Technical Report

Mechanical, fatigue and microstructural properties of friction stir welded 5083-H111 and 6082-T651 aluminum alloys

Beytullah Gungor, Erdinc Kaluc, Emel Taban, Aydin Sik

Article info

Article history:
Received 19 August 2013
Accepted 31 October 2013
Available online 9 November 2013

Abstract

In this study, 5083-H111 and 6082-T651 aluminum alloy plates in 6 mm thickness that are used particularly for shipbuilding industry were welded using Friction Stir Welding (FSW) method as similar and dissimilar joints with one side pass at PA position with the parameters of 1250 rpm tool rotation, 64 mm/min welding speed and 2° tool tilt angle. Tensile tests results showed sufficient joint efficiencies and surprisingly high yield stress values. Bending fatigue test results of all joint types showed fatigue strength close to each other. Fatigue strength order of the joints were respectively FSWed 5083-5083, 6082-6082 similar joints and 5083-6082 dissimilar joint. Cross sections of the weld zones have been analyzed with light optical microscopy (LOM) and fracture surface of fatigue test specimens were examined by scanning electron microscopy (SEM). Although there were no voids in radiographic and microscopic analyzes, 5083-6082 joint showed rarely encountered voiding effect under fatigue load. Microhardness measurements revealed rare result for FSWed AW5083 and novel result for FSWed 6082 aluminum alloy.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Aluminum and aluminum alloys have become increasingly used in production of automobiles and trucks, packaging of food and beverages, construction of buildings, transmission of electricity, development of transportation infrastructures, production of defense and aerospace equipment, manufacture of machinery and tools and marine structures with its unique properties such as corrosion resistance, high strength with low density, fracture toughness and energy absorption capacity, cryogenic toughness, workability, ease of joining (welding both solid state and fusion), brazing, soldering, riveting, bolting) and recyclability. 5083 aluminum–magnesium alloys are strain hardenable and have excellent corrosion resistance, toughness, weldability and moderate strength. 6082 aluminum–magnesium–silicon alloys are heat treatable and have high corrosion resistance, excellent extrudibility and moderate strength. Especially with their high corrosion resistance and moderate strength, these alloys are widely used in shipbuilding industry both separately and together. Single- or multiple-hull high speed ferries employ several aluminum alloys, 5083, 5383 and 5454 as sheet and plate (along with 6082 extruded shapes) with all-welded construction [1–3].

Aluminum welding was once considered limited due to the problems associated with welding processes such as oxide removal and reduced strength in the weld and heat affected zone (HAZ). New aluminum welding techniques have been developed and commercialized in significantly over the past 30 years that solves these welding problems [1,3]. Although Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) welding processes were developed in 1940s and used in many industries, there were still some joint problems that reduced joint efficiency under % 50 [1,4–6]. To improve weld performance, Friction Stir Welding (FSW) – a solid state welding process – and a milestone in aluminum welding was developed in 1991 by The Welding Institute (TWI). FSW disregarded most of the welding problems such as oxide removal, distortion and porosity associated with conventional arc welding processes without reaching melting temperature or change of phases in the base material. FSW also made all aluminum alloys weldable that were once considered unweldable or limitedly weldable. Further, the reduced welding temperature made joints with lower distortions and residual stresses, enabling improved fatigue performance, new construction techniques, and making possible the welding of very thin and very thick materials. Even though FSW produced joints that were metallurgically, environmentally and economically better than other welding processes, owing to the typically high forces in the process, FSW was usually practiced...
as a fully mechanized process, increasing the cost of the equipment compared to arc welding techniques, while reducing the degree of operator skill required. [7–10]. In spite of all of its benefits and studies that has showed better performance than fusion weldings, FSW has not been still widely commercialized around world, owing to lack of industry standards and specifications, design guidelines and design allowables, informed workforce and high cost of capital equipment and licensing [8,10].

FSW produces welds by using a rotating, nonconsumable welding tool to locally soften a workpiece, through heat produced by friction and plastic work, thereby allowing the tool to “stir” the joint surfaces. The tool serves three primary functions, that is, heating of the workpiece, movement of material to produce the joint, and containment of the hot metal beneath the tool shoulder [8–10].

As of its invention, FSW process has been found very interesting and widely studied [10]. Many studies have been carried out to understand and analyze the effect of process parameters and tool geometries on microstructural and mechanical properties and formability of joints. Taban and Kaluc successfully welded 6.45 mm thick 5086–H32 aluminum alloy with TIG, MIG and FSW processes, and their results has demonstrated that the tensile properties of FSWed joints were more satisfactory than fusion welded joints [6]. Adamowski and Szeko investigated effect of process parameters on the properties and microstructural changes in Friction Stir Welds in the aluminum alloy 6082-T6 with 22 different parameters and found that FSW welds is directly proportional to the tool rotation and welding speeds [11]. Cavaliere et al. studied effect of varying welding speeds on mechanical and microstructural properties of FSWed AA6082-T6 aluminum alloy. Cavaliere et al. welded 4 mm thick plates with 1600 rpm tool rotation and welding speed varying 40–460 mm/min. Cavaliere et al. found that welding speed had a threshold points for grain structure, yield stress and ductility that reversed these properties behavior to the opposite side [12]. Palanivel et al. studied effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083–H111 and AA6351-T6 aluminum alloys. Palanivel et al. used pin profiles of straight square, straight hexagon, straight octagon, tapered square, and tapered octagon and three different tool rotational speeds and found that straight square pin profile with 950 rpm tool rotational speed yielded highest strength [13]. Moreira et al. studied to characterize mechanical and metallurgical properties of friction stir welded butt joints of aluminum alloy 6061-T6 with 6082-T6. For comparison, similar and dissimilar material joints made from each one of the two alloys were micro structurally examined, and micro hardness, tensile and bending tests were carried out. Moreira et al. found that AA 6082-T6 aluminum alloy revealed lower yield and ultimate stress as well as lower hardness values [14]. Rajakumar et al. used 5 different values for each of tool rotational speed, welding speed, axial force, shoulder diameter, pin diameter and tool hardness parameters of FSW to understand influence of FSW process and tool parameters on strength properties of AA7075-T6 aluminum alloy joints. Rajakumar et al. found that optimum parameters for providing maximum strength properties of 315 MPa yield strength, 373 MPa of tensile strength, 397 MPa of notch tensile strength, 203 HV of hardness and 77% of joint efficiency were 1400 rpm (tool rotational speed), 60 mm/min (welding speed), 8 kN (axial force), with the tool parameters of 15 mm (shoulder diameter), 5 mm (pin diameter), 45 HRC (tool hardness) [15]. Kulecki et al. studied effects of tool rotation and pin diameter on fatigue properties of friction stir welded lap joints of AA5754 aluminum alloy. Test results showed that increasing one value while fixing other resulted worse fatigue strengths. Kulecki et al. found that optimization of tool rotation and pin diameter were required to have better fatigue performance [16]. Sarsilmaz et al. evaluated the microstructure and fatigue properties of dissimilar AA7075/AA6061 joints produced by friction stir welding by using two different pin profiles with two rotational speeds and three welding speeds. From the results of microstructure analyses and mechanical test, it was clear that welding properties, such as the microstructure and fatigue life, were strongly influenced by traverse speed and tool profile. Sarsilmaz et al. found that best fatigue performance was provided with application of treated cylindrical pin profile, 1120 rpm tool rotational speed and 250 mm/min [17]. Ericsson and Sandström studied influence of welding speed on the fatigue of friction stir welds, and comparison with MIG and TIG welded joints. According to the results, welding speed in the tested range, representing low and high commercial welding speed, had no major influence on the mechanical and fatigue properties of the FS welds while FS welds showed better fatigue performance then MIG and TIG [18]. Lombard et al. used 11 different values of combination of tool rotational speed, feed and pitch values for optimizing FSW process parameters to minimize defects and maximize fatigue life in 5083–H321 aluminum alloy. Their study has demonstrated that rotational speed governs defect occurrence in this 5083–H321 aluminum alloy and that there was a strong correlation between frictional power input, tensile strength and low cycle fatigue life [19].

Although there were many achievements in FSW of aluminum alloys and both 5083–H111 and 6082–T651 aluminum alloys were studied widely as similar alloy FSWed joints, there were not enough studies about these aluminum alloys as dissimilar alloy joints. In contradiction to their wide usage in industry, especially in shipbuilding industry, there was not enough knowledge about these alloys as dissimilar welds. We aimed to contribute to knowledge of friction stir welding of 5083–H111 and 6082–T651 as similar alloy joints and fulfill the deficiency of knowledge about these alloys as dissimilar FSWed joints. Also, we used different parameters from previous studies to vary knowledge about both similar and dissimilar alloy joints of FSWed 5083–H111 and 6082–T651 especially in low welding speed.

2. Materials and experimental procedure

In this study, 5083–H111 and 6082–T651 aluminum alloys were used as base metals. Chemical composition data obtained by glow discharge optical emission spectroscopy (GDOES) and mechanical properties obtained by tensile test are given in Table 1.

Aluminum alloy plates were cut into coupons according to TS EN ISO 15614–2 [20] for l–butt welding. H13 tool steel with chemical composition of % 0.406 C, % 1.096 Si, % 0.443 Mn, % 4.952 Cr, % 1.251 Mo, % 0.813 V, hardness of HRC48 and the dimensions shown in Fig. 1 was used as FSW tool. Welding parameters were 1250 rpm tool rotational speed (counter clockwise), 64 mm/min welding speed and 2° tool tilt angle. Similar joints of 5083–5083 (called as F55) and 6082–6082 (called as F56) and dissimilar joints of 5083–6082 (called as F66) aluminum alloys were fabricated with these parameters.

Visual and radiographical examination was performed in order to detect possible surface and inner errors after welding test samples in accordance with TS EN ISO 17637 [21] for visual examination before further destructive tests. According to test plan, test samples suitable for TS EN ISO 15614–1:2004 + A2:2012 [22] were extracted from weld plates which had past visual and radiographical examination. Tensile test specimens were prepared according to TS EN ISO 4136:2012 [23], bending test specimens were prepared according to TS EN ISO 5173 [24], fatigue test specimens were prepared according to DIN 50142 [25]. In order to determine microstructure properties of these joints, the specimens were cross-sectioned perpendicular to the weld interface using a
low-speed saw. The cross-section of these joints was metallographically polished and Keller etchant was used for LOM examination. After microstructural examinations, these specimens were used for detailed microhardness assessment under 200 g (HV 0.2) load. For further examination of microstructure, fractured surface of fatigue test specimens were analyzed with scanning electron microscopy (SEM).

3. Results and discussion

3.1. Nondestructive testing

As a result of visual inspection on welded plates, surface type errors such as too much flash, galling, and lack of penetration have not been seen. Any wormhole, kissing bond, porosity, inclusion or oxide layer has not been detected by radiography. Second phase particles and oxides alignment under shoulder were inspected by LOM and none of them were detected in weld zone [10]. Thickness reductions were measured in 0.05 mm level in zone under tool shoulder. When welding tool arrived at the end of the joints, it was allowed to run out the end of the workpiece, producing a tear out. These tear outs was trimmed away by sawing before further destructive tests (Fig. 2).

3.2. Microstructural behavior

The microstructural behavior of aluminum alloys joined by FSW was studied by employing LOM. Images of weld zones’ cross section are outlined in Fig. 3.

Although formation of onion ring has been evaluated characteristic in FSWed nugget zone [26], it might not always be seen apparently in the weld macrostructure [8,14,15,27]. Onion ring formation has not been seen in F55 joint weld nugget while clearly seen in F56 and F66 nugget zone. In the weld nuggets of all joints, grains have been refined as a result of dynamic recrystallization (continuous dynamic recrystallization (CDRX) [8,26]. The strain-hardened 5083 base material was likely completely recrystallized in TMAZ close to the nugget of F55, and the fraction of recrystallized material decreased to zero as the distance from weld nugget increased. Pancake grains in TMAZ of F66 were deformed,

### Table 1

<table>
<thead>
<tr>
<th>Aluminum alloy</th>
<th>Chemical composition (in wt.%) (data obtained by GDOES).</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Si</td>
<td>Fe</td>
</tr>
<tr>
<td>5083</td>
<td>0.076</td>
<td>0.13</td>
</tr>
<tr>
<td>6082</td>
<td>1.02</td>
<td>0.23</td>
</tr>
</tbody>
</table>
elongated and rotated due to the strain that they were subjected to [11]. Heterogeneous mixing of recrystallized fine grains of 5083 and pancake grains of 6082 had been clearly seen in F56 nugget zone. Fractured surfaces were analyzed by LOM and SEM. All fractions of all joint types have been started from between flow arm and weld nugget in advancing sides. In F55 fracture surface appeared populated of very fine dimples revealing a very ductile behavior.
of the material before failure, and fatigue striations were clearly seen in SEM images (Fig. 4) [12]. Fracture surface of F66 joints showed coarse dimples in SEM images (Fig. 6) [15]. Fracture of F56 joints were analyzed in accordance with cross section of its weld zone (Fig. 5). Although there was no weld defect like second phase particles, oxides alignment or voids detected by microscopy or radiography, fractured surfaces of F56 at the intersection point of flow arm, TMAZ and weld nugget. Three distinct regions were separated under loading as if they were bonded, not welded. These rarely encountered voids at the intersection point of flow arm, TMAZ and weld nugget. Three distinct regions were separated under loading as if they were bonded, not welded. These rarely encountered voids aroused from a fluid dynamics voiding effect, either associated with the singularities, or possibly due to vortex generation behind the tool probe while fabricating the joint [11,28].

3.3. Microhardness

Microhardness data were obtained with 200 g load (Fig. 7). 5083 similar alloy weld joint’s (F55) microhardness were measured between 80–84 HV\textsubscript{0.2} and almost there were no drops in microhardness values. 6082 similar alloy weld joint’s (F66) microhardness were measured between 67–85 HV\textsubscript{0.2}. Hardnesses in weld zone were measured around 82 HV\textsubscript{0.2}, while hardness decrease in thermo mechanically affected zone (TMAZ) were measured 67.9 HV\textsubscript{0.2}. 5083 and 6082 dissimilar alloy weld joint’s (F56) were measured between 62.6–84 HV\textsubscript{0.2}. TMAZ’s of F56 joint were slightly similar to that of F66 and F55 for same material as seen in Fig. 7.

Microhardness results of F55 joint were best of all joints as expected but hardness traverse across weldments differ from some studies [1,29]. Average hardness values were 84 HV\textsubscript{0.2} for weld nugget and 81 HV\textsubscript{0.2} for TMAZ. Hardness increase was approximately \% 4. Although hardness increase in FSWed aluminum alloys were rare, Mishra and Mahoney referred a study showing a slight increase in hardness across the weld nugget compared to the TMAZ for a slightly (less than 6%) hardened 5083-H112 as a result of the very fine grain size created by FSW [8]. Koilraj et al. also found same hardness traverse for 5083 side of dissimilar joint [30]. Surprisingly, microhardness drop had not been seen in weld zone in
Microhardness drops in precipitation hardened AW 6082 in far TMAZ of F56 and F66 were results of overaged zone where precipitate coarsening has taken place [3].

3.4. Tensile properties

Tensile properties for base material and cross-welds were given in Table 2 and comparison of the properties are provided in Fig. 8. Average yield and tensile strengths were 198.5 and 285 N/mm² for F55, respectively, for F56 193 and 212 N/mm², and for F66 189.9 and 203 N/mm². Tensile test results for F55 joints were above values results has been obtained from previous studies [29], and at the same level for F56 and F66 [11–13,18,31]. Weld performance of welded joints were %86 for F55, %65 for F56 and %62 for F66 according to average maximum strength of base metal 5083 and 6082. Failures of F55 tensile test specimens were in the weld metal. This was due to the recrystallization process accounted for majority strength loss in weldments in strain-hardened aluminum alloys with its annealing effect [1]. In contradiction to F55 joint, other welded joint tensile test specimens were fractured normally in TMAZ of AW 6082 parent material side. While welding of 6082 alloy, in far TMAZ micro hardness drops in overaged zone where precipitate coarsening has been taken place as also mentioned above in microhardness evaluation. These overaged zones were weakest zones of welded 6082 TMAZ [1,3]. Finally, yield stress results of all welded joints were surprisingly high from previous studies for all joints type [8,18,29–33].

3.5. Fatigue behavior

Fatigue test results for welded joints and base material were given in Fig. 9. Fatigue test were conducted under yield stresses.

<table>
<thead>
<tr>
<th>Tensile specimen</th>
<th>Rp 0.2 (N/mm²)</th>
<th>Rm (N/mm²)</th>
<th>Elongation (%)</th>
<th>Rupture zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>F55_1</td>
<td>191</td>
<td>281</td>
<td>14</td>
<td>Weld metal</td>
</tr>
<tr>
<td>F55_2</td>
<td>–</td>
<td>284</td>
<td>14</td>
<td>Weld metal</td>
</tr>
<tr>
<td>F55_3</td>
<td>206</td>
<td>290</td>
<td>14</td>
<td>Weld metal</td>
</tr>
<tr>
<td>F55 average</td>
<td>198.5</td>
<td>285</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>F56_1</td>
<td>–</td>
<td>211</td>
<td>5.6</td>
<td>TMAZ (AW 6082 side)</td>
</tr>
<tr>
<td>F56_2</td>
<td>193</td>
<td>214</td>
<td>5.6</td>
<td>TMAZ (AW 6082 side)</td>
</tr>
<tr>
<td>F56_3</td>
<td>–</td>
<td>211</td>
<td>5.6</td>
<td>Weld metal</td>
</tr>
<tr>
<td>F56 average</td>
<td>193</td>
<td>212</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>F66_1</td>
<td>–</td>
<td>204</td>
<td>8</td>
<td>Weld metal</td>
</tr>
<tr>
<td>F66_2</td>
<td>–</td>
<td>211</td>
<td>8.4</td>
<td>TMAZ</td>
</tr>
<tr>
<td>F66_3</td>
<td>189.9</td>
<td>194</td>
<td>7.6</td>
<td>TMAZ</td>
</tr>
<tr>
<td>F66 average</td>
<td>189.9</td>
<td>203</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Microhardness values for FSWed Joints.

Fig. 8. Comparison of average tensile properties of the base metal with welded joints.

Fig. 9. Fatigue test results for welded joints.
According to the fatigue tests results, FSWed 5083 (F55) exhibited best fatigue data from other welded joints, parallel with tensile test data and microhardness traverse. Then respectively, besides having close fatigue limits, F56 showed better fatigue limit than F56. Failures were generally occurred in the zone among the flow arm, weld nugget and TMAZ, and then propagated horizontally through this zone.

4. Conclusions

In this study, 6 mm thick AW5083 H111 and AW 6082 T651 aluminum alloys that used widely in ship building industry were welded successfully with low speed friction stir welding as similar and different alloy pair. And following conclusions were drawn:

- AW5083 H111 that readily weldable with all conventionally fusion welding methods showed also best performance of % 86 joint efficiency, bending fatigue limit close to base metal and satisfactory bending and ductility. Then respectively, dissimilar welding of 5083 and 6082 with % 65 and similar welding of 6082 with % 62 joint efficiency.
- Although fatigue limits of all joint types were close to each other, main reason of difference in tensile strengths was the overaged zone in the far TMAZ of 6082-T651 base metal side that needed further heat treatment to be eliminated [18].
- Microhardness test were resulted in novelty data for similar welding of 6082-T651 aluminum alloy depending on high heat input that caused naturally post welding aging effect. Low welding speed with high tool rotation speed resulted in high heat input that caused this hardness traverse was novelty for this study.
- Microstructure analyze of weld zone cross sections with LOM and SEM analyze of fracture surfaces of fatigue specimens of F56 revealed rarely experienced void effect while there were not any defect detected by radiography and microscopy in weld zone. A cleavage between the flow arm and weld nugget revealed voids under bending fatigue tests.
- Low speed friction stir welding of both similar and dissimilar alloy joints of 5083-H111 and 6082-T651 aluminum alloys revealed joints with high fatigue limits and satisfactory tensile strengths according to the previous studies. With low speed FSW, increasing heat treating effect provided microstructurally- and mechanically better joints while maintaining weld zones from any imperfection.

Acknowledgements

Authors would like to thank to the technical support of the following industrial companies: Assam Aluminum, ICM Makina, End Denetim.

References