

Visualization of Material Flow in a Refill Friction Stir Spot Welding Process Using Marker Materials

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ABSTRACT

Friction Stir Spot Welding (FSSW) is a relatively new solid state joining technology that has the potential to be a replacement for single point joining processes like Resistance Spot Welding and rivet technology in certain applications. Since the material flow around the pin plays an important role in determining the quality of the weld, understanding how the material moves is important to optimize process parameters and to validate the results of numerical simulations of the process. In this paper, an experimental study aimed at visualizing the material flow during the plunge phase of refill FSSW of an aluminum alloy is presented. Different marker materials were placed at a certain depth from the plate surface and metallographic samples in three mutually perpendicular directions were prepared and examined to identify the final location of the marker material after the plunge of the pin. Based on the results of the metallographic study, inferences were made regarding the path of motion of the plate material.

INTRODUCTION

Friction Stir Welding (FSW) [1,2,3] and Friction Stir Spot Welding (FSSW) [4,5,6,7] are solid state joining technologies that have been primarily used to produce high quality welds of aluminum alloys. In FSW, a cylindrical, shouldered tool with a profiled pin is rotated and slowly plunged into the plates to be joined. Then the tool is traversed along the weld line to frictionally heat the material causing it to plasticize without reaching its melting point. While the tool rotates and translates, it moves material from the front to the back of the pin where it is consolidated to form a metallurgical bond. Finally, the pin tool is retracted from the work piece once the weld is completed. In contrast, in FSSW the tool is only

plunged and retracted without any significant lateral movement leaving behind a spot weld.

FSSW is a relatively new process and there are aspects of this technology that are still under research. Once fully developed, it has the potential to be a replacement for single point joining processes like Resistance Spot Welding (RSW) and rivet technology in certain applications. The FSSW approaches currently being used can be classified in three main categories: plunge FSSW [4], refill FSSW [5] and swing FSSW [6]. A comprehensive overview of the state of the art in FSSW including detailed descriptions of the three categories mentioned above can be found in Badarinarayan et al. [7].

Extensive research efforts based on experimental studies have been conducted to understand and optimize the FSW and FSSW processes. In addition, different numerical simulation approaches (for refill FSSW see for example Kakarla et al. [8], Itapu and Muci-Küchler [9], and Kalagara and Muci-Küchler [10]) have been explored to study the mechanical and thermal aspects of these processes as well as the material flow caused by the motion of the tool. Since the material flow around the pin plays an important role in determining the quality of the weld, understanding how the material moves during the different stages of FSW and FSSW is essential to optimize the process parameters and to validate the results of numerical simulations. Once detailed knowledge about the material flow is gained, steps could be taken to improve the mixing of material and avoiding defects in the welds.

Several experimental studies aimed at understanding the flow of material in FSW have been reported in the literature. One of the earliest investigations into the material flow in FSW of

aluminum alloys was carried out by Colligan [11] who used steel balls embedded into slots at different positions relative to the joint line as tracer particles. Although the general flow of the material could be visualized using this approach, the flow pattern was changed due to the presence of the steel balls. Dickerson et al. [12] used a marker technique in which a copper strip was placed in the original joint-line prior to welding and were successful in tracing the flow during FSW. London et al. [13] conducted experiments using Al-SiC and Al-W composite markers to highlight flow patterns in FSW.

In the case of FSSW, few flow visualization experiments have been reported. Su et al. [14] studied the movement of material in plunge FSSW of Al 6061 sheets by introducing Al_2O_3 particles at certain locations. Muci-Küchler et al. [15] used aluminum foil in refill FSSW of Al 2024 to trace the vertical flow of the plate material. Also, Muci-Küchler et al. [16] employed rods of Al 1100 in refill FSSW of Al 7075 to try to visualize the motion of the material being joined. Finally, Kalagara et al. [17] presented the results of preliminary experiments involving refill FSSW of Al 7075 in which copper strips were used to try to visualize the flow patterns during the plunge phase of process. Despite the studies mentioned above, questions still remain regarding the motion of the material in the vicinity of the pin. It is interesting to note that although in FSW the flow patterns were successfully classified into different zones (see for example Arbegast [18]), apparently no such classification has been presented yet for FSSW. Since in FSSW the pin remains at one location rotating at high angular speed, understanding the material flow is more difficult when compared to FSW.

This paper presents the results of experiments conducted using copper, Al 3003, and tungsten as marker materials to try to visualize the circumferential material flow in the vicinity of the pin during the plunge phase of a modified refill FSSW process of an aluminum alloy. Based on the results of a metallographic study using samples in three mutually perpendicular directions, inferences were made regarding the path of motion of the plate material. Although the flow zones were not classified, a better insight of the material flow close to the pin was gained.

DESCRIPTION OF THE FSSW PROCESS UNDER CONSIDERATION

The refill FSSW process considered is a modified version of the one originally developed by the German company GKSS [5]. It uses the three piece tool system shown in Fig. 1, which consists of a clamp, pin, and shoulder, that can be moved in and out independently of each other. The clamp is used to restrain the material flow as well as to hold the work pieces firmly against an anvil. The pin and shoulder move with independent translational velocities but at same angular speed. Initially, the two plates to be spot welded are placed

above each other and clamped to prevent lateral movement. The rest of the process can be divided into the four stages shown in Fig. 2.

In the first stage, the pin and shoulder rotate with the same angular velocity ω and move towards the plates with the same plunge speed. During the second stage, the pin plunges into the plates until a specified plunge depth is reached, displacing the material beneath the pin and causing a material flow into the reservoir formed between the shoulder, pin and clamp. During the third stage, which corresponds to the refill operation, the pin retracts back while the shoulder continues moving down, pushing the material in the reservoir back into the plates. The end of the third stage occurs when the pin and shoulder simultaneously reach the surface of the top plate. As indicated in Fig. 2, during the second and third stages the translational speed of the pin (V_p) is greater than the one of the shoulder (V_s). Finally, in the last stage, the pin along with the shoulder and clamp are retracted back.

EXPERIMENTAL SETUP AND PROCEDURE

The first step in defining the experiments was choosing the material for the plates to be spot welded and the marker materials to be used to trace the material flow. Al 7075-T6 was selected for the plates to allow comparisons with previous flow visualization experiments reported in the literature [16, 17]. To select the marker materials, two main requirements were taken into consideration. First, the marker material needed to be easily traceable in metallographic samples of the plate material using an etching reagent. Second, the presence of the marker material should not cause a significant change in the material flow patterns during the FSSW process. This last requirement is difficult to meet since ideally the plate and marker materials should have very similar mechanical and thermal properties. Three different markers were chosen for the study: copper strips, Al 3003 strips, and fine tungsten powder. All of them are distinguishable from Al 7075 when Keller's reagent is used. A brief summary of the mechanical and thermal properties of the plate and marker materials can be found in Table 1. As can be seen from the table, Copper and Al 3003 have lower yield strengths and higher thermal conductivities than the material of the plates. Thus, they should not have an adverse impact on the overall material flow as long as markers of relatively small size, such as thin strips, are used. Since the yield strength of tungsten is higher than the one of the plate material, fine tungsten powder needs to be used to avoid affecting the flow patterns.

Table 1. Mechanical and thermal properties at room temperature of the plate and marker materials

Material	Yield Stress (MPa)	Young's Modulus (GPa)	Thermal Conductivity (W/m-K)
Al 7075-T6	504	72.4	130
Al 3003	124	68.9	163
Copper	33.3	110	385
Tungsten	750	400	163.3

All the spot welds were made using an MTS ISTIR FSW machine running under position/velocity control. Regarding the tool used, the pin and shoulder had a cylindrical geometry (see Fig. 1). The diameter of the pin, the outside diameter of the shoulder, and the outside diameter of the clamp were 0.4762 cm, 0.955 cm, and 3.175 cm, respectively. The two Al 7075-T6 plates used in the experiments had a length of 38 cm and a width of 10 cm. The thicknesses of the top and bottom plates were 0.2032 cm and 0.3175 cm, respectively.

As shown in Figs. 3 and 4, two slots with a depth of 0.0635 cm and a width of 0.238 cm were made on the top surface of the bottom plate to place the marker materials. The copper and Al 3003 strips were inserted in one of the slots (in the slot in which more plunge locations are indicated in Fig. 3) and the other slot was filled with tungsten powder. The thickness of the copper and Al3003 strips was 0.0635cm and the average size of the tungsten particles used was 50 μm . It is interesting to note that the width of the slots was half the diameter of the pin. The separation between the centers of any two plunge locations was 5.238 cm (i.e., eleven times the pin diameter). This gave a separation of ten times the pin diameter between spot welds to make sure that they did not affect each other. This separation distance was selected since numerical simulations of the process have predicted that during the plunge phase the affected region in the radial direction extends about 4 cm (i.e., about eight times the pin diameter) from the centerline of the pin (see for example Kalagara and Muci-Küchler [10]).

Before the spot welding was started, the two plates were clamped together firmly as shown in Fig. 5. The pin was plunged at the selected locations keeping the distance between its bottom surface and the bottom surface of the shoulder fixed at 0.508 cm. In all the welds, the pin was plunged at a speed of 0.083 cm/s to a depth of 0.381 cm from the surface of the top plate. The angular speed of the pin and shoulder was kept constant at 1600 rpm. Once the pin reached the specified plunge depth, the tool was retracted at a speed of 76 cm/s. It is important to emphasize that only the plunge phase of the refill FSSW process was considered in the study (i.e., the refill phase was not included).

After the plates were removed from the FSW machine, a square section about twice the size of the outside diameter of the flash (see Fig. 6) was cut at each plunge location. The specimens in which copper and Al 3003 were employed as the marker materials were used for metallographic examination. The ones in which tungsten powder was used as the marker were sent to the Center for Non-Destructive Evaluations (CNDE) of Iowa State University (ISU) to be examined using a computed tomography (CT) scan. As indicated in Figs. 7 and 8, several sections in three mutually perpendicular directions were considered for the metallographic studies. In all cases the surface of the specimen was etched using Keller's reagent and observed under a stereomicroscope and an inverted metallurgical microscope.

For the horizontal metallographic analysis, several sections were considered between the top surface of the flash and the bottom surface of the hole left by the pin. For the transverse metallographic analysis in the directions parallel and perpendicular to the slot in the bottom plate, several sections were considered until the center of the hole left by the pin was reached. Photomicrographs and photomacrographs were taken for all the sections of each sample. For the samples in which tungsten powder was used as the marker material, the CT scans were only used to obtain information in the two transverse directions. In what follows, the nomenclature used to refer each sample and its corresponding sections is presented.

As indicated in Tables 2,3,4, the sections corresponding to each sample are labeled using two upper case letters followed by a number. The first letter identifies the marker material that was used and the letters C, A, and W indicate samples with copper, Al 3003, and tungsten, respectively. The second letter identifies the direction of sectioning and the letters N, P, and H are used to indicate that the direction of sectioning corresponded to a transverse metallography perpendicular (normal) to the marker (N), a transverse metallography parallel to the marker (P) or a horizontal metallography (H). The numbering sequence used to identify the different sections considered in the tests is shown in Figure 8. For the transverse metallography the sections are numbered from the center of the weld whereas for the horizontal metallography the sections are numbered from the top surface of the flash. For example, a section corresponding to a sample with copper for which a transverse metallography perpendicular to the marker was performed at the center of the hole left by the pin is referred to as section CN1.

RESULTS

Based on the metallographic examination, four representative sections were selected for each test (see Fig. 8) except for the test corresponding to transverse metallography parallel to the Al 3003 strip and the tests with tungsten powder. For those

tests, only the sections at the center of the weld are presented in this paper. In what follows, the results observed from the transverse metallography normal to the marker strip, the transverse metallography parallel to the marker strip, and the horizontal metallography, are presented, in that order, for the three marker materials.

Table 2. Nomenclature used to identify different sections used for the transverse metallographic analysis perpendicular to the marker

Marker Material	Distance from the Centerline in Terms of the Pin Radius (r)	Sample Number
Copper	0	CN1
	0.67r	CN2
	1.7r	CN3
	2r	CN4
Al 3003	0	AN1
	0.92r	AN2
	1.35r	AN3
	2r	AN4
Tungsten	0	WN1

Table 3. Nomenclature used to identify different sections used for the transverse metallographic analysis parallel to the marker

Marker Material	Distance from the Centerline in Terms of the Pin Radius (r)	Sample Number
Copper	0	CP1
	0.87r	CP2
	1.53r	CP3
	1.92r	CP4
Al 3003	0	AP1
Tungsten	0	WP1

Before proceeding, it is important to point out some common features in the figures corresponding to each one of the different marker materials. As can be seen from Figs. 9,10,11, the copper is black in color in all the photomicrographs taken with the stereomicroscope and white in color in all the photomicrographs taken using the inverted microscope. The relatively large gap between the two plates observed in transverse metallographic sections was the result of a low clamping force during the spot welding process. As can be seen in Figs. 12 and 13, the Al 3003 is white in color in all

the photomicrographs and photomicrographs. Notice that in this case there is no gap between the two plates in transverse metallographic sections. The images corresponding to the results of the CT scans of the samples with tungsten powder at center line of the weld (WN1 and WP1) are shown in Figs. 14 and 19, respectively. The blue color in the images represents the Al 7075 while the yellow to red regions indicate the presence of tungsten (the regions with red color indicate the presence of more tungsten). Finally, it is important to point out that the direction of rotation of the pin is indicated in several figures.

Table 4. Nomenclature used to identify different sections used for the horizontal metallography

Marker Material	Distance from the Top of the Flash (cm)	Sample Number
Copper	0	CH1
	0.233	CH2
	0.33	CH3
	0.381	CH4
Al 3003	0	AH1
	0.17	AH2
	0.264	AH3
	0.355	AH4

TRANSVERSE METALLOGRAPHY NORMAL TO THE MARKER STRIP

The results corresponding to the specimens with copper strips are presented first followed by those with Al 3003 strips and tungsten powder. For the sample in which the copper strip was inserted, the photomicrographs of four sections are shown in Fig. 9. In the case of Section CN4, the copper strip moved slightly down from its initial position. From Fig. 9(a), it can be observed that at a radial distance of twice the pin radius most of the copper strip was still present as a single piece. However, the cross-sectional area decreased by approximately 27% indicating that some of the copper material was displaced. Also it is interesting to note that copper can be seen in the flash region. It must be pointed out that in this initial section, the work pieces were not completely joined based on the extent of the gap between two plates.

Section CN3 corresponds to a section at a distance of 1.7 times the pin radius from the centerline. Though this section did not come in direct contact with pin, the copper strip experienced a significant deformation and moved upwards, as in the case of a backward extrusion. From the figure, it can be inferred that the strip was initially pushed down by the pin

and later it tried to move up towards the flash. Also, as can be seen from the photomicrographs corresponding to section CN3 (see [Fig. 10](#)), the flow patterns formed by the copper particles were intermittently cyclical.

From the macrographs corresponding to sections CN2 and CN1 shown in [Figs. 9\(c\)](#) and [\(d\)](#), respectively, large chunks of copper strip were seen beneath the hole left by the pin after the plunge phase. Su et al. [14] observed a similar kind of flow pattern in their numerical model and experimental work and they termed that region as “dynamically quiescent region.” Also interleaving layered flow patterns similar to the ones observed in section CN3 were seen along both sides of the hole (see [Fig. 11](#)). While comparing sections CN1 and CN2, the copper particles seen along the left side of the hole were shifted up compared to the other side. This indicates that some of the material that was extruding up took a helical path towards the pin and stirred along with it.

[Figure 12](#) presents photomacrographs at four different locations for test AN. In the case of section AN4, the marker strip has moved down and the top surface of the marker strip adopted a “crescent moon” like shape indicating that more amount of tracer was displaced when compared to the copper marker. However, very small particles of the marker material were seen in the flash region and there was no evidence of the presence of the marker material at any other location.

In section AN3, the strip of marker material underwent considerable deformation and took an asymmetric shape. The flash produced during this weld was also asymmetrical which might be due to the inadequate clamping force applied to the plates. A truncated conical region of very light color in the region adjacent to where the pin plunged can be clearly observed in the photomacrograph corresponding to this section. That region corresponds to a zone with very fine grains indicating that a combination of high temperature and a considerable amount of plastic work led to the recrystallisation of the plate material. By careful observation, this dynamically recrystallized zone (DXZ) can also be seen in the sections corresponding to the sample with copper strip. Similar to the test with copper, the aluminum particles formed interleaving layers in the DXZ which are highly symmetric along the vertical axis of the weld.

From section AN2 it can be observed that the strip has fully deformed and tracer particles were seen around the hole left by the pin. However, there is no evidence of chunks of tracer material beneath that hole. The photomicrographs corresponding to this section are shown in [Fig. 13](#). The material that was extruding up moved towards the pin as can be seen from the path taken by the marker material in this section. The photomicrographs corresponding to this section reveal a flow pattern of equally spaced bands in the flash region (see [Fig. 13](#)). Those banded patterns might be originated by material periodically displaced upwards from

the bottom of the keyhole. Section AN1, which is at the center of the weld, exhibited a similar kind of flow with the tracer particles surrounding the keyhole.

In the case of sample with tungsten powder, the tungsten particles surrounded the keyhole as shown in [Fig.14](#). The paths taken by the tungsten particles are quite similar to the ones observed in the case of copper marker. However, the images from the CT scan were not able to show the banded regions observed in the other two cases.

TRANSVERSE METALLOGRAPHY PARALLEL TO THE MARKER STRIP

The photomacrographs of four sections corresponding to the sample with copper strip are presented in [Fig. 15](#). Section CP4, which was at the greatest distance from the centerline of the pin, shows that copper particles have reached the outer “extremities” of the flash region near the top surface, which is consistent with a backward extrusion. Also, banded regions similar to the ones seen in Section AN2 are found in this section, but recurring less frequently than the former (see [Fig. 16](#)).

In the case of section CP3, the copper particles presented in the DXZ zone were the result of the rotational motion of the material since this section did not intersect with the original location of the copper strip. The metal flow patterns within this zone are also highly cyclical and periodic both around the pin tool and upwards. The actual cause behind the formation of the cyclical flow paths seen so far in different sections could not be determined from the present set of experiments. However, one possible reason might be that, due to stick/slip between the material and the pin, material in contact with the bottom of the pin was pushed upwards to the flash layer by layer.

From the results corresponding to sections CP2 and CP1, it can be observed that the hole left by the pin was surrounded by the copper particles. Also, large chunks of copper similar to the ones seen in sections CN2 and CN1 can be observed in these sections at the bottom of the keyhole. This indicates that a large piece of copper strip was cut down and remained at the bottom of the weld. Finally, the photomacrograph corresponding to section CP1 shown in [Fig. 17](#) requires some additional explanation. The remaining portions of the copper strip on both sides of the keyhole took a peculiar shape with the tips pointing towards the flash. This suggests that the strip initially moved down, a portion was sheared, and the ends took the shape seen in the figure when some of the material was extruding back to the top.

In the case of test AP, only the results corresponding to the center of the weld are presented in [Fig. 18](#). In this section, the DXZ zone with fine grains is represented by the darker region. The marker strip in the vicinity of the pin was

completely intermixed with the parent material and there is no evidence of marker material around the keyhole in the photomicrograph. However, observation of the sample at higher magnifications revealed traces of marker beneath the keyhole, which is consistent with the case of test CP. The shape taken by the Al 3003 strips was also similar to the one observed in section CP1. However, the strips were highly thinned at the ends indicating that more plastic deformation of the marker material took place.

In the case of the sample with tungsten powder, traces of tungsten were observed around the keyhole. However, unlike the other two marker materials in which the strips were broken apart, there was a more continuous path of tungsten powder along the sides of the hole left by the pin (see [Fig.19](#)).

HORIZONTAL METALLOGRAPHY

The photomicrographs corresponding to different sections obtained from the horizontal metallography of a specimen with copper strip are presented in [Fig. 20](#). The top section (CH1) corresponds to the flash region in which copper particles were found at different locations when observed under the stereomicroscope. In all the other sections located at different depths from the flash surface, the copper particles were observed around the keyhole in concentric circles (For example see [Fig. 21](#) corresponding to section CH2). However, moving down away from the flash surface, the concentric circles of the tracer particles became wider until a certain distance and then started decreasing later, depicting the truncated conically shaped extrusion zone seen in section CP2.

From the photomicrographs corresponding to test AH shown in [Fig. 22](#), it was difficult to identify the location of the marker material. However, the flow patterns observed here were quite similar to the case of copper in which the marker material was observed in concentric circles around the keyhole. This can be more clearly observed from the photomicrographs corresponding to section AH2 shown in [Fig. 23](#).

COMPARISON OF MARKER MATERIALS

Based on the flow patterns observed from the samples corresponding to three markers, a comparison was made to select the best marker material. [Figure 24](#) presents the sections at the centerline corresponding to transverse metallography normal to the grooves in the bottom plate for the three marker materials (i.e., sections CN1, AN1 and WN1). The flow patterns observed from the three sections are relatively similar. However, section AN1 slightly differed from the other two since tracer particles were not seen beneath the keyhole as was the case with the other two marker materials (i.e., copper and tungsten). [Figure 25](#)

presents the sections at the centerline corresponding to transverse metallography parallel to the grooves in the bottom plate for the three marker materials (i.e., sections CP1, AP1, and WP1). In all the three cases, the tracer particles were observed at same locations. However, less amount of marker material was seen in the case of section AP1. This might be due to heavy intermixing of the marker material with the plate material during the plunge of the pin.

Although it is preferable to use a dissimilar aluminum alloy as the marker material for the flow visualization experiments, as seen from the results presented in the previous sections it becomes difficult to trace the marker material in the regions very close to the pin. From the present set of experiments the material flow predicted by copper and tungsten marker materials was in a reasonable agreement with that of Al 3003 which indicates that they did not change in a significant fashion the flow patterns. However, care should be taken to choose an amount of marker material that allows visualizing the material flow but without significantly changing it.

SUMMARY/CONCLUSIONS

A preliminary study was made using marker materials to visualize the material flow in the vicinity of the pin during a refill FSSW process. Based on the results corresponding to the three marker materials considered, it was observed that copper and tungsten were better choices from the point of view that it was easier to identify them in the metallographic samples. Although dissimilar aluminum alloys are attractive choices for marker materials from the perspective of having mechanical and thermal properties that are similar to the ones of the plate material, the marker material intermixes with the plate material to an extent that it becomes difficult to identify the marker material in the regions very close to the pin. Based on the results obtained in the flow visualization study presented in this paper, the material flow observed using copper strips and tungsten powder as marker materials was in a reasonable agreement with one observed using Al 3003.

A more detailed study is needed to understand the flow patterns during all the stages of the refill FSSW process under consideration and to classify the different material flow zones. In this regard, it is preferable to follow an approach in which the pin plunges into the plate at varying plunge depths, from shallow to deep, to have a better idea of how the material is moving during the first stage of the refill FSSW process.

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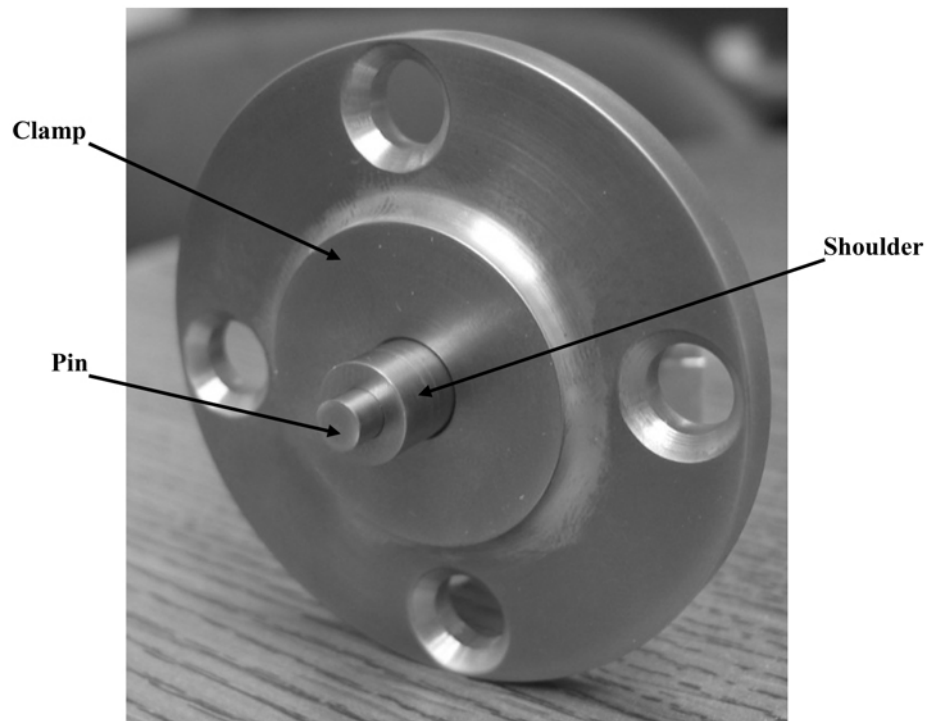


Figure 1. Tool used in the modified refill FSSW process.

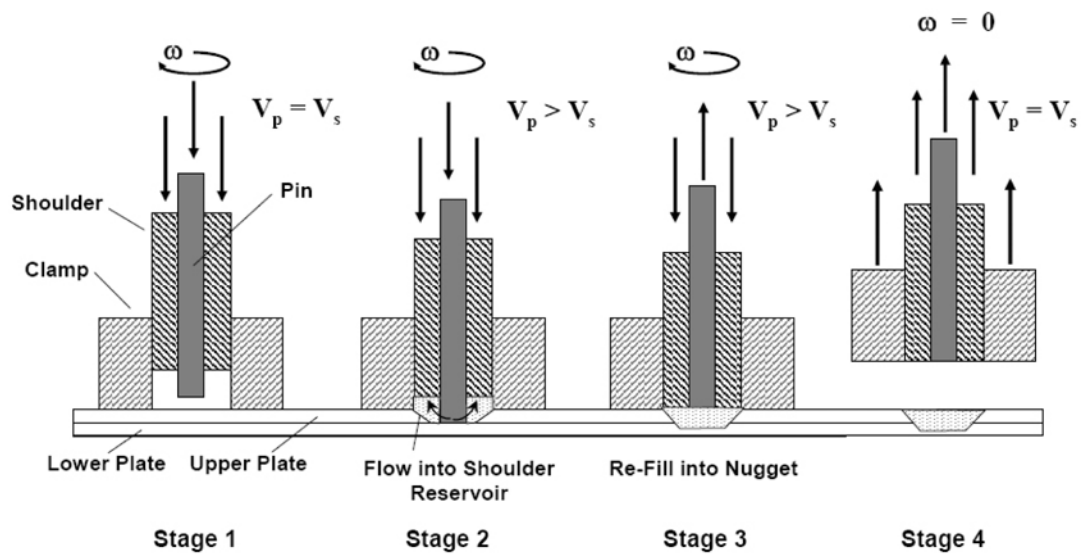


Figure 2. Stages of the modified refill FSSW process.