VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

VISUAL ANALYSIS OF MATERIAL FLOW DURING FRICTION STIR WELDING OF NYLON-6

Adeel Zafar, Mokhtar Awang, Sajjad Raza Khan and S. Emamian
Department of Mechanical Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, Tronoh, Perak, Malaysia
E-Mail: adeel_ze@ymail.com

ABSTRACT

Material flow during friction stir welding (FSW) is a challenging subject that should be studied to understand the defects produced during the process. Recent achievement of friction stir welding of polymers, necessitates the study of this process on polymers as well. In this paper material flow was studied on nylon-6 due to its wide engineering applications. For this purpose, a 1.5 mm thin polymer sheet, different in color, was used as a marker material and embedded in nylon-6 at various positions. Post-weld specimens, welded at optimum friction stir welding parameters, were cut at different sections for visual analysis of flow. Results showed that flow behavior in polymers is remarkably different from metals. Flow was limited to the pin influenced zone and no flow across this zone was seen. Uniform stirring and interesting phenomenon of far off displacement of plasticized material, even out of pin diameter range was observed. Analysis also revealed the upward vertical motion of the marker material.

Keywords: material flow, polymer, nylon-6, friction stir welding, threaded pin.

INTRODUCTION

Friction stir welding (FSW) is a solid-state joining technique used for various materials including polymers, low melting and high melting metals in various industries such as automotive, aircraft, and shipbuilding. FSW provides many benefits over other conventional joining methods because the material is usually not melted during the process. The process is performed by traversing a rotating tool through a workpiece material along the joining line. The frictional heat between the workpiece and the tool makes the joining surfaces plasticized and easy to stir. Although the material is usually not heated to its melting point during FSW, the process is characterized by high temperatures and severe plastic deformation.

A rich literature is reported addressing various aspects of joining. Material flow behavior, however is not fully understood and requires further investigation [1]. The recent success of FSW on joining of polymers demands extensive investigations covering all aspects of joining and making this process efficient on polymers as well. Study of material flow is one of the important topics of investigations because the quality of the joint depends on the degree of mixing of the two weld pieces [2]. Material flow in polymers is so far reported by Simoes *et al.* [3] with their study on 10 mm thick PMMA sheets by different pin profiles. They concluded that the flow in polymer is different from metals when compared to Arbegast [4] flow model. It was suggested that the interface of pin affected zone and base material remained straight which showed no material flow from stir zone to base material. Similarly a distinct separation can be seen between shoulder affected zone and pin affected zone.

There are some other studies of material flow but reported on metals. For example, Lorrain *et al.* [2] studied this phenomenon on 4 mm thick aluminum alloy 7020-T6 sheets utilizing two unthreaded straight cylindrical and tapered pin profiles. Pieces of 0.2 mm thin sheet of copper as markers were positioned in the specimens in longitudinal and transverse directions. Comparing with previous studies, it was observed that the material flow with unthreaded pin was the same as material flow using threaded pin. Moreover material was deposited on the advancing side in the upper part of the weld and in the retreating side on the lower part of the weld. Guerra *et al.* [5] reported different flow of material on advancing side (AS) and retreating side (RS) during friction stir welding of aluminum 6061. According to them, material in front of pin in AS rotates with pin and displaces at the back of pin in arc shape. Whereas material on RS at the front of pin will not rotate but will be displaced at the back of pin. In rotational zone flow is vortex due to the threads of pin and forms a helical trajectory. However material at the top near the shoulder has less effect of threads and move due to shoulder.

Colligan [6] studied material flow on aluminum 6061 and 7075 by inserting small steel balls as a tracer material. Steel balls were placed into grooves parallel to welding direction at various depths of specimen. After welding, the displacement of steel balls was seen by radiography. Results showed that the balls placed on advancing side were displaced to retreating side at the back of the pin. Balls of retreating side remained on retreating side but stroked behind the pin. Little rising of balls towards shoulder was also observed. Observation of pin hole showed that materials were moved behind the pin and deposited on retreating side. They believe some of the plasticized material may have been squeezed and extruded by the pin on the retreating side. Therefore Colligan [6] deduced that the flow in FSW process is due to both stirring and extrusion of material. Li *et al.* [7] used a 0.1 mm thin bronze foil as a marker which was placed into the weld interface of 7075-T651 aluminum alloy. After welding, distribution of the bronze foil in the weld was analyzed by X-Ray and optical microscope. According to their proposed model, the flow behavior of the plasticized material is different at various thicknesses of specimen. At

VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

the top position of weld, the plasticized material adjacent to the shoulder is extruded by the rotating shoulder, and moved both in the horizontal and the vertical direction. At the mid position of weld, the plasticized material is sheared and extruded by the threaded pin, and moved in the vertical direction. Whereas at the root of the weld, the plasticized material is rotated and extruded by the bottom surface of the pin and moved forward due to the effect of tilted pin.

Zhang *et al.* [8] studied the material flow by simulation using finite element technique based on the nonlinear continuum mechanics. Results showed that during flow the material in front of the pin moves upward whereas the material behind the pin moves downward. Moreover there exists swirl on the advancing side. They observed that the larger flow during welding is due to the tangent flow of material around the pin.

Edwards and Ramulu [1] used powder as a tracer material to study the material flow in FSW of Ti-6Al-4V. Thereafter, metallography was used to find the final location of the powder. After welding, the tracer material starting on the weld centerline was displaced behind the pin towards the advancing side but near the centerline. Moreover, spreading of tracer material up-to 600% wider area than its embedded area indicates some mixing in the weld nugget. However, in vertical direction very less spreading was observed. Seidel and Reynolds [9] used marker insert technique at different locations of specimen. After welding workpiece was machined little by little down from top surface, and at each step specimen was examined under microscope. They observed that the majority of the material in the weld nugget was simply moved around the pin and displaced behind the pin relative to its initial inserted position. Major stirring was seen under the shoulder and due to shoulder. In addition to it, threaded pin produced some vertical movement of material as well.

In another FSW material flow experiment Schneider [10] used wire as marker material. It was observed that material in the weld zone on the retreating side was extruded around the pin while material on the advancing side was stirred around the pin before being deposited behind the pin. Kumar and Kailas [11] reported material flow phenomenon in aluminum 7020-T6. According to them, material in aluminum flows in two different ways. One flow is due to shoulder rotation and the other is due to pin action. The shoulder-forced material flows from the retreating side and forges against the base material of advancing side whereas pin-forced material flows layer by layer around the pin. Pin-forced and shoulder-forced material thus unite together to form a weld. Arbegast [4] presented the material flow of metals in terms of analytical and numerical models and described the reason of defects formation. According to them, material from retreating side moves in two directions. One part moves down the tip of the pin and the second part enters in the advancing side by moving around the pin and amalgamates with the advancing side material. Material below the shoulder on retreating side is dragged towards the advancing side. After mixing with advancing side material, it moves downward on the same side. In this study flow process is studied on nylon-6 because of its wide engineering applications. Formation of flash and defects as observed in previous FSW studies of polymers is investigated by understanding flow in nylon-6.

MATERIALS AND METHOD

Nylon-6 (Polyamide-6) plates with thickness of 16 mm were butt-welded using VMC 2216 Bridgeport CNC machine. Right hand threaded pin tool made of H13 tool steel with double shoulder was used to control expelling out of molten material. In this experiment shoulder was not plunged in the specimen so it was maintained at a height so that shoulder’s bottom surface was just touching the specimens’ top surfaces. Optimum parameters such as 300 RPM rotation rate, 25 mm.min-1 feed rate and 15s of dwell time, obtained from previous experiments were used in this investigation [12]. Tool rotation direction in all experiments was kept in clockwise direction. A 1.5 mm thin polymer sheet with different color, was embedded in different positions as a marker material as shown in Figure1. The displacement of marker material after welding was analyzed visually by cutting the specimens in various vertical and horizontal sections.

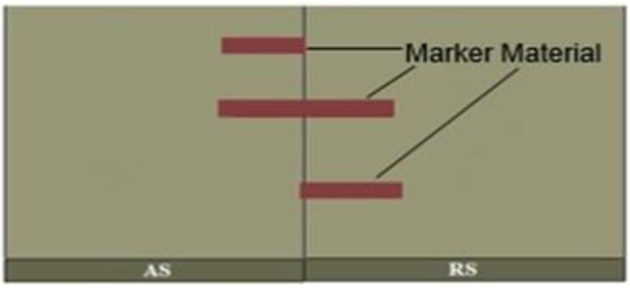


Figure-1(a). Marker material placed vertically in transverse direction.

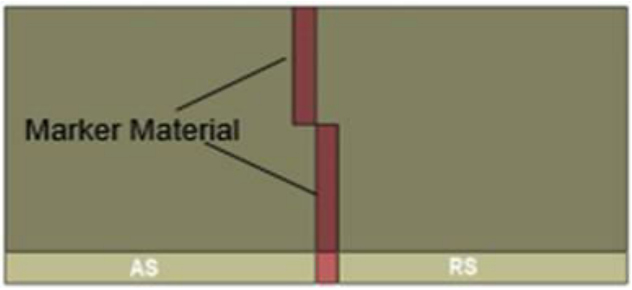


Figure-1(b). Marker material placed vertically in longitudinal direction on AS and RS.

VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

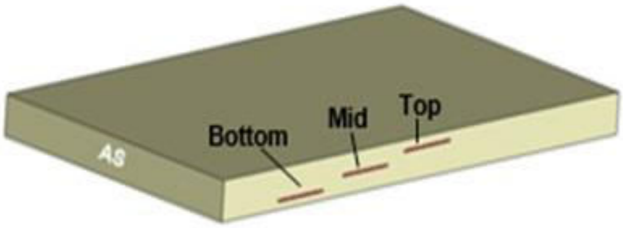


Figure-1(c). Marker material placed horizontally at different depths on AS.

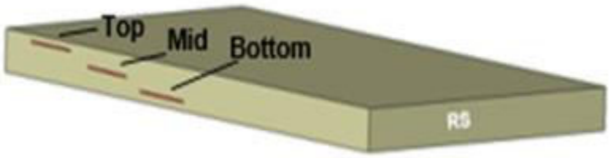
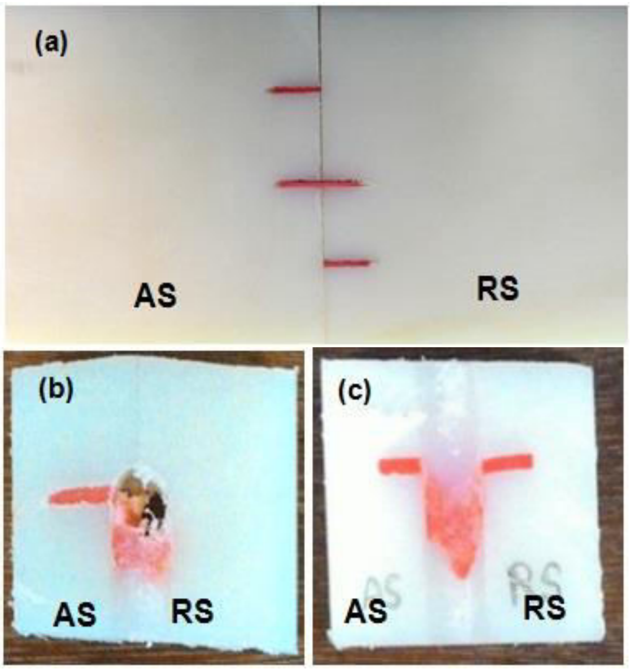


Figure-1(d). Marker material placed horizontally at different depths on RS.

RESULTS AND DISCUSSION

Figure-2(a) shows a marker material perpendicular to welding direction. It was designed to investigate the horizontal movement of the material in longitudinal direction. Specimen after welding was horizontally cut in longitudinal direction from middle of its thickness as shown in Figure-2(b-d). In Figure-2(b) it can be seen distinctly that marker material was displaced from its original position and placed at the back of the pin after stirring. An interesting phenomenon was observed when farthest displacement was measured.



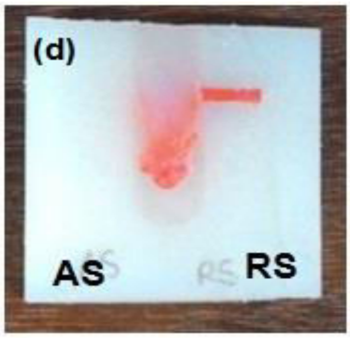
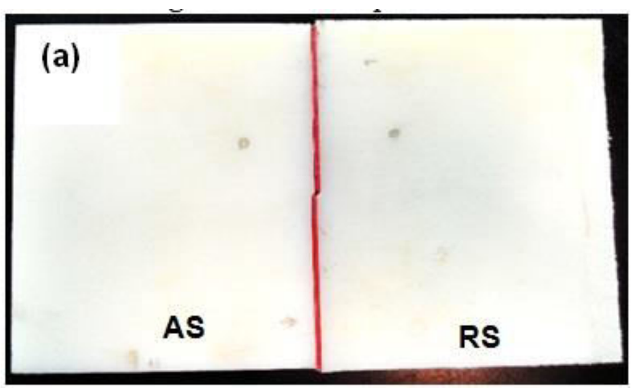


Figure-2. (a) Specimen with marker material placed vertically in transverse direction (b) Horizontal sections of samples when marker material is on AS, (c) on seam line (d) RS.

The farthest marker material was displaced 11 mm away from its original position when the diameter of pin is 7 mm. It shows that the pin forced the material away during its rotation. The stirring of material was almost uniform except a farthest narrow part which was 2 mm long and placed exactly on seam line.

In Figure-2(c) the movement of marker material when it was only on AS side is shown. It can be seen that displacement was limited to 6 mm away from its original position and expanded uniformly unlike Figure-2(b) specimen. In Figure-2(d), a little different flow at the farthest part was observed when marker material initially was placed on seam line covering the AS and RS sides. This displacement actually can be divided into two parts. Narrow part which is farthest part and 4 mm long is located on RS side. After observation of Figure-2(b) and 2(c), it can be said that this displaced material on retreating side was taken from RS side. The other 7 mm long part is uniformly stirred and extended on both AS and RS sides. The stirring width is equal to the diameter of the pin. The absence of marker material at its original position after welding, supports the fact that the plasticized material stirred around the pin is finally displaced behind the pin and spreads out far away, even larger than the pin diameter. It can be assumed that the farthest part is squeezed and extruded by pin and similar to Colligan [6] study on metal in which he considers the welding due to stirring and extrusion process.



VOL. 11, NO. 6, MARCH 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

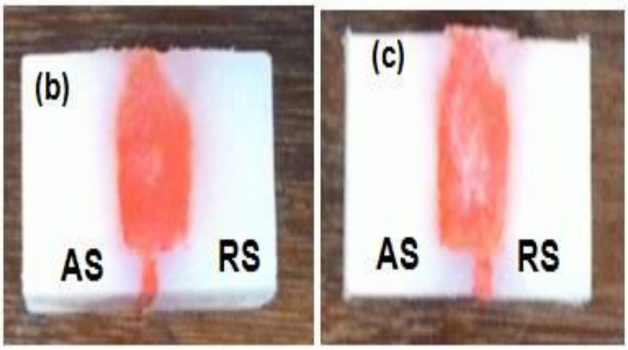


Figure-3. (a) Specimen before welding with the placement of marker material in vertical- longitudinal direction on AS and RS side. Cross section of samples after welding, when marker material is on (b) AS and (c) RS side.

In order to analyze the stirring uniformity and horizontal spreading in transverse direction, marker material was placed on AS and RS sides as shown in Figure-3(a). Figure-(b) is the cross sectional view of specimen after welding when marker material is on AS side. From Figure-3(b), it is clear that 1.5 mm thick marker material polymer is uniformly spreaded up to 7 mm wider area which is equal to the diameter of the pin. It proves the uniform mixing of material all along the welding zone. Similarly, in Figure-3(c) marker material expanded in complete welding zone, and stirring is uniform. However in both figures, Figure-3 (b) and (c) it can be seen that mixing at the top of the specimen is limited to 3 mm maximum width and located on AS side. It is believed that this narrow region which is 2.5 mm long is due to almost 2.5 mm long unthreaded part of pin at the bottom. Furthermore, the 13.4 mm total depth of welding zone is equivalent to pin length. It indictes that there was no flow of material below the tip of pin and srirring remain limited to the pin plunged area.

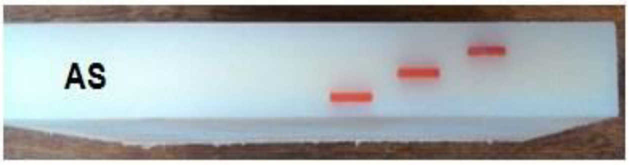


Figure-4(a). Specimen with marker material placed horizontally at different depths on AS.

Figure-4(b). Vertical section of figure. 4(a) specimen after welding.

Figure-4(c). Specimen with marker material placed horizontally at different depths on RS.

Figure-4(d). Vertical section of figure. 4(c) specimen after welding.

Vertical movement of material during FSW is another important phenomenon to understand uniform mixing and flash forming. For this, Figure-4 (a) and (c) shows the placement of marker material at different depths in workpieces on AS and RS side respectively. Marker materials were placed in top, middle and bottom positions in such a way that their top surfaces are 2mm, 6mm and 11mm deep respectively. Figure-4 (b) and (d) shows the sections of AS and RS samples cut at the seam line in longitudinal direction. Visually it can be seen that 1.5mm wide marker material is expanded upward up to the top surface of specimen. Very minor downward flow was observed. In Figure-4(b) formation of flash produced by top positioned marker material is also visible. As a conclusion it can be said that right hand threaded pin when rotated in clockwise direction causes the plasticized material to move upward till maximum height. From here it can be assumed that the anticlockwise rotation of pin will make downward movement of material. This vertical movement can be resembled with Guerra *et al.* [5], Li *et al.* [7] and Seidel and Reynolds [9] study on aluminum in which large vertical movement was observed.

Comparing the flow of the polymer weld with Arbegast [4] model, it becomes obvious that Zone III; in which stirring due to shoulder rotation occurs, is absent from the polymeric welds. It is due to the squeezing out of plasticized polymer. Similarly no such flow was observed in which stirring material enters the base material by crossing weld zone interface. Therefore pin influence zone remains straight and parallel to pin unlike metals' flow described by Arbegast [4]. Furthermore a straight line at the bottom of the pin indicates that zone IV is also absent in polymers. Simoes and Rodrigues [3] also described the same flow phenomenon in PMMA polymer in which pin influenced zone remained isolated from surroundings including shoulder affected zone.

CONCLUSIONS

Material flow in nylon-6 during friction stir welding can be concluded by combining all the sectional analysis. During the rotation of pin, plasticized material taken from RS front side of pin was displaced at the back of the pin and divided into two parts. One part is pushed away even more than pin diameter opposite in welding direction. The other RS plasticized part stirred with AS material and spread in complete welding zone, which was equivalent to pin diameter. During stirring of AS and RS material some upward movement of material was also observed. Comparing with Arbegast [4] flow model on metals, zone III-shoulder affected zone and zone IV-pin tip affected zone were not observed.

ACKNOWLEDGEMENTS

Authors would like to acknowledge the financial support of Universiti Teknologi Petronas for the presented work.

REFERENCES

[1] P. D. Edwards and M. Ramulu, "Material flow during friction stir welding of Ti-6Al-4V," Journal of Materials Processing Technology, vol. 218, pp. 107-115, 4// 2015.

[2] O. Lorrain, V. Favier, H. Zahrouni, and D. Lawrjaniec, "Understanding the material flow path of friction stir welding process using unthreaded tools," Journal of Materials Processing Technology, vol. 210, pp. 603-609, 3/1/ 2010.

[3] F. Simões and D. M. Rodrigues, "Material flow and thermo-mechanical conditions during Friction Stir Welding of polymers: Literature review, experimental results and empirical analysis," Materials & Design, vol. 59, pp. 344-351, 7// 2014.

[4] W. J. Arbegast, "A flow-partitioned deformation zone model for defect formation during friction stir welding," Scripta Materialia, vol. 58, pp. 372-376, 3// 2008.

[5] M. Guerra, C. Schmidt, J. C. McClure, L. E. Murr, and A. C. Nunes, "Flow patterns during friction stir welding," Materials Characterization, vol. 49, pp. 95-101, 9// 2002.

[6] K. Colligan, "Material flow behavior during friction welding of aluminum," Weld J, vol. 75, pp. 229s-237s, 1999.

[7] W. Y. Li, J. F. Li, Z. H. Zhang, D. L. Gao, and Y. J. Chao, "Metal Flow during Friction Stir Welding of 7075-T651 Aluminum Alloy," Experimental Mechanics, vol. 53, pp. 1573-1582, 2013/11/01 2013.

[8] H. W. Zhang, Z. Zhang, and J. T. Chen, "3D modeling of material flow in friction stir welding under different process parameters," Journal of Materials Processing Technology, vol. 183, pp. 62-70, 3/5/ 2007.

[9] T. U. Seidel and A. P. Reynolds, "Visualization of the material flow in AA2195 friction-stir welds using a marker insert technique," Metallurgical and Materials Transactions A, vol. 32, pp. 2879-2884, 2001/11/01 2001.

[10] R. S. Mishra and M. W. Mahoney, Friction Stir Welding and Processing: ASM International, 2007.

[11] K. Kumar and S. V. Kailas, "The role of friction stir welding tool on material flow and weld formation," Materials Science and Engineering: A, vol. 485, pp. 367-374, 6/25/ 2008.

[12] Zafar, M. Awang, S. R. Khan, and S. Emamian, "Effect of Double Shoulder Tool Rotational Speed on Thermo-Physical Characteristics of Friction Stir Welded 16mm Thick Nylon6," Applied Mechanics and Materials Journal, vol. 799-800, pp. 251-255, 2015.