Friction Stir Welding of Dissimilar Aluminum Alloys AA5086 and AA7039

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Abstract. Friction stir welding of dissimilar aluminum alloys AA 5086 and AA7039 were carried out and results are presented. The specific attention was given to microstructure evolution in welds after dissimilar friction stir welding. Single pass, dissimilar butt welds were made using optimized parameters and threaded cylindrical tool, keeping AA5086 plate on retreating side. Integrity of welds was assessed by visual inspection. Initial microstructure of base metals was transformed and zones specific to friction stir welding were observed in stir zone. Microstructure was heterogeneous in the stir zone. The transition boundary had large population of strengthening precipitates than region rich in Zn or Mg. The selected dissimilar aluminum alloys are weldable by friction stir welding with attractive weld properties.

Keywords: Dissimilar aluminum alloys, Friction stir welding, Microstructure, Material flow, Strengthening precipitates.

1. Introduction
Traditionally automobile industries made use of steel as they can be machined and joined to obtain desired size and shape to meet various requirements economically. The use of light weight, strong corrosion resistant alloys such as aluminum, magnesium etc. in modern automobiles is obvious to reduce weight and fuel consumption. This necessitate the need of joining dissimilar materials or different alloy systems such as steel to aluminum, aluminum to magnesium or one class of aluminum alloy to other. Such dissimilar welds comprising a variety of materials can be produced by a number of fusion and solid state welding processes [1-4]. The dissimilar joints are finding increasing applications in automobiles, trains, ships, aeroplanes, and armored vehicle for achieving weight reduction, reduced fuel consumption and CO2 emission for sustainable development coupled with enhanced corrosion and ballistic piercing resistance. Though many techniques are available, still dissimilar welding is quite challenging because of varying composition, thermal conductivity, thermal expansion, melting temperature etc. Formation of dissimilar weldments is limited due to tendency of formation of intermetallic compounds, imperfections, degraded mechanical and corrosion properties beside porosity, voids, cracks, and distortion arising from the re-solidification of metal in fusion zone [3-6].

Many industries have already started using solid state friction stir welding (FSW) for making similar and dissimilar welds of difficult to fusion weld materials for miscellaneous applications in automotive, aerospace, railway, space, marine and other industries [6, 7]. Formation of dissimilar weld without imperfection and desired joint properties by FSW is mainly dependent on material flow in the vicinity
of traversing and rotating tool. The dissimilar base metal plates had difference in their melting temperature so as different softening behavior. The flow stress decreases with the temperature and can cause improper mixing and flow of materials resulting in undesirable imperfection and weld quality. Beside this, successful FSW of dissimilar materials calls for meticulous selection of process parameters, tool geometry, placement of base metals etc. [6, 8].

The FSW of dissimilar aluminum alloys AA5182 and AA6061 yielded onion ring pattern with intercalated dark (AA5182) and bright (AA6016) layers [9]. Similarly, distinct light and dark dynamically recrystallized regions comprising both the base metals i.e. AA2024 and AA7039 were seen in the nugget zone of dissimilar weld joints of these alloys [10]. Further, weld structure was heterogeneous as evident from Cu or Zn rich zones. Mechanical mixing of base metals in stir zone and incomplete diffusion formed such heterogeneous structure in welds [8]. The placement of AA5052 aluminum alloy on advancing side exhibited better and improved mixing of base metals in the stir zone of dissimilar weld of AA5052 and AA6061. Whereas the placement of base metals did not affect the location of fracture as the welds failed from advancing side of weak HAZ [11]. Change in rotary speed from 1000 to 1500 rpm resulted in better mixing of AA5052 and 5J32 aluminum alloys owing to higher flowability due to the availability of higher temperature at high rotary speed [12].

The tool rotary speed affected mechanical properties and residual stresses of AA5083 and AA6082 dissimilar welds more significantly than welding speed. Further, residual stresses were greater on AA5083 side than other side as dissolution of hardening precipitates reduced the yield strength transiently after welding. [13]. The use of tapered hexagon tool for friction stir welding of dissimilar AA2024 and AA5083 aluminum alloys caused higher tensile strength and elongation than straight cylinder tool. While tensile strength increased with tool rotary speed, welding speed and axial force to supreme value and then falls [14]. Increase in welding speed greatly reduced the grain size of similar joints of AA7075 and AA5083 while no such effect was observed in case of dissimilar joints and remained unchanged with change in welding speed from 50 -200 mm/min. Further, ultimate tensile strength efficiency varied from 77 to 87% under various welding speeds [15]. Dissimilar welds of AA2024 and AA7039 alloy showed nearly similar tensile strength and elongation efficiency opposite to the observations of others researchers [8] Multifaceted hardness behavior of AA5086 and AA6061 dissimilar alloy weld joints was due to unlike strengthening mechanisms of base materials [16].

Though some research papers are available on similar friction stir welding of AA5086 and AA7039 [17-24], however, no research paper is available on dissimilar friction stir welding of these two important aluminum alloys. Therefore, in this research an attempt was made to explore the possibility of joining these dissimilar alloys and study microstructure evolution of resulting dissimilar welds.

2. Experimental details
Dissimilar aluminum alloy AA5086 and AA7039 were chosen as base metals in the present research. Six millimeter thick, rolled plates of AA5086 were supplied in annealed “O” condition. While extruded, five millimeter thick strips of AA7039 were supplied in peak hardened “T6” condition. The plates/strip were cut using hacksaw and subsequently machined to have pieces with measurements of 5 x 50 x 300 mm². The machining was done to ensure complete contact at faying surfaces. Table 1 and 2 enlists chemical composition and important mechanical properties of base metals respectively.

| Alloy   | Zn | Mg | Mn | Fe | Si  | Cu  |
|---------|----|----|----|----|-----|-----|
| AA5086  |    | 4.11 | 0.51 | 0.12 | 0.09 | 0.01 |
| AA7039  | 4.69 | 2.37 | 0.68 | 0.69 | 0.31 | 0.05 |
Table 2. Mechanical properties of base metals AA5086 and AA7039

| Alloy  | Ultimate tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Microhardness (Hv) |
|--------|---------------------------------|----------------------|----------------|-------------------|
| AA5086 | 294.8                           | 203.7                | 21.2           | 76                |
| AA7039 | 414                             | 328.0                | 15.1           | 135               |

Prior to welding, pieces were cleaned with acetone to remove oxide layer and any extraneous substances e.g. dirt, oil or grease. The plates of AA5086 were kept on retreating side and that of AA7039 on advancing side respectively for welding. A vertical milling machine (HMT India) was equipped with indigenously fabricated fixture and tool holder for performing friction stir welding. Extensive pilot experiments were done to obtain optimum combination of rotary and traverse speeds and tool geometry. The flat shoulder and truncated cylindrical pin with thread produced welds without defects. The diameter of tool shoulder was 16 mm. The diameter at top and bottom of truncated conical pin was 6 mm and 4 mm respectively. Anticlockwise threads with 1 mm pitch were machined on 4.7 mm long pin. For FSW, plates secured firmly in position and single pass butt weld were made using rotating and traversing speed of 635 rpm and 75 mm/min, constant axial load and tool plunge of 0.2 mm. The tool travelled along center line during FSW. Figure 1 shows the schematic diagram of the cylindrical tool with dimensions of flat shoulder and conical pin. Only, defect free welds were used to make specimens or samples for microstructural and mechanical characterization. A light optical microscope (Leica, Germany) was used for microstructural study of dissimilar alloy welds using samples polished and etched in Keller’s reagent. The linear intercept method was used for obtaining grain sizes of α aluminum in base metals and welds. Scanning electron microscope (SEM) (Make: Zeiss Ultra Plus Germany) was used for Energy dispersive spectrometry (EDS). With the help of EDS, chemical composition of base metals and weld metal in stir zone and secondary strengthening particles in dissimilar welds were obtained.

Figure 1. Photograph of the tool used for friction stir welding of dissimilar aluminum alloys

3. Microstructure

Figure 2 shows the photograph of developed weld of dissimilar aluminum alloys.

Figure 2. Photograph of friction stir weld of dissimilar aluminum alloys
The welds were sound and free from surface defects such as tunnel defect, lack of penetration, excessive flashing, crack etc. The tool stir marks were clearly visible in the stir zone. The edges of stir zone were surrounded by the flash. The amount of flash on AS was considerable while that on RS was negligible. The exit hole was well defined and had no infilled region on the side walls.

Macrograph presented in Figure 3 exposed the effect of friction stir welding on original structure of dissimilar base metals which altered the same to form different zones.

![Figure 3. Different zones in friction stir welds of dissimilar aluminum alloys](image3)

Figure 3. Different zones in friction stir welds of dissimilar aluminum alloys

The weld joint presented stir zone and heat affected zones (HAZ) surrounded by the base metal on advancing and retreating side. Stir zone is the region below tool shoulder and receive maximum thermomechanical deformation. Stir zone is divided into two zone vis. weld nugget zone (WNZ) and thermomechanically affected zone (TMAZ). WNZ is the central region and experience maximum thermomechanical deformation as it lies just beneath the tool shoulder. The extreme thermomechanical deformation caused by rotary and traversing tool transformed the starting coarse grain structure of base metals. Thermomechanical deformation caused thermal and mechanical stresses leading to dynamic recrystallization in this zone. Dynamic recrystallization changed coarse rolled/equiaxed grain structure of dissimilar base metals into equiaxed grains of significantly finer size. TMAZ surrounds the WNZ on both the sides and showed thin, elongated unrecrystallized grains as compared to base metals due to mechanical deformation. Thus deformation decreased the width of grains in TMAZs. TMAZ exhibited unrecrystallized grains. The induced thermal and mechanical stresses were less to overcome the stacking fault energy so initiated the recrystallization but could not complete the same suggesting partial recrystallization in TMAZ region adjoining to WNZ as evident from Figure 4.

![Figure 4. Partial recrystallization in TMAZ of weld of dissimilar aluminum alloys](image4)
HAZ surrounded the TMAZs on both side of the welds and microstructure is affected by the heat conducted from stir zone, not by the mechanical deformation. Therefore, HAZ revealed grain structure similar to base metal(s). Significantly coarser grains were seen in HAZ than the base metal as conducted heat caused coarsening of strengthening precipitates which decreased the pinning effect hence coarser grains owing to post weld static grain growth.

The solid state flow and resulting evolution of microstructure in stir zone of welds of dissimilar aluminum alloys are shown in Figure 5. Figure 5 a showed material flow just beneath the tool shoulder and depicted peak and valley structure due to tool advancement in one revolution. The material flow was clearly asymmetric. Welds displayed mix structure consisting of both the base metals as evident from bright and dark regions (Figure 5 a & b).

![Figure 5](image.png)

Figure 5. Material flow in stir zone of dissimilar welds (a) intercalation structure (b) complex flow feature owing to mechanical mixing of AA5086 and AA7039

Base metals AA5086 and AA7039 were mechanically mixed in stir zone of dissimilar welds. Further, mixing was intimate and incomplete as evident from banded microstructure and complex solid state flow arrays. Tool shoulder moved the material from leading edge of advancing side to trailing end of retreating side and consolidated the material to form the weld as a result of friction stir welding. Since advancing and retreating side had dissimilar base metals so it is expected that material flow in batches resulted in banded microstructure where one base metal is surrounded by other (Figure 5 a & b). The dark and bright regions were found rich either in Mg or Zn. Further, the weight % of Zn and Mg is found to vary from advancing to retreating side and vice versa as confirmed by EDS analysis. The bonding between the two alloys was found to be complete as no void or poorly consolidated region was observed in the stir zone. Similar microstructural features were also observed by other researchers [8, 9]. No, other typical feature e.g. vortex flow, onion rings etc., arising from material flow in solid state could be seen. In the stir zone, the two base metals were delineated abruptly from dark to bright regions due to transition in the constituents of base metal and resulted in different contrast. This suggest ineffective diffusion of elements from region rich in Zn to rich in Mg or vice versa on account of insufficient mechanical mixing and dwell time.

The microstructure of WNZ of dissimilar aluminum alloys is presented in Figure 6. Figure 6 exhibited the region of base metal AA5086 surrounded by another base metal AA7039.
Figure 6. Recrystallized heterogeneous microstructure in stir zone showing the mixing and evolution of grain structure (a) low magnification (b) high magnification micrograph shows the clustering of precipitates at the transition boundary

The high magnification micrograph of weld nugget zone is shown in figure 6 b which clearly depicts region containing either AA5086 or AA7039 only. Thus WNZ had heterogeneous mix structure including both base metals because of mechanical mixing (Figure 5 & 6). High magnification micrographs presented in figure 6 b obviously establish the existence of recrystallized equiaxed grains in region rich in AA7039 while grains of AA5086 could not be observed possibly due to their finer size. The fine equiaxed grain of AA7039 were surrounded by tiny MgZn₂ precipitates at grain boundaries with few coarsen precipitates. Whilst fine precipitates were distributed uniformly in case of AA5086. This suggest the reprecipitation of dissolve strengthening precipitates. Surprisingly, the transition region is found to have significantly greater population of strengthening precipitates rich in Zn and Mg.

Nonuniform thermomechanical stresses developed different zones with varying grain structure in dissimilar friction stir welds of AA5086 and AA7039. Mechanical mixing without mixing at atomic level of base metals caused creation of different lamellar/banded regions, heterogeneous microstructure and variation of Zn and Mg in the stir zone. Uniform chemical mixing of the base metals on account of complete diffusion may abolish solid state flow features [10]. The thermomechanical deformation generates high temperature (~425-480 °C) sufficient to cause dynamic recrystallization in WNZ and forms fine equiaxed grains and dissolution of strengthening precipitates. The room temperature post weld aging resulted in reprecipitation of tiny precipitates [24]. Dissolution/ uniform distribution of fractured particles diminished the occurrence of strengthening precipitates (MgZn₂)/ intermetallic particles [22-24]. While dissolution of fine secondary precipitates due to available temperature (250-350 °C) retards pinning effect and caused grain coarsening in HAZ [24].

4. CONCLUSIONS
Dissimilar aluminum alloys AA7039 and AA5086 are fairly weldable by friction stir welding with attractive weld characteristics. Developed welds were defect free and sound. The welds showed features typical to dissimilar friction stir welding of aluminum alloys. Welds exhibited heterogeneous microstructure comprising base metal AA5086 and AA7039. Size of equiaxed grain WNZ, deformed grains in TMAZ was smaller than base metals and opposite trend was found for coarsened grains in HAZ. Bended/lamellar structure having zone rich in either Zn or Mg was formed due to mechanical mixing. The microstructure was heterogeneous and had varying weight % of Zn and Mg in stir zone. It is suggested to increase the dwell time by reducing tool traverse speed to abolish features related to material flow in solid state to have uniform chemical mixing of the base metals.
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