Mechanical and Metallurgical Characterization of Friction Stir Welding Aa6351

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ABSTRACT

Friction stir welding of Aluminum 6351 alloy was performed in butt joint configuration using varying welding speed and varying rotary speed. Tensile tests were performed to determine ultimate tensile strength, yield strength and % elongation. Microstructure was investigated using optical and scanning electron microscope. Micro hardness measurements across the transverse cross section of FSW joints were carried out to identify variations in micro hardness in different zones. An optimum combination of welding and rotary speed (41 mm/min and 1800 rpm) was obtained to produce sound and defect free FSW joints that yields maximum mechanical properties. An increase in welding speed first increased the ultimate tensile strength, and yield strength of FSW joints while % elongation decreased with increase in welding speed. Welding speed influenced the mechanical properties and mode of fracture of FSW joints.


1. Introduction

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of the United Kingdom in 1991 as a solid-state joining technique and was initially applied to aluminum alloys (Thomas, 1991). Friction stir welding is the most significant development in metal joining in recent decades and considered as a green technology due to its energy efficiency, environmental friendliness and versatility. In comparison to conventional welding methods, FSW consumes less energy, cover gas or flux is not required, and no harmful emissions are evolved during welding. In FSW, a non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges and subsequently traversed along the joint line. Figure 1 illustrates process of friction stir welding. Friction between the tool and work adiabatic heat from metal deformation leads to localized heating that softens and plasticizes the work piece. During FSW, the material undergoes intense plastic deformation due to traverse of rotating pin along the butting surfaces and after welding, recrystallization results in significant grain refinement in welded joints. FSW does not involve the use of filler metal and there is no melting. Aluminum alloys can be joined effectively without any concern of composition compatibility, solidification cracking and oxide inclusions issues associated with fusion welding and welding speed governs the maximum temperature generated during welding and the time length during which the material is subjected to welding. Also, similar aluminum alloys and composites can be joined with equal ease. The degree of softening and...
tensile properties is significantly affected by welding process parameters such as welding speed and rotational speed. In FSW, welding parameters such as tool design, rotation speed and translation speed should be regulated precisely to control the energy input into the system reported that the conical threaded pin with shoulder angle of $3^0$ achieves higher mechanical properties and the yield strength of AA6351 weld was found about 12% greater than that of the base metal. Sato, 2003 found that the hardness distribution at the precipitation strengthened type Al alloy weld can be explained by the density of strengthening precipitation. Reporter that the yield and ultimate tensile strengths of the as-welded weld were significantly lowers than those of the base material of aluminum 6351. found that heat treatment results in improved tensile strength. Friction stir welding has been used extensively in the aluminum superstructures of cruise ships such as the ‘Seven Seas Navigator’ which contain many kilometers of friction stir welds, mostly in 6351 grade extrusions. High speed aluminum railcars such as the Japanese Shinkanen are normally built from complex double skin extrusions in 6351 alloys. Literature review reveals that little work is reported on 6351 aluminum alloy till date. In this work, an attempt has been made to find the optimum combination of welding speed and rotary speed of the tool to obtain the better mechanical properties of the FSW welded joint Plunging force, constant plunge depth and constant revolution per minute 1800 rpm. FSW was performed using four different welding speeds in the range of 10 mm/min to 40 mm/min. Further, speeds were categorized as low welding speed 20 mm/min, 21 mm/min and high welding speed 40 mm/min and 42 mm/min. The plates welded at different welding speed. The microstructure was investigated using optical and scanning electron microscopy.

Fig.1 Schematic diagram of the Friction Stir welding process

2. LITERATURE REVIEW

Effect of welding parameters on microstructure and mechanical properties of friction stir spot welded 5052 aluminum alloy. The change law of the tensile/shear strength is similar to that of the cross-tension strength. The joints strength decreases with increasing tool rotational speed, while it’s almost independent of the given tool dwell times. At the rotational speed of 1541 rpm, the tensile/shear strength and cross-tension strength reaches the maximum of 2847.7 N and 902.1 N corresponding to the dwell time of 5s and 15s. Compared to normal FSSW, the strength of the joints welded by walking FSSW improves a little. (Binlian Zou et al, 2004) Post-weld formability of friction stir welded Al alloy 5052.Friction stir welding; Aluminum alloy; Microstructure; Formability. (Yutaka S. Sato et al, 2004)
Friction stir welding of 5052 aluminum alloy plates friction stir welding; aluminum alloy; microstructure mechanical properties Defect-free weld is successfully obtained at all tool rotation speeds. Especially at 1000, 2000 and 3000 rpm/min, the welds exhibit very smooth surface morphologies. At all tool rotation speeds, the gain size in the SZ are smaller than that in the base metal, and are decreased with increase of the tool rotation speed. At 500, 1000 and 2000 rpm/min, the tensile strength of the FSW plates is similar to that of the base metal (about 204 MPa). The elongation is lower than that of the base metal (about 22%). However, it is noticeable that the maximum elongation of about 21% is obtained at 1000 rpm/min. (Yong-Jai KWON et al, 2009)

Dissimilar friction stir welding between 5052 aluminum alloy and AZ31 magnesium alloy dissimilar friction stir welding; 5052 aluminum alloy; AZ31 magnesium alloy; microstructure evolution; mechanical property. Sound weld between 5052 Al alloy and AZ31 Mg alloy could be produced through FSW with a rotation speed of 600 rpm/min and welding speed of 40 mm/min. Micro-hardness profiles presented uneven distributions and the maximum value of micro-hardness in the stir zone was twice higher than that of the base materials. The fracture position located at a distance of 2.5 mm from the joint center leaning to the advancing side (aluminum side), where the hardness gradient was the sharpest. (YAN Yong et al, 2010)

Effect of welding parameters on microstructure and mechanical properties of friction stir spot welded 5052 aluminum alloy Non-ferrous metals and alloys Welding Mechanical. (Jialong et al, 2011)

Influence of tool plunge depth and welding distance on friction stirs lap welding of AA5454-O aluminum alloy plates with different thicknesses. Friction stirs lap welding; AA5450-O aluminum alloy tool plunge depth; welding distance, mechanical properties. The maximum tensile shear load of the FSLWed plates exhibits much higher than that of the adhesive bonded aluminum alloy plate. Especially, under the FSLW condition of the plunge depth of 1.8 mm and the welding distance of 40 mm, the tensile shear load of the FSLWed plate reaches a level about 41% greater than that of the adhesive-bonded aluminum alloy plate. In addition, the maximum tensile shear load of the FSLWed. (Jun-Won Kwon et al, 2012)

Effect of tool rotational speed on force generation, microstructure and mechanical properties of friction stir welded Al–Mg–Cr–Mn (AA 5052-O) alloy. Friction stir welding Tensile strength Vickers hardness test Inter-metallic phase. In this study, effect of tool rotational speed on the joining performance of the friction stir welded AA 5052-O plates was investigated. The welded joint produced at 1000 rpm gave a maximum tensile strength of 132 MPa which was 76% of the base material. In all cases the ultimate/yield strength of the welded joints was lower than the base material strength. (Raza Moshwan et al, 2014)

3. Experimental work

The high strength aluminum alloy, magnesium alloy, and silicon alloy. General corrosion resistance and good weld ability. A high strength extruded sheets of aluminum alloy AA6351 of 4 mm thickness, originally in annealed condition were used for experimental purpose. The Specimen prepaid by EDM Wire Cutting Machine. The specimen size 100 mm (length) × 15 mm (width) × 4 mm (thick) In present study, die steel tool (pin length: 3.5 mm, pin diameter:
5 mm at bottom, shoulder diameter: 18 mm) was used to fabricate the FSW joints. The depth of shoulder plunge was kept 3.5 mm from work piece. To carry out the FSW experiment vertical milling machine of (HMT 1 H.P. and 1440 rpm) was used to produce friction stir butt weld. Dispersive X-ray (XRD) analysis was carried out in order to determine the composition of alloy. The nominal composition of alloy is given in Table 1 while Figure 3.3 shows XRD.

![Fig. 3.1 Vertical Milling Machine Tool and FSW Tool designs, dimensions](image)

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Tool Design</th>
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<tbody>
<tr>
<td>Pin Length (mm)</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Shoulder ɸ (mm)</td>
<td>18 mm</td>
</tr>
<tr>
<td>Pin ɸ (mm)</td>
<td>5 mm</td>
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Table. 1 Proportion of elements in AA 6351

<table>
<thead>
<tr>
<th>Element</th>
<th>Fe</th>
<th>Si</th>
<th>Mn</th>
<th>Ti</th>
<th>Cu</th>
<th>mg</th>
<th>Zn</th>
<th>Al</th>
<th>Other</th>
</tr>
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<tbody>
<tr>
<td>Weight (%)</td>
<td>0.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.01</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>98.55</td>
<td>0.8</td>
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</table>

![Fig. 3.2 Weld samples](image)
4 Results and discussion

4.1 Micro hardness

Fig. 3 shows the variation of micro hardness with various welding speeds. It was observed that irrespective of welding speed, all friction stir weld joints had higher average micro hardness of the WNZs (in range of HV/0.1 to HV0.5) than the base metal (46.1 HV). Lee et al., 2003 reported the same trend of increase in hardness in the weld zone due to presence of fine equaled grains and re-precipitation of the dissolved precipitates. The average micro hardness of WNZs first increased with increase in welding speed from 7.62 mm/min to 41.86 mm/min, than decreased with further increase in welding speed to 190 mm/min. The average micro hardness of WNZs increased from HV/0.1 to HV0.5 with increase in welding speed from 7.62 mm/min to 40.90 mm/min. With further increase in welding speed from 21.07 mm/min to 41.86 mm/min, average micro hardness of WNZs decreased from HV/0.5.

The influence of welding speed on average micro hardness of HAZs was similar to that of WNZs. The average micro hardness of HAZs was also greater than the base metal that first
increased with increase in welding speed from 7.5mm/min to 41 mm/min, than decreases with further increase in welding speed to 40 mm/min. The average micro hardness of HAZs increased from HV/0.1 to HV/0.5 with increase in welding speed from 7.5 mm/min to 20.25 mm/min (Figure 9). With further, increase in welding speed from 7.5 mm/min to 41.86 mm/min, average micro hardness of HAZs decreased to HV/0.1 from HV/0.5. The location of minimum micro hardness was at the end of HAZ or the base metal for friction stir weld joints developed using various welding speeds. The increase in micro hardness of FSW joints in WNZ and HAZ region is because of favorable re-precipitation of strengthening precipitate owing to better natural aging response.

4.2 Microstructure evolution

Figure 4 illustrates the SEM photographs of the cross-sections of welds S1 and S2. It is obvious that all nuggets are filled with large fragments of steel and small platelets sheared off from the steel plate, which is believed to be a result of the abrasion, wear and shearing by tool rotating action. According to Fig. 4(a), no tunnels or voids are produced in the microstructure of weld S1. Figure 4(b) shows the microstructure of weld S2. Several defects, which are pointed by arrows, can be seen in the microstructure reported the formation of tunnel defect in welds which were performed with high rotation and low traverse speed (i.e. high heat input of the weld). It is necessary to note that by decreasing the heat input, the large tunnel in weld S1 changed to the scattered voids in weld S2, as shown in Fig. 4(b).

![Fig. 4 Enlarged SEM images of inter metallic compound layer and scattered particles in welds: (a) S1; (b) S2](image-url)

Figure 4 shows high magnification SEM images of the Al/Fe interface in welds S1 and S2, respectively. It is necessary to note that the tiny cavities in Fig. 4(b) are the result of etching solution and do not relate to the friction stir process. From Fig. 4(a), it can be seen that a continuous inter-metallic layer exists at the Al/Fe interface. In addition, scattered particles of inter-metallic compound (IMC) exist in the weld nugget. The results of
XRD quantitative analyses of points 1 and 2 in Fig. 4(a) are (98.55% Al, 28.34% Fe) and (98.23% Al, 0.51% Fe, 0.46% Mn in mole fraction), respectively. The atomic ratios of Al to Fe at points 1 and 2 are 2.52 and 6.8, respectively. Therefore, it is probable from the analysis and Al–Fe phase diagram that the phases are the HIF of weld S1 by 20% results in the increase of IMC thickness by a factor of 90% in weld S2. This matter shows that there is a critical heat input factor (HIF) above which the IMC grows rapidly and joint strength decreases drastically. The microstructures of welds S1 and S2 are similar to those of the other welds and not presented here. It is necessary to note that a continuous layer of inter-metallic compound was formed at the Al interface identified as Al5Fe2 (the XRD analysis is not shown here). It is worthy to note that by increasing the welding speed from 40.20 mm/min (weld S1) to 41.86 mm/min (weld S2), the large tunnel is eliminated.

Table -1, Sample-1

<table>
<thead>
<tr>
<th>Test</th>
<th>Dwell time</th>
<th>Measurement (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV/0.1</td>
<td>10 sec</td>
<td>141.02</td>
</tr>
<tr>
<td>HV/0.3</td>
<td>10 sec</td>
<td>79.30</td>
</tr>
<tr>
<td>HV/0.5</td>
<td>10 sec</td>
<td>68.30</td>
</tr>
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</table>
Fig. 4 SEM fractographs of (a) BM, Respectively different micrometers -500 µm, 400 µm, 200 µm, 150 µm, 100 µm, 40 µm, 20 µm at the same feed rate 41.86 mm/min and Same Rotational Speed 1800 rpm.

4.3 Fracture surface

Fracture surfaces of the BM and the FSW joints can be seen in Fig.5 Tensile fractured surface of the BM was mainly composed of cleavage steps and tearing edges which are characteristic of trans granular fracture. The macro fractography of the tensile tested samples (1800 rpm 41.86 mm/min) exhibited a shear fracture mode at about 45° to the tensile axis, there were large deep dimples and some residual phases (as shown in area A in Fig. 5(b)), which are both typically observed in a trans granular dimple fracture. Although large quantity of thick second phase particles were seen diffusely distributed on the fracture surfaces of the sample produced by the second parameter set, massive tiny and shallow dimple were still present Fig. 5(c) and (d)The fracture morphology of the sample produced with the third parameter set was similar to that produced with the second parameter set. A typical chevron pattern, a feature of brittle fracture, was observed in the macroscopic view of the joint produced at 1800 rpm 41.86 mm/min Fig. 5(e). As shown in the high magnification images Fig. 5(f), the dimples and second phase particles were far smaller than those in the joint produced with the second parameter set. Samples produced by the fifth parameter set showed similar fracture morphology, both of them were typical inter crystalline brittle fracture. By energy spectrum analysis the thick particles observed were identified as the quaternary phase with a broad composition range.

Table-2, Sample-2

<table>
<thead>
<tr>
<th>Test</th>
<th>Dwell time</th>
<th>Measurement (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV/0.1</td>
<td>10 sec</td>
<td>74.94</td>
</tr>
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</table>
Fig. 5 SEM fractographs of (a) BM, respectively, different micrometers -500 μm, 400 μm, 200 μm, 150 μm, 100 μm, 40 μm, 20 μm at the same feed rate 21mm/min and Same Rotational Speed 1150 rpm.

Fig. 5 shows the distribution of second phase particles in the BM and the NZs produced with different welding parameters. In the BM, some large residual phases (10 μm) with the chain-like distribution were found to be quaternary T phase (Al6351) by means of EDX, which was mainly derived from the binary with Cu and Al substituting Zn at the Zn sub lattice. In the NZs, as shown in Fig. 5(b), at a low welding speed of 21 mm/min, the size of the second-phase particles almost remained unchanged but the particles became disperse. Fine precipitates found within grains and at grain boundaries due to re-precipitation during the cooling in welding thermal cycle are shown in Fig. 5(c) at higher magnification. The size of the second-phase particles decreased with the increasing tool rotation rate from 1150 to 1800 rpm (Fig. 5(d), (e), and (f)). The density of the strengthening precipitates has decreased and it is obvious that the precipitates coarsened as of elevated temperature and severe stirring.

5 Conclusions

Welding speed was found to have a significant effect on macrostructure, microstructure, and micro hardness. Increase in welding speed decreased the width of WNZ and
resulted in voids in FSW joints. Increase in welding speed first increased the average micro hardness of the WNZ, which then decreased, with further increases in the same. An increase in welding speed shifts fracture locations from BM to WNZ. The careful selection of FSW process parameters can avoid the formation of void; maximize mechanical properties by minimizing softening, change fracture location and mode of fracture of FSW joints of AA6351 aluminum alloy.

After FSW, NZs of all joints had fine equiaxed grains. The grain size in the center of the NZ decreased with the increasing welding speed from 21 to 41 mm/min, and increased with the increasing tool rotation rate from 1150 to 1800 rpm. The conditions of 1150 rpm 21.86 mm/min and 1850 rpm 41.86 mm/min resulted in large quantity of kissing-bond in the NZs.

Two zones with different microstructures, BM and HAZ are observed using the microstructure. The microstructure grows coarser with increasing tool rotational speed. In addition, the low sheet material underneath the hook doesn’t flow into the upper sheet.

Further research on optimizing FSW parameters should focus on avoiding the formation of kissing-bond defect reducing the effect of HAZ softening by controlling local cooling rate to decrease the non-uniformity of microstructure, and minimizing the formation of thick second phase particles in the BM to decrease the number of the stress concentration sites.

References


