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Material Flow Behavior in Dissimilar Friction Stir Welds of AA2024 and AA5086 Aluminum Alloys

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ABSTRACT

This research aims to investigate the material flow behaviour and microstructure evolution in friction stir welded joints of dissimilar aluminium alloys AA2024/AA5086. AA2024 plate was placed on re- treating side; welded using threaded conical flat shoulder tool rotating at 635 rpm and moving along the joint line with a speed of 75mm/min. Mixing of both the material was clearly visible in stir zone and resulted in features typical to dissimilar friction stir welding and solid state flow patterns beside different zones. Onion rings, laminar flow, vertex flow was main flow features observed in the stir zone. Non- uniform mixing of different chemical composition base material is behind the formation of these flow features and inclusive chemical mixing may abolish solid state flow features.

Keywords: Friction stir welding; Aluminium alloys; Material flow; Microstructure; Vortex flow; Laminar flow.

INTRODUCTION

Now a day's more and more dissimilar materials are used for single application and are usually joined by mechanical fastening, riveting, fusion welding and friction stir welding to fabricate light weight and stronger components as well as large structures for miscellaneous engineering applications [Singh et al., 2016, & Sharma et al., 2014]. Application of aluminum and its alloys have witnessed tremendous upsurge as engineering material in most of the areas of human life owing to their attracting properties [Mishra et al., 2005 & Sharma et al., 2012]. The welding of aluminum is challenging not only in dissimilar combination but also in similar combination [Sharma et al., 2015]. Friction stir welding (FSW) has proven its capability to join difficult to fusion weld aluminum alloys in similar and dissimilar combination and with other materials also. FSW produces high quality stronger butt, lap, T welds etc. of metals and non-metallic materials [Mishra et al., 2005 & Khan et al., 2017]. In fusion weldments defects like voids, porosity, hot cracking, segregation, distortion, brittle intermetallic formation etc. are common and requires careful selection of selection of process parameter, filler wire etc. [Khan et al., 2017, Koilraj et al., 2012 & Sharma et al., 2015a]. Grain boundary liquation and severe grain boundary segregation of alloying element Si and Mg happened in partiality melted zone on AA6061 alloy side which weakened the metal inert gas welds of dissimilar wrought AA6061 and cast A356 aluminum alloys owing to the formation of needle like β-Al5FeSi and irregular π Al9FeMg3Si5 phases [Nie et al., 2018]. The absence of fusion welding related defects and problems and recrystallized finer grain structure in place of cast dendritic structure enhanced mechanical corrosion and fatigue behavior of friction stir welds of dissimilar aluminum alloys substantially [Mishra et al., 2005 & Khan et al., 2017].

Recently, extensive research has been conducted on FSW of dissimilar aluminum alloys/ materials. In FSW, joining is achieved because of severe deformation and flow of material in solid state facilitated by dynamic recrystallization (DRX). Extensive mechanical mixing of dissimilar materials/alloys is observed in stir zone. Chaotic dynamic mixing resulted in the creation of vortex, whorl, swirls, complex intercalation features. Lamellar shear bands rich in either one or other material of material combination were present in stir zone [Somasekharan et al., 2004, Murr et al., 1998 & Priya et al., 2009]. Material flow patterns and quality of welds is affected significantly by the location of dissimilar material [Koilraj et al., 2012]. Stir zone consists of advancing side material for AA2219/AA6061 welds [Priya et al., 2009] and retreating side material for A356/AA6061 welds [13 Lee et al., 2003]. Mechanical mixing and insufficient diffusion produced heterogeneous stir zone comprising AA2024 and AA7039 base metals with Zn or Cu rich zones and lamellae flow patterns [Sharma et al., 2021 & Ouyang et al., 2002]. Stronger base material is placed on retreating side to achieve higher mechanical properties [Lee et al., 2003]. Position of deforming material in stir zone influences material flow patterns, degree of material mixing and thickness lamellae while welding parameters affected the width and shape of nugget zone. Higher rotary speed leads to uniform mechanical mixing of materials in stir zone [Ilangovan et al., 2015]. In view of great impact of material flow on the formation of welds and evolution of microstructure, present research aims to investigate material flow and associated microstructural features in welds of dissimilar aluminum alloys AA2024/AA5086.

MATERIAL AND EXPERIMENTAL METHOD

Base metals for this work were AA2024 and AA5086 plates of size 300 mm × 50 mm × 5 mm. Rolled plate of AA2024 alloy and AA5086 were supplied in T6 and O condition. The chemical composition of base metals was determined by Electron Dispersive X-ray (EDAX) analysis. AA2024 comprised of 3.83% Cu, 2.56% Mg, 0.34% Mn, 0.55% Fe, 0.13% Si whereas AA5086 comprised of 4.11% Mg, 0.51% Mn, 0.12% Fe, 0.09% Si, 0.01% Cu, 0.02% Zn. The plates were machined to have complete metal to metal contact at faying surfaces. AA5086 and AA2024 plates were placed on advancing and retreating side respectively for welding. Single pass FSW was performed on vertical milling machine (HMT India, 5 kW) equipped with suitable fixture for holding the plates securely in position without slip- ping and lifting. A tool with flat shoulder and threaded cylindrical pin was used at rotary speed of 635 rpm and traverse speed of 75 mm min-1. Only defect free welds were used to make metallographic specimen by sawing. Then ground and polished following standard metallographic practices to get sample for microstructural description. Specimens were etched using Keller's reagent for 90 s. Optical microscope (Leica, Germany) was utilized for studying various microstructural and material flow features.

RESULTS AND DISCUSSION

Macrostructure

Optical macrograph of transverse cross section (i.e. perpendicular to welding direction) of friction stir weld joints is shown in Figure 1.

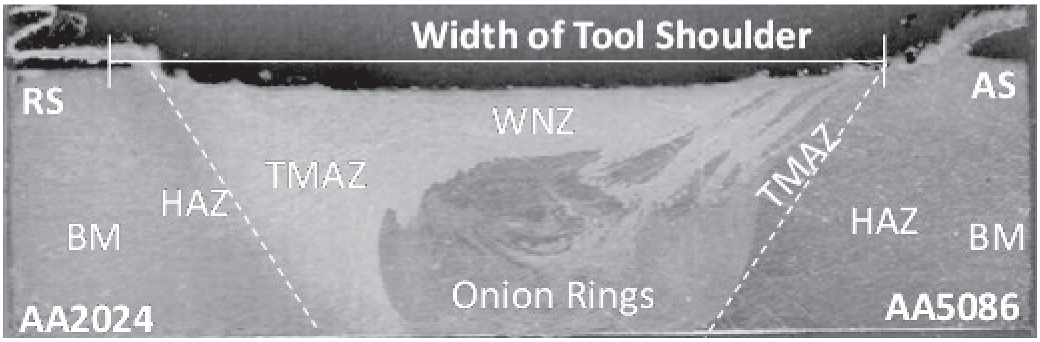

Figure 1. Macrograph showing the evolution of different zones and the formation of dissimilar friction stir weld joint

The weld joints exhibited proper mixing of both the base materials and complete assimilation of abutting edges resulting in the formation of sound and defect free weld joints. No volumetric defect e.g. tunnel defect, lack of penetration, unfilled section and kissing bond, was observed on the transverse cross-section of the weld joints. The weld joints displayed well defined zones i.e. WNZ, TMAZ, and HAZ characteristic to dissimilar FSW. Presence of dark and bright regions and intercalation features confirms the mixing of both the materials in thermo-mechanically affected stir region just beneath the tool shoulder. The hook i.e. transverse section of flash is also clearly visible on the advancing side of the joints as shown in figure 2. No other defects like kissing bond, tunnel, or crack was not observed. The rotating and traversing tool generates large heat owing to the plastic deformation of base materials and friction between tool and base materials surfaces in contact, resulting in higher temperature. The use of fast rotary speed and slow travel speed of tool further increases the generation of heat and raise the peak temperatures during weld thermal cycles which in turn softens the materials around the tool.

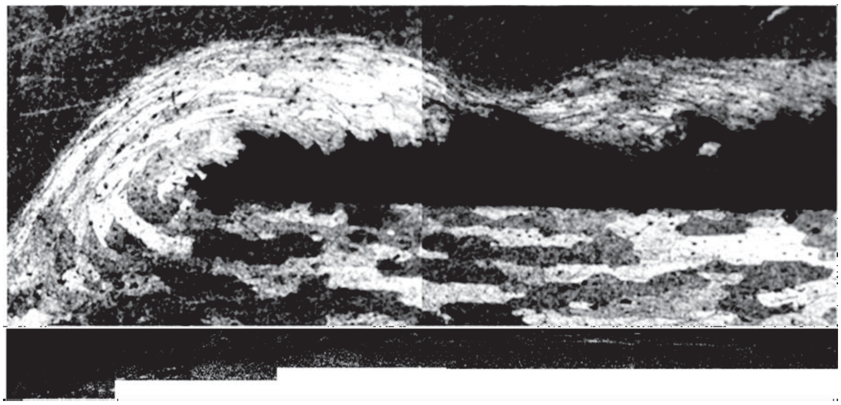

Figure 2. Micrograph showing the flow of material for the formation of flash in dissimilar friction stir weld joint

Material is removed (transported) by tool to leading edge on retreating side from advancing side, creating a cavity there which is filled by materials deposited (transported) to trailing edge advancing side from retreating side. Ideally, volume of material removed from advancing side to retreating and material deposited on advancing side from retreating must be equal to avoid the formation of defect on account of improper material flow. Poor or sluggish material flow because of low flowability in case of low heat input is unable to the created cavity thus creates a volumetric defect in stir zone. On the other hand, excessive plasticity leads to turbulent flow which extrude flowing material at the top edges and forms flash [Ilangovan et al., 2015]. Excessive thickening of flash leaded to defect i.e. unfilled of the cavity due to lost material. For successful FSW, downward axial force is must to forge this soften material at trailing edge of tool. The downward axial force is achieved by plunging (~ 0.2 mm) the tool shoulder into the top surface of plates being welded. Thus, flowing material is extruded upward by the tool and flash is formed at the crown surface on both sides of the weld surface. The asymmetric material flow further moves up AA2024 much more into the AA5086 plate raising the height of flash i.e. hook.

MATERIAL FLOW

The asymmetric pattern of material flow is clearly visible in the micrographs of dissimilar weld joints shown in figure 1 and 3. Weld microstructure showed mix structure consisting of both the base materials. The mechanical mixing of base material AA2024 and AA5086 in the dissimilar weld joints seems to be intimate and far from complete as evident from randomly distributed different regions of constituent's base materials. Moreover, the bonding between the two alloys is clearly complete. Extra ordinary solid- state feature generally observed in dissimilar friction stir welding e.g. vortex flow, on- ion rings, layered pattern could be seen easily (Figure 1 and 3). The two base materials were clearly delineated by an abrupt transition in the alloy constituents identified by the change in contrast. The material flow initiated by rotating and traversing tool led to the entrapment of very thin layers of AA2024 alloy (Black) in AA5086 alloy (Bright).

The parallel layers had varying distance between them (Figure 3a). Somewhere, the layer of alloy AA5086 was sand witched between the layers of alloy AA2024, thick dark and thin bright layer showing recrystallized grains (Figure 3b). In other locations, small recrystallized regions of alloy AA2024 were surrounded by large region of alloy AA5086. The boundary line separating both the alloys was curved/ zigzag and of random orientation (Figure 3 c & d) suggesting volumetric flow similar to gases and fluids.

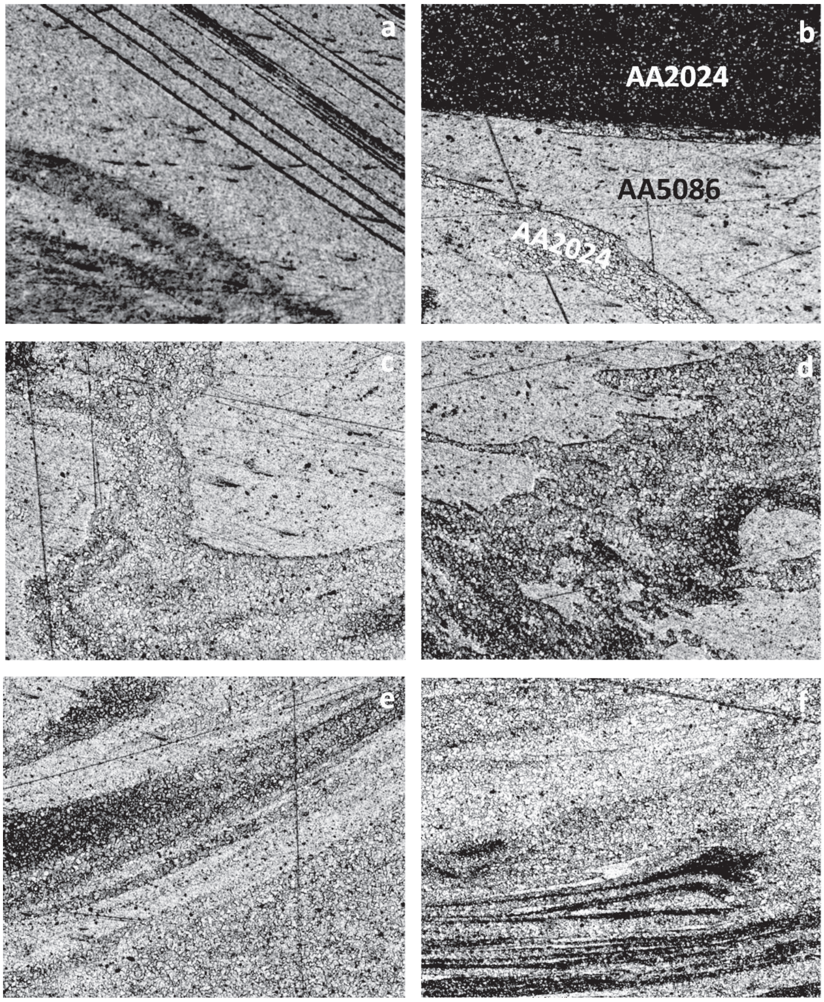

Figure 3. The complex solid-state flow patterns in WNZ of dissimilar weld joints (a) and (b) intercalation structure (c) and (d) Solid state complex flow resulting from the mechanical mixing of AA2024 and AA5086 (e) and (f) Enlarged view showing the transition from AA2024 (Dark) to AA5086 (Bright).

Figure 3e; depict layered flow features where layer of one material surrounded by other material layer whose size is of opposite nature to that of first layer. If the size of one layer is more at one location than at other it will be small or vice versa. Similarly, at the root side of the weld both the materials were found sand witched as evident from figure 3f. Lamellae and vortex features are shown in Figure 4. Other authors were reported similar observation for FSW of dissimilar aluminum alloys. Somasekharan et al. 2004 [10] observed intercalated microstructure along with swirls, vortexes in the stir zone during dissimilar FSW of AA6061 and Mg alloy.

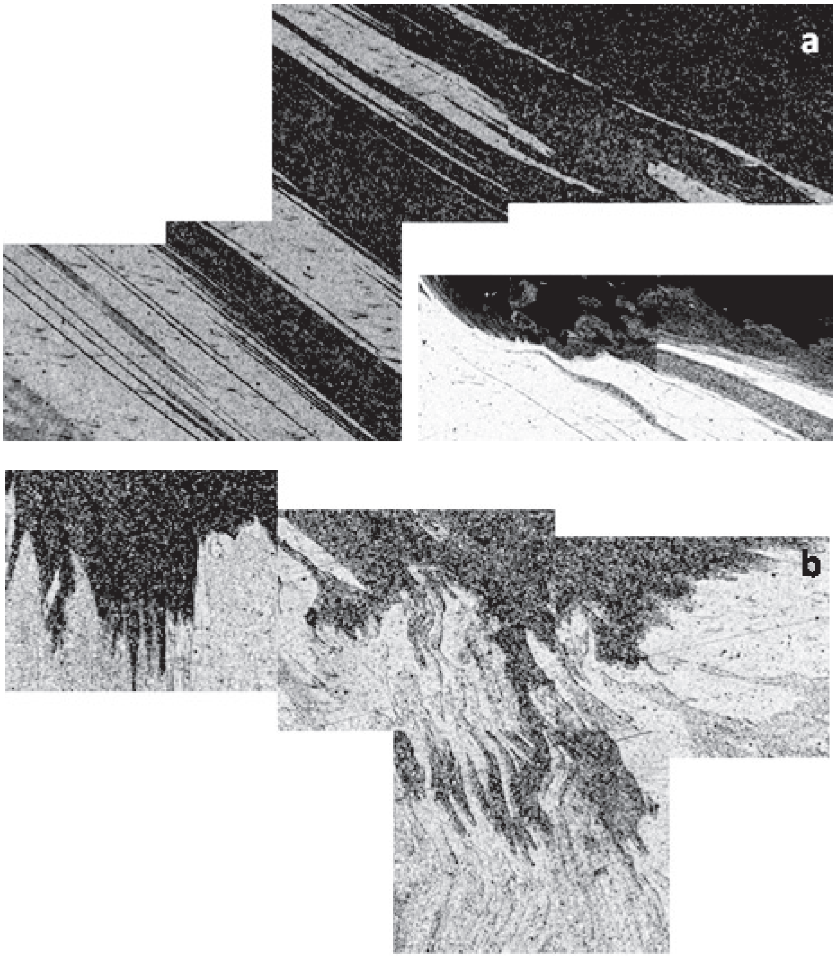

Figure 4. Material flow (a) laminar and (b) vortex flow observed in stir zone of dissimilar weld

Mg or Al rich lamellar shear bands were also observed in the welds. Dynamic recrystallization facilitates solid state flow of plasticized material and these characteristic features of dissimilar welding [Somasekharan et al., 2004].

Figure 5, presents some more solid-state flow feature observed in WNZ during dissimilar friction stir welding of precipitation and solution hardening aluminum alloys AA2024 and AA5086. Vortex flow feature is shown in Figure 5b exhibiting close mixing of both the base materials. The enlarged view of the middle region of the micrograph 5b is shown in Figure 5c which clearly demonstrate the formation of layered pattern as well as entrapment of one material by other, on account of flow of material in batches. The recrystallization is evidently observed in alloy AA2024 while same could not be seen in alloy AA5086 (Figure 5d-f). Moreover, small region of AA5086 was seen completely bounded by AA2024 (Figure 5d). Figure 5e, unveil the fact that contrast difference is because of etching as in this micrograph, recrystallized grains of AA2024 are present in both dark and bright contrast. A narrow strip of AA5086 is found surrounded by AA2024 on both sides. On the right side of the micrograph alloy AA5086 and AA2024 both are present in bright contrast; however same could be clearly differentiated from the grain structure (Figure 5f). In the WNZ, precipitates were found finer than the respective base materials. The precipitates were found to align themselves at interface of two base materials.

It can be concluded that formation of dissimilar weld joints is because of complex, intercalation and vortex flow, which results in the formation of different zones and features characteristics to dissimilar friction stir welding. Further, elongated coarse grains in AA2024 were recrystallized and equiaxed. The grain boundaries could not be re- solved in case of AA5086 indicating the formation of extremely finer recrystallized grains after FSW. The strengthening precipitates/particles were dissolved or fractured/ distributed during FSW leading to their disappearance or smaller sizes.

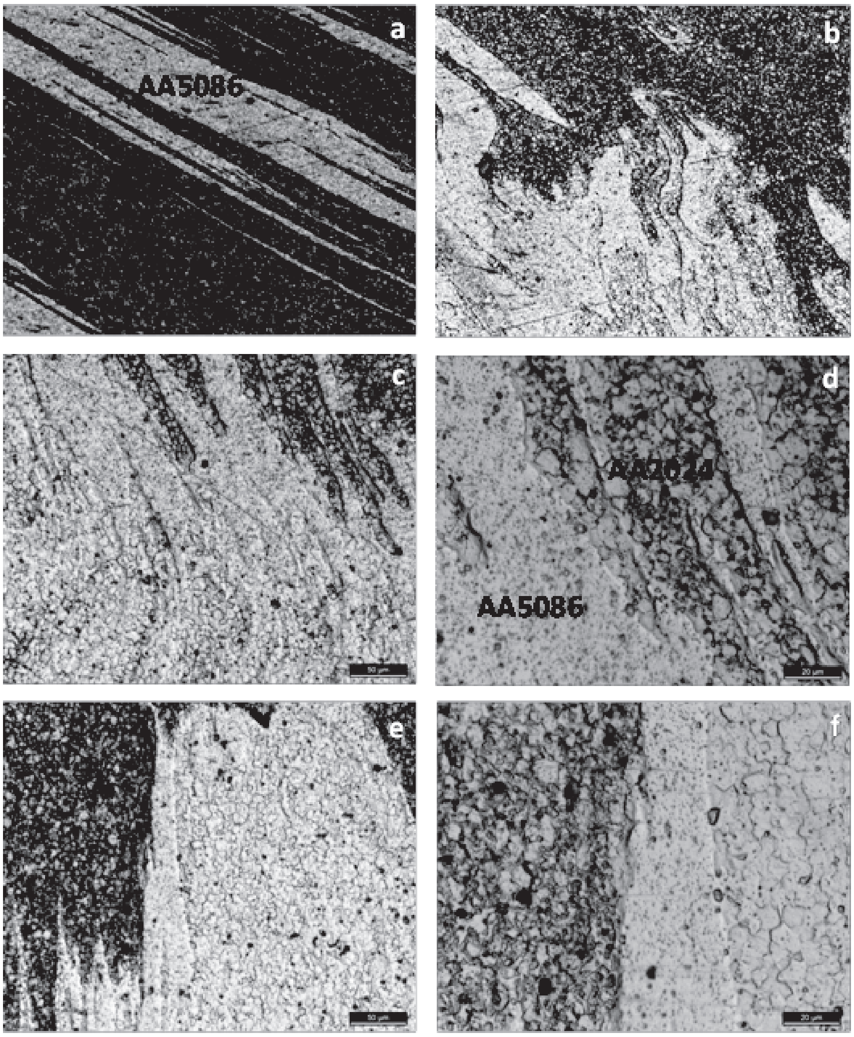

Figure 5. The evolution of microstructure in WNZ of dissimilar welds (a) and (b) Recrystallization of grain structure in AA2024 (Dark) and AA5086 (Light), (c) and (d) High magnification micrographs showing the mixing of AA2024 and AA5086 (e) Enlarged view of dark region showing the morphology of precipitates and grains in AA2024, and (f) Enlarged view at the interface of micrograph e, showing the morphology of precipitates and grains.

CONCLUSION

Friction stir welding is viable technique to form high quality defect free joints of AA2024 and AA5086. Weld joints exhibited features characteristics to friction stir welding as well as of dissimilar solid state welding. Well defined onion rings were observed in the stir zone along with WNZ, TMAZ and HAZ. After friction stir welding grains were coarsened in HAZ, deformed and elongated in TMAZ and equiaxed in WNZ. Stir zone microstructure comprised a solid state mixture of both the base materials and dominated by material placed on advancing side. Formation of dissimilar weld joints is because of complex, intercalation and vortex flow on account of mechanical mixing in solid state. It is believed that reducing tool traverse speed i.e. dwell time may abolish such features owing to complete chemical mixing of the base materials.

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