C.B. Jagadeesha¹

Flow analysis of materials in friction stir welding

¹ Indian Institute of Science, Mechanical Sciences, Bengaluru, India, E-mail: jagscb1966@gmail.com**Abstract:**

The aim of this study was to analyze the flow behavior of materials in friction stir welding (FSW) of magnesium (Mg) alloy to aluminum (Al) alloy materials at a low rotational speed of 300 rpm and at a low welding speed of 50 mm/min. It was observed that during the dissimilar welding at 300 rpm, some of the material of the advancing side (AS) rotated almost 360° and transferred to the position just behind the previous position, i.e. initial AS position and some of the material of leading edge region transferred to the trailing edge region and such a change continued. Material transfer takes place layer by layer from front to back portions of the FSW tool; a thin layer of material adhered to the tool in the front portion for every half rotation and transferred to the back portion of the tool and this repeated in subsequent rotations. Wrinkle formation began at the front side of the forward moving tool and as the material transferred to backside they became an onion ring pattern, and this was inevitable because the formation of onion rings instantly in the backside region of the tool was clearly impossible.

Keywords: AA 2024-T3 Al alloy, AZ31B-O Mg alloy, flow analysis, friction stir welding**DOI:** 10.1515/jmbm-2018-0020

1 Introduction

Friction stir welding (FSW) is a solid state joining process. The materials, especially light metals, such as aluminum (Al) [1], magnesium (Mg) and their alloys [2], [3], [4], [5], [6], [7], which cannot be welded properly by fusion welding can be welded effectively by FSW [8]. In an FSW tool, the advancing side (AS) lies where the linear velocity vector of the rotating tool and the welding direction are one and the same, whereas the retreating side (RS) lies where the linear velocity vector of rotating tool and the welding direction are opposite to each other. The AS of the tool moves counter to the material flow during FSW. In FSW, the front portion of the moving tool is the leading edge (LE) and the backside of the moving tool is the trailing edge (TE).

As the rotating FSW tool pierces down into the abutted plates the following things occur consecutively. The initial heat generation occurs owing to the friction between the tool pin and the work piece; as the heat generation increases and the material around the tool softens, simultaneously the tool gets heated. Within a short time seizure occurs between the tool surface and the plasticized material around the tool. Plasticization of the material adjacent to tool surface is highest and decreases, radially outwards up to interface of the base metal and the weld volume's outer surface; between these two surfaces or regions in the weld volume, sticking and shearing between layers of materials occurs leading to heat generation among the layers and thus there is increase of temperature in the weld volume. At this juncture there will be no friction between the tool and the material and also no heat generation owing to the nullified friction.

The analysis of the material flow is an important tool to understand the role of FSW tools on the weld formation [9]. There have been many experimental studies [10], [11], [12], [13], [14] and computational procedures [15], [16], [17] performed to analyze the material flow, and it has been reported that the material flow in FSW is very complex and not clearly understood. The computed streamlines in the horizontal planes around the tool pin showed the presence of nearly circular closed streamlines, indicating the presence of a plug of material [15]. The tangent movement of the material takes the main contributions to the flow of the material in FSW [16].

Fratini et al. [18] made an important contribution to material flow visualization by relating material flow with microstructural evolution. The formation of onion ring patterns in FSW was studied by Fratini et al. [18] and Krishnan [19]. Krishnan [19] described this using a clay model, and pointed out that this was a geometric effect. He reported that semi cylindrical sheets of material were extruded during each rotation of the tool and cross-sectional slices through a set of semi cylinders would form onion ring patterns. Studies show visible patterns in colder welds, with no observable ring pattern at hotter welds [20]. There is no correlation between onion ring patterns and the resulting quality of the weld nugget [13], [21]. There is no experimental evidence that confirms the mechanism of onion ring formation proposed by researchers [9].

C.B. Jagadeesha is the corresponding author.
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Reynolds [22] mentioned that understanding of the flow of the material is critical to determine the accurate thermomechanical processing conditions during FSW. Tool geometry is the prime parameter in the type of flow during FSW. Analysis of flow of material is an important tool to understand the mechanism of weld formation and physical insight of the process, which in turn is necessary to manipulate the welding parameters to produce defect-free welds. Li et al. [13], [23] studied the flow of material in a joint of AA2024 and A6061 using the differential etching technique. They suggested that the dynamic recrystallization must take place to provide the super plastic effect to assist the instantaneous solid-state flow. They studied the microstructure and revealed the complex intercalated, lamellar-like flow patterns in the weld volume forms vortex, whorl and swirl features which are characteristic of chaotic dynamic mixing.

Schmidt et al. [11] took copper as a marker material in vertical, longitudinal and combined configurations combined with X-ray computer tomography. They classified the material flow zones into three zones, namely; deflection zone, transition zone and rotation zone. Material in rotation zone rotates with the tool pin, the deflection zone which is slightly away from tool is affected by slight deformations, and the transition zone is between these two zones. As the tool advances, the base metal in the LE enters the deflection zone, then transition zone and finally the rotation zone.

Guerra et al. [12] inserted a 0.1 mm thick high purity copper in between Al alloy plates and traced it back by metallographic means after instantaneous stopping of the tool. They reported two types of material flow, first, AS material entered into the rotating zone and advanced simultaneously with the pin, which was sloughed off behind the pin in the arc shaped feature. The second flow is the extrusion of the material around the tool, on the RS. The former is controlled by the rpm and the latter is controlled by the welding speed. Seidel and Reynolds [24] and Reynolds [14] studied the material flow in butt welded AA2195-T8 using markers made of AA5454-H32. They found that the material in the AS moves down, while the material in the RS moves up. Reynolds [22] states that the friction coefficient will strongly affect the material flow and the microstructure. He pointed out that material flow occurs in three horizontal parallel zones.

Sinha et al. [25] suggested that material flow occurs in two modes, first, layer by layer flow caused by the shearing action of the tool shoulder and second, extrusion of the plasticized metal around the tool pin. Schneider and Nunes [26] (Nunes kinematic model) classified the material flow as a straight through current which bypasses the tool pin and maelstrom current which goes several rotations around and with the pin. Abregast's metal working model [27] regards FSW as a material working process that involves five zones: preheat, initial deformation, extrusion, forging and post-weld cool down.

Pourahmad and Abbasi [28] performed a weld between Al 6013/Mg and observed micrographs of cross-section of welds revealing three regions. The first upper region experienced extensive extrusion and stirring action where zigzag interfaces, interlocking and islanding were observed. The second middle region experienced less extrusion of Al into Mg than the upper portion where the weld interface was smoother. The third bottom region is around the weld root and the extrusion of Al into Mg was the least.

In this report the role of the threaded tool on the FSW formation of dissimilar materials (AZ31B-O Mg alloy to 2024-T3 Al alloy) and the resulted material flow were analyzed at a low rotational speed (300 rev min^{-1}).

2 Experimental methods

An indigenously developed computer controlled FSW machine (BiSS Bangalore, India) was used for all FSW experiments. The base materials used were 2024-T3 Al alloy and AZ31B-O Mg alloy. Composition of 2024-T3 Al alloy: 4.3–4.5%, copper; 0.5–0.6%, manganese; 1.3–1.5%, magnesium and less than a 0.5% of silicon, zinc, nickel, chromium, lead and bismuth. This has a tensile strength = 400–427 MPa, yield tensile strength = 269–275 MPa, elongation = 10–15%, Young's modulus = 73 GPa. Composition of AZ31B-O Mg alloy: 2.5–3.5%, aluminum; 0.7–1.3%, zinc and 0.20–1.0%, manganese. This has tensile strength = 240 MPa, yield tensile strength = 140 MPa, elongation = 10%, Young's modulus = 145 GPa.

The size of Al alloy and Mg alloy plates: 250 mm length $\times$ 80 mm breadth $\times$ 5 mm thickness. During the displacement controlled FSW, 2024-T3 Al alloy and AZ31B-O Mg alloy plates were kept in AS and RS of the FSW tool, respectively. The FSW tool material was hot die steel (HDS) and the tool had a threaded (two and a half rounds of left hand threads to a little depth on the pin surface) pin with a rounded tip, a top pin diameter of 6 mm, a bottom pin diameter of 4 mm, a pin length of 4.67 mm and a smooth tool shoulder of diameter 15 mm. Initially FSW was performed on dissimilar materials by setting the welding speed to 100 mm/min, the interface offset (IO) to zero, the tool plunge depth to 4.88 mm, with the rpm varying from 300 to 400 and observing a through hole at the bottom of the weld nugget (WN). This through hole did not disappear even for 80 mm/min and 60 mm/min welding speeds.

Finally, with a 50 mm/min welding speed, a defect-free sound weld was obtained; this was due to increased forging action on the weld volume by a reduction of welding speed from 100 mm/min to 50 mm/min. So, for a sound weld, the following FSW parameters were set: zero IO, welding speed = 50 mm/min, tool plunge depth = 4.88 mm and rotational speed varied from 300 rev min⁻¹ to 400 rev min⁻¹ (Figure 1). After welding, metallographic samples were obtained from the weld coupon at every 12 mm interval (Figure 1). A defect-free weld was obtained for a sample at 305 rev min⁻¹ (Figure 2).

Figure 1: Weld coupon obtained at the parameters 300 rev min⁻¹ to 400 rev min⁻¹, 50 mm min⁻¹ optimized welding speed; scale in cms.

Figure 2: Optical micrograph of cross-section sample, at 305 rev min⁻¹ and 50 mm min⁻¹ welding speed. Arrow coming out of page is the welding direction.

A varying IO FSW (Figure 3) was conducted on 2024-T3 Al alloy and AZ31B-O Mg alloy, a dissimilar material combination for the following optimized parameters: rotational speed = 300 rev min⁻¹, starting IO = 2 mm in RS and ending IO = 2 mm in AS, welding speed = 50 mm s⁻¹, plunge depth = 4.88 mm, weld length = 200 mm and tool tilt angle = 2°. After welding, metallographic samples and tensile samples were extracted alternatively from the weld coupon (Figure 3). In metallographic samples, the Al alloy side was etched using Keller's Reagent (1 ml HF + 1.5 ml HCl + 2.5 ml HNO₃ + 95 ml distilled water) for 30–50 s; the Mg alloy side was etched by solution (14 ml of a 2 g picric acid + 20 ml ethanol solution + 2 ml acetic acid + 2 ml water) for 5 s [29]. Figure 4 is the cross-sectional macrostructure of a joint sample at zero IO, cut from the interface varied weld coupon shown in Figure 3.

Figure 3: Surface morphology of the FSW of Al alloy to Mg alloy weld coupon, obtained by interface offset varying welding with optimized parameters: rotational speed = 300 rev min⁻¹, welding speed = 50 mm min⁻¹.

Figure 4: Cross-sectional macrostructure of the joint sample at zero interface offset, cut from the interface varied weld coupon shown in Figure 3.

3 Results and discussion

3.1 Flow analysis by steel shot tracer technique [10]

Small steel balls (0.38 mm diameter or 0.015 in) 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 travelling around the welding tool. Post-weld placing of the steel balls in each weld, as investigated by X-ray radiography indicated an orderly flow of the material around the tool pin. Based on the opening into the weld zone, only some of the flow of material seemed to be forced downward by the threaded pin, while the rest seemed to be simply rotated from the front to the back of the tool pin [10]; in Ref. [10], welding parameters have not been stated.

If one observes Figure 5 and Figure 6, the offsets (with respect to the tool centerline) of steel shot tracers, 1, 5, 9; 2, 6, 10, 13; 3, 7, 11, 14; and 4, 8, 12 are the same, i.e. shots 1, 5, 9 have the same offset with the tool centerline; similarly, shots 2, 6, 10, 13 have the same offset, and so on. Let us denote the offset position of shots 1, 5, 9 as "A"; of shots 2, 6, 10, 13 as "B"; of shots 3, 7, 11, 14 as "C" and of shots 4, 8, 12 as "D".

Figure 5: 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 work piece plate, as shown in this schematic.

Figure 6: 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 work piece plate, as shown in this schematic.

By observing Figure 7 and Figure 8, the tracers' positions or points before welding can be located at A, B, C, D (Figure 9). After welding, the tracers were carried or deposited approximately to positions A¹, B¹, C¹, D¹, respectively, i.e. A to A¹, B to B¹, C to C¹, D to D¹; note that positions A¹, B¹, C¹, D¹ (Figure 9) are averaged positions of the steel shots after welding as shown in Figure 7 and Figure 8.

Figure 7: 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 Figure 5.

Figure 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 Figure 6.

Figure 9: Plan view of the tool pin; angular arrow is the rotational direction and arrow is the welding direction.

3.2 Flow analysis in dissimilar materials FSW

During FSW, the FSW tool has two distinct motions; one is the forward linear motion of the tool, and the other is the rotational motion of the tool. The forward motion of the tool, being highest at the LE, with which (the tool) compresses or squeezes the material ahead of the LE. The combination of these two motions transfers the material ahead of the tool to the backside region of the tool. Extrusion of the material occurs because of the rotation of the tool from the AS, through the LE and through the RS, i.e. extrusion occurs in the curved region “AS-LE-RS”. Extrusion reaches maximum at the RS, i.e. why the maximum temperature develops at the RS [30], and as there are more groupings of flow lines in the RS region, the weld volume becomes unsymmetrical. The extruded material will be laid in the RS-TE-AS curved region at the backside of the forward moving tool.

A defect-free FSW was obtained at a 300 rpm and 50 mm/min welding speed between 2024-T3 Al alloy and AZ31B-O Mg alloy materials; the arrow coming out of the page is the welding direction (Figure 4). Conceive that

you are sitting inside the tool pin while the welding is going on, and you are looking in the welding direction. At the front left side of the material is the Al alloy and at the front right side of the material from you is the Mg alloy (Figure 4). If you watch the developments taking place in the rear part over the material, from the place where you are sitting, motionless or with fixed body, you can see that the same Al alloy from the front left part of the material is transferred straight to the rear left part of the material and the same Mg alloy from the front right part of the material is transferred straight to the rear right part of the material. For this type of transfer mechanism to take place, the material flow pattern and the material transfer are to be as follows. Two ways of explanation can be given; the first one follows.

The material at point A begins to seize up the tool (Figure 10 and Figure 11) and again the material begins to seize up the tool at point B over the layer of the material stuck previously to the tool at point A and again at point C the material seizes up the tool over the layer of the material previously stuck to the tool at the point B. The same process occurs continuously until point H. The tool carries the material already stuck to it at A up to A¹ and leaves it stuck over the material at that point A¹. It carries the layer of material already stuck to it at B up to B¹ and leaves it stuck over the material at the point B¹; and further it carries the layer of material stuck to point C and leaves it stuck over the material at C¹; and further it carries the layer of the material stuck to it at D up to D¹ and leaves it stuck over the material at D¹. This process continues up to point H; but the layer of the material stuck to the tool at H remains stuck to the material at the same position, and is not carried farther. Zhang et al. [16] reports that the flow of the material in front of the pin on the RS is faster but the flow behind the pin on the RS is slower.

Figure 10: Top view of the tool pin from the shoulder side; angular arrow is the direction of rotation.

Figure 11: Exaggerated top view of the tool pin (around middle length of pin); angular arrow is direction of rotation; arrow is the welding direction.

This aforementioned type of flow of material has been reported by authors (Reynolds [14] and London et al. [31]) in their studies with markers. It is logical to come to the conclusion that material at AS rotates almost 360° and gets deposited at the rear AS position. Only this logical argument can explain the type of material transfer occurring in the weld volume. Because if one assumes that the AS (position A in Figure 10) material comes to the TE (position D¹) position and the LE (position D) material comes to the AS (A¹), then this assumption is

false because this can never happen as the motions of the materials crisscross each other in the region behind the forward moving tool. At higher rpms, a plug of material rotates around the tool, so at a lower rpm, the material makes one revolution, i.e. the material at the AS (in front of the tool) will be laid back to the AS (behind the tool), i.e. the material rotates by almost 360° .

So the flow of materials in the weld volume is the same for FSW of Al alloy with embedded steel shots (Figure 9), as well as for dissimilar material welding (Figure 11); in Figure 9, see the various positions of material points before welding (A, B, C, D), and the transferred positions after welding (A^1 , B^1 , C^1 , D^1) and in Figure 11, see the various positions of material points before welding (A, B, ... G), and transferred positions after welding (A^1 , B^1 , ... G^1). So one can conclude that the explanation of material flow behavior given previously for dissimilar welding is correct and this explanation or hypothesis predicts the material flow in the weld volume, which is the same as the material flow happening in the FSW of Al alloy with embedded steel shots or the dissimilar FSW process at low rotation speed. All the aforementioned analysis of flow of material in the weld volume equally applies to FSW of similar materials also. A second way of explanation follows.

During FSW, seizure occurs between the tool surface and the work piece material. In cold working, deformation won't produce any heat generation, but how does the heat generation take place in the FSW volume during FSW? As soon as the heated material (initial heat generation occurs due to friction between the tool surface and the work piece material) seizes the tool, the plastically deformed material near to the tool surface moves along with the layer of the material that is seized or adhered to the tool surface, as heat generation due to friction is maximum at the tool and work piece interface, the temperature is highest here and goes on decreasing radially away from the tool surface. So as the material moves along with the seized layer of material, this gets separated from the nearby material just away from the tool surface; there occurs shearing of the material, leading to the formation of adiabatic shear bands due to this strong shearing, layers of material are rubbed together while deformation is taking place, leading to heat generation in the FSW volume. This heat softens the material away from the tool and this phenomena takes place in the entire weld volume; note that there is no shear deformation in material near to thermomechanically affected zone (TMAZ). The shear deformation and heat generation is restricted to WN only. Several adiabatic shear bands get formed throughout WN. So as the plastic deformation takes place in the layers of material around the FSW tool, simultaneous heating of the material also takes place in WN and this leads to dynamic recrystallization of the material in WN and is restricted to WN only. The seizure or adhering or sticking and shearing takes place throughout WN between different layers of material and termed in the literature as adiabatic shear banding (ASB).

First ASB forms just away from the tool surface (tool means including tool pin). As the tool rotates from AS to RS through LE, a very thin layer of material between the adhered layer of material to the tool surface and first ASB gets trapped and moves along the tool. This layer gets deposited to the backside of the RS-TE-AS region, as explained below, and this phenomenon gets repeated as the tool advances in the welding direction.

In the line of the welding direction, there is a layer of plasticized material, "A1, A2, A3, M1, M2, M3" (Figure 12B), adhered to the tool surface, between the harder tool material and the non-plasticized work piece material. This layer has adhered to the front portion of the moving and rotating tool. As the tool rotates, material M3 detaches from the tool (at point 5 on the tool surface) and adheres to the already deposited material in the wake of the moving tool, just to its (M3) left side (RS). As the tool further rotates, material layer "M3, ..., A1" peels off continuously from the pin surface and gets deposited along the backside curved region as shown in Figure 12B–J. Peeling off starts at point 5 on the tool surface and continues to point 4 (Figure 12D) and then continues as shown in Figure 12E–J. One can see that material in the front portion (Figure 12B) has been completely transferred to backside of the tool (Figure 12J). This process repeats as the tool rotates and advances. Note that the material layer initially at "A1, A2, A3" in Figure 12B, on the AS, is transferred to A1, A2, A3, on the AS, in Figure 12J, which is on the same side of the original material A1, A2, A3 in Figure 12B and similarly the material layer initially at "M1, M2, M3" in Figure 12B, on the RS, is transferred to M1, M2, M3, on the RS, in Figure 12J, which is on the same side of the original material M1, M2, M3, in Figure 12B. So the material M3 on the RS is totally unmoved or moved only a little distance. Zhang et al. [16] reports that the flow of the material in front of the pin on the RS is faster but the flow behind the pin on the RS is slower.

Figure 12: 1, 2, 3, 4, 5 are the points on the periphery of the tool pin. A1, A2, A3 are the Al material regions on the Al side (AS). M1, M2, M3 are the Mg material regions on the Mg side (RS). A1, A2, A3, M1, M2, M3 is the layer of material (A and B), which is transferred and deposited as A1, ... M3 (J) to backside of the tool pin. This process repeats (B–J) itself for revolutions after revolutions.

The plasticized material layer A1, ... M3, while in the region of the front portion of the tool experiences considerable pressure on it due to the forward motion and rotation of the tool. On the other hand, transferred material at the backside of the tool is free of pressure due to the free space created by the forward moving tool. So at the backside region of the forward moving tool, the peeling off of the layer of material from the tool surface takes place rather than the shearing off of the same material at the region from the surface of the tool. Peeling off of material layer "A1, ..., M3", at the front region or LE region of tool is not possible as the layer of material is under considerable thrust exerted continuously by the forward moving tool. Only seizure or adherence of the layer of material on the tool surface is possible. There is no gap for the plasticized material at the front region to peel off from the tool surface; the other way, there is no slot or gap in the backside region of the moving tool for the layer of material at the backside region of the tool to get peeled off from the tool surface in the wake of the tool. In the low rpm weld, the material transfer is uniform, consecutive and systematic in the horizontal planes, parallel to top and bottom surfaces of the work piece throughout top to bottom of the WN. So at low rpm, an almost extrusion-type flow of materials in horizontal layers occurs in the weld nugget, as one can discern this type of flow from Figure 4, where there is no mixing of materials in the WN, and the Al material on the front left side was transferred to the back left side, similarly the Mg material from the right side was transferred to the back right side layer by layer, one after the other.

So the flow of materials in the weld volume is the same for FSW of Al alloy with embedded steel shots (Figure 9), as well as for the dissimilar material welding (Figure 12); in Figure 9, see the various positions of material points before welding (A, B, C, D), and the transferred positions after welding (A¹, B¹, C¹, D¹). In Figure 12, see the various positions of material points before welding (A1, A2, ... M3 in Figure 12B), and the transferred positions after welding (A1, A2, ... M3, in Figure 12J). So one can conclude that the explanation of material flow behavior given previously for dissimilar welding is correct and this explanation or hypothesis predicts the material flow in the weld volume, which is the same as the material flow happening in FSW of the Al alloy with embedded steel shots or the dissimilar FSW process at low rotation speed (at 300 rpm). All the aforementioned analysis of the flow of material in the weld volume equally applies to FSW of similar materials.

Plasticized material which is adhered on the tool surface shears off from the non-plasticized material ahead of it. The layer of plasticized material, one end is at the RS and its middle is at the LE and the other end is at the AS. This layer rotates along with the tool. Material M3 enters constriction at the RS (Figure 13) and adheres to the already deposited material at the RS and the peeling off of layer A1... M3, starts at the RS (Figure 12); as the material peels off the tool advances a little, creating a larger gap enhancing the peeling off of material and layer A1 ... M3 deposits to the backside region (TE region) in the wake of the tool, then the peeling off of the material ends at AS (Figure 12J). There is a greater amount of adhered material at the LE center region (Figure 13), by the above mechanism; this greater amount of material exactly transferred to the larger gap at the TE center region. Little or no plastic deformation occurs behind the moving tool; on the other hand, only the deposition of material, layer by layer, takes place in the behind or the TE region of the tool. So, much of the plastic deformation or shearing off of the material from the parent material occurs in front or the LE region of the tool. So contribution to temperature rising in the weld volume occurs from the front region of the tool and shear and compressive stresses and strains are also highest here at LE region, owing to the highest plastic deformation of material there.

Figure 13: Showing the tool pin and the constriction at the RS of the tool pin.

The threaded tool performs two functions, one is the pushing of the material downwards and the other is effectively breaking the interface of the two butt plates and plastically deforming the interface, which may not be properly achieved by an unthreaded tool pin. At higher rpms, both functions will be performed to a higher degree by the tool pin; but at lower rpms (such as 300 rpm here) the former function of the pin is of a lesser extent than the latter function. Also, materials at the front side of the moving tool, as they are, are transferred to the backside of the tool. This is possible if and only if there is no mixing within the materials and if there is no considerable top down and bottom up movement of the material in the weld volume, especially at regions slightly away from the tool pin. So one can conclude that, at lower rpms, the transfer of material occurs in almost horizontal layers, parallel to top and bottom surfaces of the plates. This is justified in Figure 4 where the material transfer and deposition is uniform, consecutive and systematic in horizontal planes, throughout top to bottom of WN. So at low rpms an almost extrusion type of flow of materials in horizontal layers occurs in the WN. Similar observations had been made by Colligan [10]; see Section 3.1, first paragraph. Colligan's [10], subsequent studies [12], [24], [31] have shown that inserted copper foil, plated surfaces and composite markers justified these observations. All studies pointed that the flow of material was orderly, with the material seeming to flow along defined path.

Okayasu et al. [32] stated that the difference in stored energy in the material due to difference in deformation leads to differential etching contrast in the region of the onion rings. As the extruded material is in a crescent-shaped cross-section with a wider top and narrow bottom [19], [33] (Figure 14), during rotation of tool from the AS to the RS through the LE, there occurs the formation of horizontal layers (but perpendicular to the pin axis) with folds or wrinkles (Figure 14) in the "extruded material in crescent shape". Those wrinkles, rucked up from top to bottom of the crescent in the said material are formed due to the slanted orientation of the crescent shaped material on which the shoulder pressure is being applied. These wrinkles, with more degrees of deformation, become onion rings after they reach the TE region of the tool. And this process will be elaborated on in more detail further.

Figure 14: Extruded material in crescent shape.

While the layers of the material were being extruded at the various points like A to A¹, etc. (Figure 9), the maximum pressure occurs on the material in the TE central position. The occurrence of maximum pressure is caused by the backward tilted tool. And also the void slot occurring beneath the shoulder in the TE is caused by the forward motion of the tool pin. On either side of slot, there is no plasticized base metal at lower region and over this there are the HAZ plus TMAZ plus plasticized material. Owing to lesser resistance offered at the slotted portion compared to the resistance offered at the regions (on either side of slotted portion) of BM plus HAZ plus TMAZ plus plasticized material, the layers of material that reach the TE region and fill the slot sag more at the slot or the WN region than, at the regions of base metal plus HAZ plus TMAZ plus plasticized material. That is why the onion rings being shaped in that process get sagged at the central and the bottom portion of the weld nugget. A few strata of onion rings, owing to the eddy flow of material as seen in Figure 2, at the bottom portion of weld nugget support the present argument.

Another possibility of wrinkles formation is, in the weld volume, on the surfaces of contact i.e. on pin surface and on shoulder surface where highest velocity occur, owing to seizure between the material and the tool surface. Material at the contact has high velocity and the velocity of the material in the weld volume decreases radially and vertically (from top to bottom) until the TMAZ zone of the weld volume is reached, where the velocity of the materials reaches zero. Owing to the different velocity at different places in the weld volume, shearing between material layers occurs or shear bands occur in horizontal surfaces from top to bottom of the weld volume. This shear banding also occurs radially, owing to the rotating pin, but the intensity of this is lower than that caused by the shoulder having high velocity along its surface. These shear bands will become onion rings when the material is transferred to the backside region of the rotating tool.

During the forward motion of the tool, the pin driven material is in front of the shoulder driven material; first the pin driven material is deposited backside, i.e. in the cavity created by the forward moving tool. Over this material the shoulder driven material is deposited. During this type of deposition the rings formed due to wrinkles will become curved and bent upward and fall above the sagged rings forming onion rings in the WN, e.g. as observed by Kumar et al. [33]. Wrinkles formation begins at the front side of the forward moving tool and as the material is transferred to the backside it will become onion rings pattern, and this is inevitable because the formation of onion rings at once in the backside region of the tool is clearly impossible.

The compelling evidence of flash can be seen in weld coupon (Figure 1 and Figure 3), which accentuates the flash of material that occurred on the top portion (i.e. at the RS) of the weld coupon along the length of the weld. This flash formation can be analyzed as follows. The flash occurred at the RS, first due to the distending of material at the LE portion caused by the backward tilted tool with a built-in or protruded tool pin being ploughed into the material in the welding direction and while the material was distending, some of it was pushed aside to the RS by the shoulder and second, when the tool shoulder was being angularly pushed over the material between the TE and the AS, some portion of the material at and around the LE bulged and pushed aside to the RS by the shoulder. Zhang et al. [16] reports that the material in front of the pin moves upward and the material behind the pin moves downward in FSW. If the plunge depth is more than flash occurs on both sides, i.e. on the AS as well as on the RS of the tool.

4 Conclusions

- It is observed that during the welding, some of the material of the AS rotated 360° and transferred to the previous position, i.e. the AS and some of the material of the LE transferred to the TE and such a change continues. This flow mechanism applies for similar as well as dissimilar material combination FSW.
- In the low rev min⁻¹ weld, the material transfer is uniform, consecutive and systematic in horizontal planes, parallel to the top and bottom surfaces of the work piece throughout the top to bottom of the WN. So at low rpms, an almost extrusion type of flow of materials in horizontal layers occurs in the weld nugget.
- Material transfer takes place layer by layer from the front to back portion of the FSW tool; a thin layer of material adhered to the tool in the front portion for every half rotation and transferred to the back portion of the tool and this repeats in subsequent rotations.
- Wrinkles formation begins at the front side of the forward moving tool and as the material is transferred to the backside they will become an onion rings pattern, and this is inevitable because the formation of onion rings at once in the backside region of the tool is clearly impossible.
- It must be noted that thorough mixing of materials in FSW cannot be achieved as there the material in the weld volume is in the solid state (like paste) but not in the liquid state.

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