Effect of FSW welding speed on microstructure and microhardness of Al-0.84Mg-0.69Si-0.76Fe alloy at moderate rotational tool velocity

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Abstract: The plate of 7.0 mm thickness was double side welded using friction stir welding is investigated. The rotational velocity of friction stir welding tool is used 1400 rpm. The influence of welding speed on the microstructure and microhardness values of Al-0.84Mg-0.69Si-0.76Fe aluminum alloy is presented. Two welding speeds 25 mm/min and 31.5 mm/min are used. The microhardness values of friction stir weld are measured at various locations from the weld interface. The microhardness values in stir zone of weld are found larger than lower welding speed at constant rotational velocity of 1400 rpm of friction stir welding tool. The similar effects on microhardness values are found in the thermo-mechanically affected zone and heat affected zone. The fine microstructure is observed at 31.5 mm/min welding speed compared to the 25 mm/min welding speed at 1400 rpm.

1. Introduction

Many techniques are available to join the different types of metals and alloys. Welding is one of the processes to join similar or dissimilar metals and alloys. The efficiency of joint of reactive metals and alloys is found poor when they are produced by fusion welding processes. The main reason of poor performance of such joints is formation of detrimental phases in the weld. To overcome this problem, solid state joining of metal is adapted. In this context, friction stir welding process is popularly used to weld the reactive metals and alloys preferably. The friction welding is used to weld 6061 aluminum alloy in T6 condition. Friction stir welding consists of rotating tool of specific geometry. The plastic deformation takes place due to friction between tool and base plates [1]. The length of the tool is slightly smaller than the thickness of the plates to be welded. The distortion and defects are found less compared to fusion welding [2-6]. The possibility of change in properties of base metal is due to involvement of high temperature produced to friction during the welding [7]. This welding process does not require filler metal and shielding gases. Therefore, it is known as environmental friendly welding process. The joint prepared by this technique exhibit three zones. These zones are termed as stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). The fine grain structure of SZ leads to increase in tensile strength and fatigue resistance [9]. Y. C Chen reported defect free lap FSW lap joint with the higher tensile strength for lower welding speeds [10]. Good joint of 6061 aluminum alloy can be produced with the tool length equal to thickness of the plates to be welded [11]. Aluminum alloy contains Mg and Si main alloying elements and iron is found in traces [12]. The study of joining of dissimilar metal is investigated by Lee and Yean [13]. The size of silicon and aspect ratio decreases by increasing rotational
velocity of friction stir processing tool of A356 [14]. Tensile strength and yield strength decrease by increasing distance from interface of friction stir processing [15]. The microstructures can be etched by HF for metallographic observation [16]. The FSW technique of metal joining in solid state was developed in 1991 in UK by the welding institute and has become very much popular in recent days. Variety of metals similar or dissimilar can be welded with better joint strength. Friction welding stir welding requires less energy consumption and carried out without flux and filler metals. Many aluminum alloys can be welded without considering composition compatibility [17-24].

2. Experimental details

The rod of square cross sectional area 20 mm × 20 mm and length 200 mm in T6 extruded condition was received from supplier manufactured by Hindalco Industries Limited. The plates of dimension 50 mm × 20 mm × 7 mm were machined from as received square rod. The specimens were polished to make flat surfaces. After polishing the plates were placed under the fixtures on the friction stir welding (FSW) machine platform. Thereafter, the interface of the plates to be welded was aligned in direction of FSW tool velocity. After the alignment of specimens, FSW tool was moved to one end of the specimens and lowered in such a way that the complete tool length is covered by thickness of the specimen. After that, a load of 7 kN was applied on FSW tool with 1400 rpm rotational velocity. The FSW welding of two specimens were carried on both sides with a welding speed of 25 mm/min and 31.5 mm/min respectively. After completing the friction stir welding, the welded samples were cut into smaller size (10 mm × 10 mm) for further analysis. For the microstructural observation, these specimens were polished on emery papers of grits 400, 600, 800, 1000 and 1200 followed by cloth polishing on disc using 3 µm diamond paste. Thereafter, the specimens were cleaned in acetone (C₃H₆O) and dried. After drying, the specimens were etched using Keller’s reagent (95 ml H₂O + 2.5 ml HNO₃ + 1.5 ml HCl + 1 ml HF). The microstructures of etched specimens were examined under Lieca microscope. Thereafter the microhardness values were measured on Vicker’s hardness scale under the application of 200 gm load on indenter. The indenter of microhardness tester is of pyramidal shape with a cone angle of 136°. The X-ray diffraction pattern of welded specimen was obtained using Cu-Kα radiations. The specimen was scanned with a scanning rate of 0.4° per minute in the range of angle of 20° – 90°. The welding parameters are shown in table 1.
Table 1 The variables of friction stir welding process.

| Variable                        | Value     |
|---------------------------------|-----------|
| Rotational Speed (rpm)          | 1400      |
| Traveling speed (mm/min)        | 25, 31.5  |
| Axial force (kN)                | 7         |
| Pin length (mm)                 | 3.5       |
| Tool shoulder diameter (mm)     | 15        |
| Pin diameter (mm), Upper        | 3.5       |
| Pin diameter (mm), Lower        | 2.0       |

Images of field emission scanning electron microscope (FE-SEM) microstructures of specimens were captured at different magnification. The FE-SEM exhibit image resolution of 0.5 - 1 nanometer and FE-SEM has 3-6 times better resolution than scanning electron microscope (SEM). The FE-SEM used here is manufactured by Carl Zeiss.

3. Results and Discussion

3.1 XRD Pattern

![XRD Pattern Image]

Figure 2. X - Ray diffraction pattern of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy, 1400 rpm, 25 mm/min.
3.2 Microstructures

3.2.1 FE-SEM microstructures.

**Figure 3.** The images of Field Emission Scanning Electron Microscope (FE-SEM) microstructures of base metal of Al-0.84Mg-0.69Si-0.76Fe alloy, (a) Asb image, at 1410X, (b) Inlens image, at 4960X.

**Figure 4.** The images of FE-SEM microstructures of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 25 mm/min, (a) Asb image, 116X, (b) Asb image, 1530X.
Figure 5. The images of FE-SEM microstructures of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, (a) SE image, 25 mm/min, 509X, (b) SE image, 31.5 mm/min, 509X.

Figure 6. The images of FE-SEM microstructures of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, (a) Inlens image, 25 mm/min, 5000X, (b) Inlens image, 25 mm/min, 10000X.
The images of FE-SEM microstructures of Al-0.84Mg-0.69Si-0.76Fe alloy (base metal) and friction stir joint are shown in Figure 3, 4, 5 and Figure 6. The FE-SEM microstructures of base metal are shown in Figure 3 (a) and (b). The FE-SEM microstructure which is shown in Figure 3 (a) was taken in Asb mode at magnification of 1410X while Figure 3 (b) represents the FE-SEM microstructure taken in Inlens mode of FE-SEM at magnification of 4960X. The FE-SEM microstructure of Figure 3 (a) reveals aluminum solid solution matrix (bright) and etch pits (dark). The FE-SEM microstructure of Figure (b) of base metal reveals the aluminum solid solution matrix (bright) and intermetallic (Mg2Si) (dark) embedded in the matrix of aluminum solid solution. The images of FE-SEM microstructures shown in the Figure 4 are of friction stir welding joint at the interface of stir zone and base metal. These FE-SEM microstructures were captured in Asb mode at the magnifications of 116X and 1530X respectively from the specimen which was welded with the tool velocity of 1400 rpm and 25 mm/min of welding speed. The Figure 4 (a) shows the of stir zone, interface, heat affected zone (HAZ) and base metal while the FE-SEM microstructure shown in Figure 4 (b) reveals thick heat affected zone (HAZ) near the interface towards the base metal which is very clearly visible in this microstructure. The FE-SEM microstructure shown in the Figure 4 (b) also reveals elongated aluminum solid solution (α-aluminum) grains near the interface in the side of stir zone of the FSW weld. This zone is termed as thermomechanically affected zone (TMAZ). On the extremes of Figure 4 (b), it reveals stir zone (left side) and base metal (right side). The similar type microstructure is observed from the specimen welded with 31.5 mm/min of welding speed with constant rotational velocity of friction stir tool (FSW tool). For the better grain resolution of stir zone, the FE-SEM microstructures of both of samples welded with welding speeds of 25 mm/min and 31.5 mm/min with constant rpm of FSW tool were captured in secondary electron (SE) mode at the magnification of 509X as shown in the Figure 5 (a) & (b). The grains of the FE-SEM microstructure of Figure 5 (a) are slightly larger than Figure 5 (b). This small difference in the grain size of two specimens of the FE-SEM microstructure of Figure 5 (a) & (b) lead to change in hardness values. The FE-SEM microstructure of Figure 5 (b) reveals α-aluminum grains and some fine cracks, this may be possible due to larger velocity of FSW tool. Figure 6 represents the FE-SEM microstructures of stir zone of specimen welded with 25 mm/min captured in Inlens mode of imaging at magnification of 5000X and 10000X. The FE-SEM microstructure of Figure 6 (a) reveals α-aluminum matrix (bright), precipitate Mg2Si (dark) embedded in the matrix while some elongated precipitate particles are observed in Figure 6 (b).

The Figure 2 shows the X-Ray diffraction pattern of friction stir welded joint. Three major peaks are found at the angles of 38.4°, 44.5° and 78.2° respectively and the corresponding planes of reflections are (111), (44.5) and (311). And these peaks are identified as aluminum. The highest intensity peak is found at 38.4° on (111) plane. Two minor peaks of aluminum are also observed at angles of 65.2° and 82.5° on the reflection planes of (220) and (222) respectively. And one minor peak is found at the angle of 40.27° on the reflection plane of (220). This minor peak is identified as of Mg2Si. It is clearly observed from XRD pattern shown in the Figure 2 that both of the precipitate (Mg2Si) and aluminum peaks aluminum are observed. It indicates that the dissolution and formation of precipitate has taken place in friction stir welding process. Since the broaden peaks are not observed, hence the residual stresses are expected to be associated in the weld joint.
3.2.2 Optical microstructures.

**Figure 7.** Optical microstructure of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 25 mm/min, (a) Left interface, 100X, (b) Stir zone (SZ), 100X.

**Figure 8.** Optical microstructure of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 31.5 mm/min, (a) SZ, 50X, (b) SZ, 100X.
3.3 Measurement of microhardness

Figure 9. Optical microstructure of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 31.5 mm/min, (a) Left interface, 500X, (b) Right Interface, 500X.

Figure 10. Microhardness vs. distance plot of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 25 mm/min, at corresponding positions shown in the microstructure placed in the bottom of the curve.
The microhardness values are measured using microhardness tester of Omni Tech Company. For the measurement of microhardness values, the weight of 200 gm was applied on indenter. Figure 10 shows the variation of microhardness values from weld center towards the interface and base metal of the specimen welded at 1400 rpm with the welding speed of 25 mm/min. The measurements of microhardness values are made at 1 mm distance. It is observed from Figure 10 that stir zone (SZ) shows maximum value of 60 HV on Vickers’s hardness scale. The microhardness values measured from weld centre at 1 mm distances of specimen welded at 1400 rpm with 25 mm/min are 58.1 HV, 59.5 HV, 60 HV, 56.9 HV, 54.3 HV, 55 HV and 57.1 HV respectively. The microhardness values are observed lower towards the interface including themomechanically affected zone (TMAZ) and heat affected zone. The heat affected zone and interface show lower values of microhardness due to overage condition of specimen during friction stir welding.

![Figure 11. Microhardness vs. distance plot of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 31.5 mm/min, at corresponding positions shown in the microstructure placed in the bottom of the curve.](image-url)
The variation of microhardness values from the weld centre towards the interface and base metal of the specimen welded at 1400 rpm with welding speed of 31.5 mm/min are presented in the Figure 11. The measured microhardness values on Vickers's scale are 62.6 HV, 62.9 HV, 63.4 HV, 58.9 HV, 57.1 HV, 58.2 HV, 59.4 HV and 67.3 HV. The maximum value of microhardness in the stir zone is observed 64.4 HV. Here also, the microhardness values are almost constant in the stir zone and found decreasing near to themomechanically affected zone (TMAZ) including heat affected zone (HAZ).

**Figure 12.** Microhardness vs. distance plots of friction stir welded joint of Al-0.84Mg-0.69Si-0.76Fe alloy at 1400 rpm, 25 mm/min (Black), and 31.5 mm/min (Red) curve.

The variation of microhardness values measured from specimens welded at 1400 rpm with welding speeds 25 mm/min and 31.5 mm/min are shown in the Figure 12. The plot (black) of hardness variation with distance of specimen welded with welding speed of 25 mm/min in the Figure 12 is below of the plot (red) of hardness variations of specimen welded with welding speed of 31.5 mm/min. All values of microhardness of specimen welded with welding speed of 25 mm/min are lower than the microhardness values of specimen welded with welding speed 31.5 mm/min at constant rpm of 1400 for both of the samples. The welding speed of 31.5 mm/min produced better hardness and strength than specimen welded with 25 mm/min of welding speed at constant rpm of 1400 as shown in Figure 12. The microstructures of specimen welded with 25 mm/min of welding speed at 100 X magnification shown in the Figure7. In this figure, Figure 7 (b) shows the microstructure of stir zone which reveals fine grains of α-aluminum (bright) and etch pits (dark). The formation of fine α-aluminum has taken place due to stirring action of friction stir tool. The fine structure of stir zone exhibits higher microhardness and strength. The value of stir zone is found 60 HV as shown in Figure 10. This value of microhardness is more than the values measured near
the interface. The microstructure of the interface of friction stir welded specimen with the welding speed of 25 mm/min at 100X magnification is shown in the Figure 7 (a). This microstructure reveals stir zone (left side) and TMAZ and HAZ on right side. The grain sizes of TMAZ are larger than the grain size of stir zone. Therefore, the microhardness values of TMAZ (54 HV) is found lower than the stir zone (60 HV).

The microstructures of specimen welded with larger welding speed (31.5 mm/min) than the previous specimen are shown in the Figure 8 (a) & (b), Figure 9 (a) & (b). The optical microstructure shown in Figure 8 (b), at 100X magnification reveals fine gain structure of $\alpha$ – aluminum (bright) and etch pits. The significant difference in the size of grain is not observed in optical the microstructures. The grain size difference can be observed in FE-SEM microstructure shown in Figure 5 (a) & (b). This confirms that the microhardness values of this later specimen should be larger than the first specimen. And Figure 8 (a) shows microstructure of the stir zone at magnification of 50X. The optical microstructures of left interface and right interface of specimen welded with welding speed of 31.5 mm/min at the magnification of 500X are shown in the Figure 9 (a) and Figure 9 (b) respectively. These microstructures reveal very fine grained stir zone, coarsened TMAZ and HAZ. It is clear from the microstructures shown in the Figure 7 (a), at 100X and Figure 9 (a), at 500X that the fine grain structure is found in the Figure 9 (a), at 500X which is the specimen welded with welding speed of 31.5 mm/min at 1400 rpm.

4. Conclusions

a) It is found that the welding speed of 31.5 mm/min at 1400 rpm produced finer grain microstructure than the microstructure of specimen welded with 25 mm/min of welding speed at constant rotational velocity of friction stir welding tool.

b) The microhardness values of the specimen welded with 31.5 mm/min are found larger than the specimen welded with welding speed of 25 mm/min (shown in Figure 5).

c) The microhardness values on the interfaces and near the interfaces towards the base metal are found lower than the microhardness values of the stir zone and of base metal.

d) Wide heat affected zone (HAZ) is observed in FE-SEM microstructure as shown in the Figure 4.

e) The microhardness values of stir zone of specimens welded with welding speeds of 25 mm/min and 31.5 mm/min are 60 HV and 64 HV respectively.

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