; E — upward distortion of material.

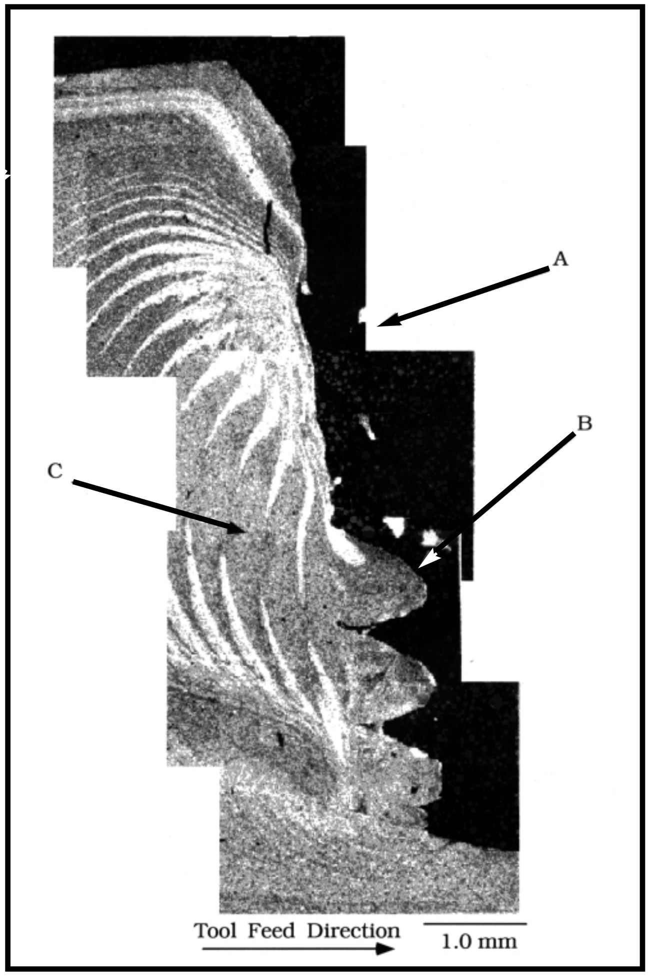

Fig. 12 — An enlargement of the specimen from Fig. 10 in the region behind the pin. A — Area with no material filling behind the pin; B — fully filled threads; C — material filling behind the pin from below.

icantly change its depth or lateral position. It appears that there is only slight material movement in this region.

Referring to Figs. 8 and 9 for welds in 7075, it can be seen that similar results were observed in this alloy. It should be noted that these tests were done on a welding machine that could not perform the "stop action" pin withdrawal, and as a result, the tracer dispersal patterns very near the pin should not be interpreted as being representative of those present during actual welding. Positions 1 through 3 show the same chaotic dispersal pattern as was seen in the 6061 radiography results. The steel shot is slightly lifted in advance of the welding tool pin and is then driven to a greater depth within the weld. For example, in position 3 the steel shot originates at a depth of 1 mm and is deposited behind the pin as deep as 4 mm, or ⅔ of the plate thickness (twice as deep as that observed in the 6061 for a similar tracer line position).

In position 4 the steel shot also rises as the pin passes but is not driven down into the welded plate. Instead, the steel shot remains just below the surface and is reoriented counterclockwise behind the pin by a small distance. The majority of the steel shot is deposited in a straight line with a percentage of the tracer material being deposited in a somewhat different pattern. This pattern is somewhat different from position 4 in the 6061.

In positions 5 and 9 the dispersal patterns observed are quite similar to those observed in the 6061 results. In position 5 the steel shot is lifted in advance of the pin to very near the upper surface of the material under the shoulder of the welding tool and is slightly pushed away from the pin. In position 9 the shot is also lifted in advance of the pin and most of the tracer material passes the pin without much lateral movement, except for a percentage of the tracer material that is captured by the pin, moved counterclockwise and deposited on the retreating side of the pin.

The tracer material dispersal patterns seen in positions 6 through 8 and 10 and 11 are similar to each other, as were the corresponding positions in the 6061 results. In these positions the tracer material is delivered counterclockwise around the pin and delivered to different positions behind the welding tool. At the same time, the tracer material is lifted nearly to the upper surface of the weld, just behind the pin and pushed back down into the weld as the shoulder passes. In all cases the final vertical position is above the original vertical position. Positions 6, 7, 10 and 11 differ from the 6061 counterparts only in that the tracer material is left more directly behind the pin in the 7075 case than in the 6061 and the lifting as the pin passes is more pronounced in the 7075 case than in the 6061. Based upon the regularity of the dispersal pattern behind the pin in each case, it is likely that the tracer material does not make more than a partial revolution around the pin in all cases ex-

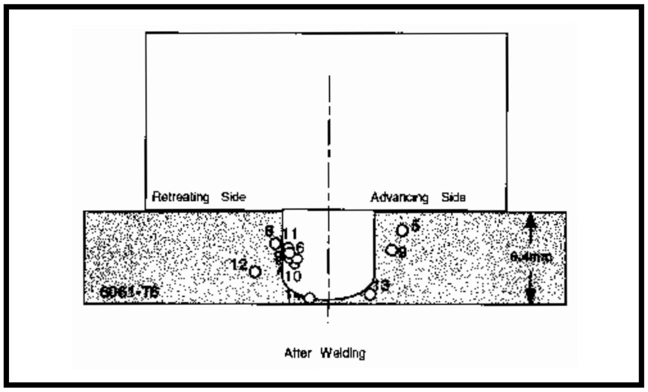

Fig. 13 — A schematic view of the average final positions of steel shot tracer material in a 6061-T6 transverse section for positions 5 through 14. The initial positions are shown in Fig. 3.

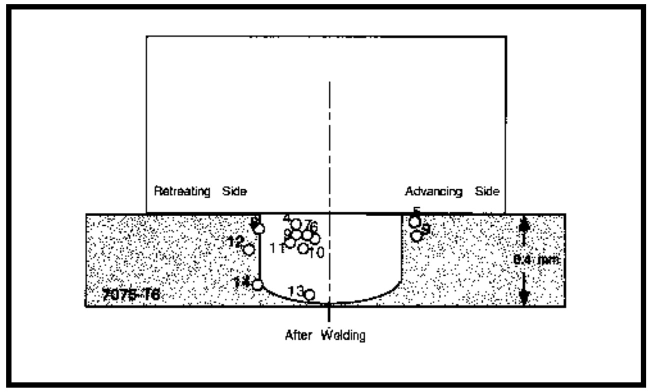

Fig. 14 — A schematic view of the average final positions of steel shot tracer material in a 7075-T6 transverse section for positions 4 through 14. The initial positions are shown in Fig. 4.

cept for positions 1, 2 and 3.

In positions 13 and 14 the tracer material approximately remains at its original depth in the plate, but the lateral location is slightly reoriented to the retreating side of the weld.

Stop Action Test Results

To gain further insight into the mechanisms of material flow in friction stir welds, an analysis of weld sections taken from the keyhole region of welds in 6061 was undertaken. The welds studied were produced using the "stop action" technique described above. A number of weld keyholes specimens were examined, produced by taking a longitudinal section in 6061 and etching for 60 s in a concentrated Keller's etch. These welds were produced using a two-piece welding tool that had an H13 tool steel body and a tungsten carbide pin with smoothly ground threads. Figure 10 illustrates a typical microstructural morphology. Starting from the right side of the photograph, the unwelded base metal in advance of the welding tool is horizontally banded, with the upper and lower thirds being darker than the center third. As the welding tool advances, these bands reveal an upward distortion of material, contacting the leading edge of the welding tool shoulder. Behind the welding tool, the weld can be seen to consist of a number of horizontal layers. The top layer consists of a thin band of horizontally striated material extending from the upper portion of the back edge of the pin, along the welding tool shoulder surface, and on down to the fully developed weld (feature H in Fig. 10). The next layer down, comprising about half of the thickness of the weld, consists of vertically oriented bands, which appear to emanate from the lower portion of the back edge of the pin (feature F). Previous investigations have shown this banded structure to be associated with differences in grain size (Ref. 7). The bottom half of the weld consists of a layer that is also vertically banded but much fainter. The very bottom layer of the weld is very dark in appearance and is not as distinctly structured as other portions of the weld.

As can be seen in Fig. 10, the hole left by the threaded pin is bounded by aluminum that occupied the thread spaces when the welding tool was retracted. Close inspection of the hole left by the pin reveals that the profile in front of the pin (the right side of the hole) is different from the trailing side. Looking from top to bottom along the front side of the hole, the thread form appears to gradually develop from curls of aluminum that increase in size, progressing downward (detail B in Fig. 10) until the fully developed thread form is observed at about halfway through the thickness. Looking from top to bottom along the trailing side of the hole, the hole is smooth sided in the top half of the thickness (detail D) and has fully formed thread shapes in the bottom half of the weld (detail E).

Figure 11 shows a higher magnification view of the leading edge of the keyhole. The progressive filling of the thread form can clearly be seen in the top half of the weld (detail A), with the bottom half of the hole having fully developed thread forms (detail B). In addition, a dark vertical band (detail C) is seen just in advance of the pin, leading from the dark horizontal band in the lower portion of the base metal (Fig. 10), up along the leading margin of the pin and into the first fully formed thread form. Material in front of the pin in the upper portion of the plate is seen to be distorted first upward and then downward near the tool (detail D), while in the lower portion of the weld the material is only distorted upward (detail E). Finally, the fully formed thread forms are vertically banded with light and dark material.

Figure 12 shows a higher magnification view of the trailing edge of the keyhole from the weld in Fig. 10. The upper portion of the keyhole does not contain thread-formed material, but instead is relatively smooth (detail A). The lower portion of the keyhole contains full thread forms (detail B). The depth at which fully formed threads are seen on the trailing side closely matches the depth of the first fully formed threads observed on the leading edge, as can be better seen in Fig. 10. The vertical light and dark banding behind the pin can be seen in this view (detail C) emanating from the region of the fully formed threads on the trailing side of the keyhole.

Discussion of Results

Steel Shot Tracer Results

The tracer line tests performed on both 6061 and 7075 give insight into the flow of material in the region around the welding tool pin. First, the material flows indicated from the various positions in Figs. 6 through 9 can be divided into two general categories: those where the continuous line of steel shot was reoriented and deposited as a roughly continuous line of steel shot behind the pin, and those where the line of steel shot was deposited chaotically behind the pin. In Figs. 6 through 9, positions 1, 2 and 3 (for both alloys) represent situations where the material was chaotically deposited, and positions 4 through 14 represent continuous line deposits of tracer material. In this context, chaotic dispersal of tracer material refers to production of a tracer pattern in which no evidence of the original line of tracer remains. In this type of dispersal, individual tracer elements are scattered in an unpredictable way within a relatively broad zone behind the welding tool pin.

It should also be noted that in those cases were the tracer material was chaotically deposited, the tracer material was also moved from its original depth and scattered through the thickness to a somewhat greater depth. Conversely, in those cases where the tracer material was deposited in a nearly continuous line of material behind the pin, the tracer material was moved from its original position to a final position that was somewhat closer to the upper surface of the material.

Based on these observations, it is apparent that those cases where the tracer material was deposited as a roughly continuous line of material behind the pin represent cases where the aluminum immediately surrounding the original tracer line position was simply extruded around the pin. In this case, extrusion refers to a flow of material where plastic deformation takes place without mixing, *i.e.,* adjacent elements of material are deformed but remain adjacent to each other.

If the lateral and vertical positions of the lines of tracer material are measured from the drawings in Figs. 6 through 9 and plotted on a cross section of the weld schematic, the final positions can be compared with the original positions, as shown in Fig. 13 for the 6061 and Fig. 14 for 7075. The data from positions 1 through 4 are omitted from these drawings since the final dispersal pattern could not be represented as a point on a cross section drawing, as was the case with the extruded lines of tracer material. These drawings reveal that in the case of the 6061, material from positions 6 through 11 is deposited in an area on the retreating side of the pin just behind the edge of the pin. Material from positions 5, 9 and 12 are moved upward and outward away from the pin, while material that passes under the pin was only slightly displaced. Similar results were observed for the 7075, but the zone where material from positions 4, 6, 7, 9, 10 and 11 was deposited is higher in the weld and closer to the centerline of the weld than in the 6061 case.

It seems clear from these results that as the welding tool approaches, material from the mid-section of the plate directly in the path of the pin is lifted and extruded around the pin in the direction of pin rotation. Material from the mid-section of the plate, which is aligned with the margins of the pin, is also lifted, but is less affected by the shear forces imparted by the rotating pin. On the advancing side of the weld, this marginal material may be captured by the pin's rotational flow and carried around to the retreating side, or it may simply lift and be pushed away from the weld centerline. On the retreating side the mid-thickness material, which is aligned with the margin of the pin, is simply lifted as the surrounding material extrudes by the pin without much displacement laterally.

Material that passes below the pin, from positions 13 and 14 in both alloys, is not greatly displaced, although in the case of the 7075, the tracer material did appear to be under the influence of the rotation of the pin and was displaced in a manner similar to that of the mid-section material (positions 5 through 12). In the case of the 6061, this effect was less, and differences in the pin geometry between these two welds is likely responsible. For example, the welding tool used for the 6061 had a smaller pin diameter and had a relatively flat end when compared to the tool used for the 7075 welds, which would certainly alter material movement patterns in the bottom portion of the weld.

Stop Action Weld Results

The welding tool affects material from the upper portion of the plate in a much different manner than in the case of the other positions within the weld. Based upon the stop action welds, it appears that material from positions 1, 2 and 3 is curled directly into the threads of the welding tool pin and is then delivered deeper into the weld. Figure 11 clearly shows material that was filling the thread space at the time the tool was retracted. This mechanism of filling the thread space shows that the material curling into the thread space is still attached to the base metal directly in front of the pin as it is extruded into the thread space. If this is the case, the material being curled into the thread space is not rotating with the pin, but is sliding against the rotating thread surface. Therefore, relative to the material in front of the pin, the thread is moving downward as it rotates and is moving forward with the overall motion of the welding tool; thus, the curl of material continuously grows as it is extruded into the thread space. Also, the existence of a void behind the pin, seen in Fig. 12, detail A, supports the notion that the material curling into the thread space is attached to the base metal in front of the pin and not traveling around the pin with the rotation of the threads, although other interpretations are possible.

It should be noted that no material was detected clinging to the welding tool pin after welding. In order for this technique to work, it is important that the threads of the welding tool pin should be free of aluminum alloy, with the exception of the thin film of aluminum that commonly clings to friction stir welding tools after use.

Material curls into the thread space until the space is filled, at about the midpoint of the plate thickness. The evidence produced by the stop action tests is less clear about what happens at this point, but Fig. 12 provides two clues that allow speculation about how material is transported around the pin. First, the thread-formed material that is seen behind the pin occurs only at the depths where fully formed threads exist on the leading edge of the pin. Second, it appears that the material rising behind the pin (detail C) originates from the thread-formed material on the rear of the pin. It can be speculated that once the thread space is filled, the continued downward motion of the thread relative to the material in advance of the pin causes the material captured inside the thread space to be separated from the surrounding material by a narrow band of excessively strained material. The material inside of the thread space then begins rotating with the welding tool pin. As the material within the thread space comes around the back of the pin, it is then deposited behind the pin.

Validity of the Techniques Used

The above discussion describes material movement in the upper portion of the weld as being caused by material curling into the welding tool's threads at a rate dictated by the amount of forward motion of the tool in each revolution. Since this rate is about ⅓ the diameter of the steel shot tracer material, it is likely that the tracer material does not flow into the thread space in the same way as the alloy. Therefore, it is expected that in the portions of the plate where this type of material movement takes place the tracer does not accurately reflect movement of the aluminum alloy. Instead of continuously curling into the thread space, it is likely that the steel shot is pushed out of the thread space by the thread's downward motion. However, the downward movement of tracer material seen in positions 1 through 3 for both alloys does support the conclusion reached based on stop-action testing of 6061 plates: that material from the upper portion of the weld is pulled down by the thread form and deposited low in the weld behind the pin. Although using a smaller tracer material would improve its ability to accurately reflect material deformation, the smaller tracer materials would also be more difficult to detect using radiography.

In the middle and lower portions of the plate, aluminum appears to move by a more orderly deformation process. This is reflected in the way that the tracer material largely remains in a line even after passage of the welding tool. It is expected that in this area the geometry of the tracer material used is adequate as an indicator of deformation in the surrounding alloy, and conclusions can be inferred from the tracer dispersal patterns observed.

The use of steel shot as a tracer material could also be an inaccurate indicator of material deformation due to the difference in thermal conductivity and mass between the tracer and surrounding aluminum alloy. The line of closely packed steel shot will certainly reduce heat conduction along its length in advance of the welding tool, and will therefore disturb the temperature distribution in the surrounding aluminum. However, the small size of the steel shot should have prevented this inhomongeneity from altering the main heat conduction properties of the alloy. Also, the high thermal conductivity of the aluminum would tend to reduce thermal gradients in the vicinity of the line of tracer material.

The difference between the mass of the tracer material and the aluminum alloy causes inertial forces to develop between the materials in cases where they are accelerating. This effect is greatest where the acceleration is greatest, such as where the tracer and alloy are being pulled around the welding tool pin. Since the steel tracer material has a higher mass than the surrounding alloy, it would be expected that the tracer material should lag behind the surrounding alloy for positive accelerations. However, at the temperatures expected in the weld zone (Ref. 6), the aluminum alloy still has high viscosity and would likely resist relative motion between the alloy and the tracer material. Therefore, it is expected that the difference in masses between the alloy and tracer material is not significant for this study.

Normally, when making a butt joint weld using the friction stir technique the butt joint is located on the centerline of the welding tool path. The tracer method used in this study requires that the butting surfaces be located in various lateral positions relative to the welding path in order to place the tracer material as desired relative to the welding tool path. The butting surfaces form a heat transfer barrier due to incomplete contact when compared to continuous material. In the friction stir welding process, there is a large thermal gradient in the radial direction, along the length of the butting surfaces, but one would not expect a significant thermal gradient across the butting surface. As a result, it is reasonable to expect that moving the butting surfaces laterally a small distance from their normal position should not significantly disturb the heat flow radially away from the welding tool.

With respect to the stop action method, the main concern about the validity of the technique relates to the acceleration and deceleration profiles of the axes of the machine tool used to make the welds. In order for this technique to be valid, the longitudinal axis must quickly decelerate while the out-of-plane axis accelerates to full retract speed, leaving the material that was within the threads during welding intact and undisturbed. The theoretical acceleration and deceleration rates of the machine tool can be calculated based on information from the machine tool manufacturer. One revolution of the welding tool takes about 39 ms. The longitudinal axis takes only 1.07 ms to decelerate from the full welding speed to zero, representing 9.9 deg of welding tool rotation. The vertical axis accelerates at the same rate but must reach a higher speed. This transition from zero speed to maximum retract rate takes about 8 ms, or 74-deg rotation, which results in pushing the material within the threads down by about 0.1 mm. This distortion of the thread form left within the keyhole is much less than the thread spacing, about 1 mm. While there are other sources of axis motion error, such as backlash in the drive system and deflection of each axis, the welding tool and the tooling, it is expected that this small distortion does not invalidate the conclusions suggested by this technique.

Conclusions

Based upon welds in 6061 and 7075 aluminum, it is apparent that in friction stir welds not all material influenced by the pin is actually "stirred" in the welding process. Much of the material movement takes place by simple extrusion. The material that is stirred originates from the upper portion of the path of the welding tool pin. The stirred material is forced down in the weld by the threads on the pin and is deposited in the weld nugget. Other material in the weld zone simply extrudes around the retreating side of the welding tool pin, rising in the weld as it goes around the pin.

The objective of this study was to perform tests to reveal the material movement patterns that take place in friction stir welds. The conceptual model proposed here is preliminary, and additional work must be undertaken to refine the conceptual model and give a more detailed understanding of how friction stir welds are made, especially to investigate the behavior of other aluminum alloys. The ultimate goal is to gain sufficient understanding to formulate idealized models of the process, which can be used to predict welding tool forces, temperature profiles and other parameters of interest, thereby, allowing researchers to evaluate changes to welding tool design and operating parameters and possibly suggest new improvements to the process.

Acknowledgments

The author would like to acknowledge the assistance of Lane Ballard of the Boeing Co. who performed and analyzed the tracer material welds in 6061, the assistance of Chris Dawes of The Welding Institute, Cambridge, U.K., for his help in preparing the welds in 7075 and the assistance of Dr. Denny Graham of the University of Adelaide and Dr. Murray Mahoney of the Rockwell Science Center for their reviews of the first draft of this paper.

References

1. Thomas, W. M., *et al.* 1991. Friction Stir Butt Welding. U.S. Patent No. 5,460,317.
2. Dawes, C. J., and Thomas, W. M. 1995. Friction Stir Joining of Aluminum Alloys. TWI Bulletin 6, p. 124.
3. Dawes, C. J., and Thomas, W. M. 1996. Friction stir process welds aluminum alloys, *Welding Journal* 75 (3): 41.
4. Christner, B. K., and Sylva, G. D. 1996. Friction stir weld developments for aerospace applications. *International Conference on Advances in Welding Technology, Joining of High Performance Materials*, Columbus, Ohio.
5. Ranes, M., Kluken, A. O., and Midling, O. T. 1995. Fatigue properties of as-welded 6005 and 6062 aluminum alloys in T1 and T5 temper condition. *4th International Conference on Trends in Welding Science and Technology*, Gatlinburg, Tenn.
6. Rhodes, C. G., Mahoney, M. W., and Bingel, W. H. 1997. Effects of friction stir welding on microstructure of 7075 aluminum. *Scripta Materialia* 36(1): 69–75.
7. Mahoney, M. W., *et al.* 1998. Properties of friction stir welded 7075 aluminum. *Metallurgical and Materials Transactions* 29A.
8. Midling, D. T., Morley, G. J., and Sanvick A. 1994. Friction Stir Welding. International Patent Application WO 95/26254.
9. Thomas, W. M., *et. al.* 1997. Friction Stir Welding, U.K., Patent Application GB 2-306366-A.
10. Haagensen, P. J., and Midling, O. T. 1997. The friction stir welding process — mechanical strength and fatigue performance of a 7xxx series aluminum alloy. *Faculty of Civil Engineering,* The Norwegian University of Science and Technology, Trondheim, Norway.