2023


Aiman H. Al-Allaq  
Old Dominion University

Manish Ojha  
Old Dominion University

Yousuf S. Mohammed

Srinivasa N. Bhukya  
Virginia State University

Zhenhua Wu  
Virginia State University

See next page for additional authors.

Follow this and additional works at: https://digitalcommons.odu.edu/mae_fac_pubs

Part of the Engineering Mechanics Commons, Mechanical Engineering Commons, and the Mechanics of Materials Commons

Original Publication Citation

This Article is brought to you for free and open access by the Mechanical & Aerospace Engineering at ODU Digital Commons. It has been accepted for inclusion in Mechanical & Aerospace Engineering Faculty Publications by an authorized administrator of ODU Digital Commons. For more information, please contact digitalcommons@odu.edu.
Authors
Aiman H. Al-Allaq, Manish Ojha, Yousuf S. Mohammed, Srinivasa N. Bhukya, Zhenhua Wu, and Abdelmageed A. Elmustafa

This article is available at ODU Digital Commons: https://digitalcommons.odu.edu/mae_fac_pubs/146

Aiman H. Al-Allaq
Manish Ojha
Yousuf S. Mohammed
Srinivasa N. Bhukya
Zhenhua Wu
Abdelmageed A. Elmustafa (✉ ael MUSTA@odu.edu)
Old Dominion University Frank Batten College of Engineering and Technology

Research Article

Keywords: Friction stir welding, Micro-structured/surface characterization, Heat treatment processes

Posted Date: March 30th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2720330/v1

License: © ① This work is licensed under a Creative Commons Attribution 4.0 International License.  Read Full License

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on October 10th, 2023. See the published version at https://doi.org/10.1007/s00170-023-12407-9.
Abstract

Post weld heat treated AA6061-T6 alloy resulted from the application of a Cu donor stir assisted (CDSA) friction stir welding (FSW) material was examined for crystal structure and mechanical properties. CDSA FSW samples were tested at a constant tool rotational speed of 1400 rpm and a welding translational speed of 1 mm/s. CDSA samples of 20% and 60% thickness of the AA6061-T6 base alloy were selected to assist the FSW joining at the plunge stage. The FSW AA6061-T6 samples were solid solution treated at 540 °C for one hour, followed by quenching in water at room temperature. The samples were then artificially aged at 180 °C for 6 hours, respectively, followed by air cooling. The samples were tested for microstructure, crystal structure, chemical composition, and mechanical properties using optical microscopy, scanning electron microscopy, X-ray diffraction, and nanoindentation. The microstructure shows the additional grain refinement in the stir zone (SZ) due to recovery and recrystallization with increasing aging time. Examination of the chemical contents of the FSW AA6061-T6 alloy samples using scanning electron microscopy with energy dispersive spectroscopy (EDS) revealed Al (parent material) as the predominant element, while Cu (CDSA) was minimally present as expected. XRD results of the CDSA FSW samples depicted crystal orientations similar to the orientations of the AA6061-T6 alloy. Nanoindentation tests revealed softening effects due to the dissolution of hardening precipitates at the SZ. The hardness of the base metal (BM), left and right regions, is reported as ~ 6.5 GPa, whereas at the SZ, the hardness is ~ 5.5 GPa at a depth of indentation of 4.7 µm.

1.0 Introduction

Lightweight materials possess unique properties that are of great interest to DoD industries. Aluminum alloys (AA) represent lightweight materials used in various military applications due to their high strength-to-weight ratio and low fabrication cost compared to steel, titanium, and magnesium alloys. Aluminum alloys AA5083, AA2139, and AA7039 are often used in armored vehicles and military vessels [1]. These alloys meet the military standards for projectile resistance, corrosion resistance, lightweight, and weldability. Ballistic and armor-piercing tests are commonly performed on aluminum armored plates to ensure the strength and safety requirements are met for military applications. Although these alloys are used in armored vehicles, the complexity in manufacturability and sustainment of selecting appropriate aluminum alloys for vehicles' hull structures increased due to the lack of sufficient and efficient welding techniques. These aluminum alloys perform poorly in conventional fusion welding. FSW, a solid-state welding process, emerged as a promising alternative for welding aluminum alloys and overcoming defects such as porosities, solidification cracking, high residual stress, etc., generally associated with fusion welding[2]. FSW produces low-cost quality welds compared with other welding processes. However, the loss of strength due to heat generation at the weld zone during welding is still a major concern [3–6]. For example, for gas metal arc welded (GMAWed) of AA2139-T8 alloys, weld strength, and elastic elongation, which are measures of the weld quality, are only 35–55% of the base material.

To strengthen aluminum alloy weldments, a solution heat treatment followed by rapid water quenching is recommended [6]. This solution heat treatment process results in a metallurgical structure within the alloy that enhances the strength of the weld [7]. The formation and distribution of precipitants depend on the solution treatment temperature and the artificial aging time levels. Si and Mg are the two major alloying elements of the 6000-aluminum series that are typically added in the proportions required for the formation of hardening precipitates of Mg2Si. Since Mg2Si constitutes the main precipitants of the 6000-aluminum alloy series, this results in making the 6000-aluminum alloy series heat treatable by solutionizing and artificial aging processes.

Heat treatment influences the internal microstructure and hence the mechanical properties of metals and alloys, including hardness, yield strength, ultimate tensile strength, and corrosion resistance. Metals and alloys can be processed using various heat treatment approaches, such as changing the solutionizing temperatures and using different aging time levels [8]. Several manufacturing industries follow ASTM B917 and ASTM B91 standards for precipitation hardening or the so-called "T6 heat treatment". T6 heat treatment involves a solution heat treatment at a temperature of 540°C with a residence duration between 6 to 12 hours, followed by artificial aging at 155°C between 3 to 5 hours [9]. Rosso and Actis suggested that solutionizing metals for 1 hour rather than 6 hours would yield significantly better tensile strength. They also concluded that further
subjecting metals to 180°C for 4 hours using artificial aging would yield better mechanical properties [10]. Shivkumar et al. [11] and Zhang et al. [12] concluded that a solution heat treatment temperature of 540°C followed by the artificial aging time between 3–5 hours at 155°C is sufficient to yield better hardness and strength. Cabibbo et al. [13] studied the effect of post weld heat treatment (PWHT) on FSW of AA6056 alloy and reported a significant increase in the tensile strength due to the formation of high-density precipitation of Mg2Si. Jamshidi and Serajzadeh [14] also reported that artificial aging increased the hardness of the friction stir welded AA6061 alloy. Although the formation of fine recrystallized grains, the dissolution and growth of precipitates were noticed in the weld zone after FSW [5]. Aging resulted in the formation of hardening precipitates, which led to a full recovery of the mechanical properties. Previous studies indicated that post-artificial aging is necessary to produce sufficient strength and hardness at the weld zone of a friction stir processing of 6000 series aluminum alloys. Priya et al. [15] investigated the PWHT on FSW AA6061-T6 and AA 2219-T6 alloys and concluded that their ultimate tensile strength was increased due to the presence of fine precipitated particles. Hu et al. [16] performed PWHT of friction stir welded AA2024 alloys and noticed that their mechanical properties were not changed but enhanced the weld's elongation. Recently, Bhukya et al. [18] reported the effects of using copper donor stir assisted material of FSW of AA6061-T6 alloy on the microstructure and mechanical properties of the welded specimens but not on PWHT. The PWHT research work has been accomplished on regular FSW aluminum alloys. However, the effect of PWHT on Cu donor stir assisted FSW AA6061-T6 alloy has not yet been investigated. This study used various techniques to investigate the chemical, microstructure, and mechanical properties, including FE-SEM, XRD, SEM-EDS, optical microscopy, and nanoindentation. The samples were subjected to a solid solution heat treatment at 540°C for 1 hour, followed by artificial aging for 0 and 6 hours at 180°C.

2.0 Experimental Procedure

The CDSA sample preparation is detailed in [18]. In this study, a base metal of extruded AA6061-T6 alloy sheets with dimensions of 304.8 mm (length) x 76.2 mm (width) x 6.35 mm (thickness) was used to fabricate the test coupons. Test coupons, with dimensions of 152.4 mm (length) x 76.2 mm (width), were sectioned from the as-received sheets, and the edges were milled along the length. A trough with dimensions of 63.5 mm (length) x 25.4 mm (width) was forged onto the workpieces for positioning the donor stir-assisted material. Before welding, the trough and the donor stir-assisted material were cut and shaped using a CNC mill. A CDSA with 20% and 60% of the AA6061-T6 alloy thickness were selected for the current investigation. Tables 1 and 2 list the chemical composition and mechanical properties of the AA6061-T6 and Cu-110 alloys, respectively. FSW experiments were conducted in the position control mode, using a triangle tapered pin-type tool head made of H13 steel. More information about the FSW machine used in this study can be found in [18]. The joints were friction stir butt-welded at a translational welding speed of 1mm/s and a tool rotation of 1400 rpm.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Al</th>
<th>Cu</th>
<th>Cr</th>
<th>Fe</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>Ti</th>
<th>Zn</th>
<th>Zr</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>A6061-T6</td>
<td>95–98</td>
<td>0.05–0.05</td>
<td>0.4–0.8</td>
<td>0.01–0.7</td>
<td>0.8–1.2</td>
<td>0.01–0.15</td>
<td>0.001–0.05</td>
<td>0.001–0.05</td>
<td>0.001–0.05</td>
<td>0.001–0.25</td>
<td>0.001–0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Cu 110</td>
<td>99.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 1

Chemical composition of AL6061-T6 and Cu 110 alloys.
Table 2

<table>
<thead>
<tr>
<th>Material</th>
<th>A6061-T6</th>
<th>Cu 110</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockwell Hardness</td>
<td>40–60</td>
<td>55</td>
</tr>
<tr>
<td>Yield strength MPa</td>
<td>241</td>
<td>255</td>
</tr>
<tr>
<td>Ultimate strength MPa</td>
<td>262</td>
<td>345</td>
</tr>
<tr>
<td>Thermal conductivity W/mK</td>
<td>151</td>
<td>183</td>
</tr>
<tr>
<td>Melting Point °C</td>
<td>585</td>
<td>1084</td>
</tr>
</tbody>
</table>

The influence of PWHT on the mechanical/structural properties was investigated by dividing the weldments into two groups: As-Welded (AW) and heat-treated (HT) samples. The heat treatment process involved solution heat treatment in the furnace at a temperature of 530°C for 1 hour, followed by immediate water quenching. The samples were then artificially aged inside the furnace at a temperature of 180°C for 0 and 6 hours. The heat-treated metallography samples were cold-mounted, ground, polished, and etched with Keller’s reagent for approximately 120 seconds to reveal the grain structure. An Olympus optical microscopy with quantitative image analysis software was used for microstructure and macrostructure studies. The friction stir welded coupons were sectioned using a wire electrical discharge machine (WEDM) in the direction perpendicular to the welding direction (WD) to examine the microstructures in the weld cross-sections.

The fractured surface of the friction stir welded samples were subsequently examined using a JEOL 6700 FE-SEM equipped with three-dimensional (3-D) fractographic analysis capacity.

Indentation experiments were conducted on the AW samples using a Nanoindenter XP with a high-load attachment for the XP head that could apply a load of up to 10 N. The standard XP head and high load attachment enabled experiments from the nano to the micro regime using a single Berkovich diamond indenter tip. The nanoindenter tip was calibrated using a standard fused silica standard. Each indentation was made using the standard NanoSuite XP continuous stiffness method (CSM) protocol with a maximum depth of 5um.

3.0 Results And Discussion

3.1. Microstructure analysis

Figure 1(a-c) shows the microstructure of the 20% CDSA, the 0, and 6 hours solution treated AA6061-T6 samples. The samples represent the SZ location. The microstructure in the SZ consists of grains with slightly uneven boundaries, perhaps resulting from the high plastic deformation during the FSW process and the dissolution of the strengthening particles commonly occurring in the T6-treated base plate.

Small grains were formed, and the grain size increased with the solution treatment time, Fig. 2(a-b). The FE-SEM of Fig. 2b depicts smaller dark particles of the PWHT sample. These particles were not present in the FE-SEM of the AW sample PWHT precipitated strengthening particles in the SZ, as shown in Fig. 2(a). The development of the small dark particles in the PWHT is attributed to the presence of the Mg$_2$Si intermetallic contents [20]. This type of particle development can generally be found in AA6061-T6 alloy when the alloy undergoes heat treatment followed by an artificial aging process. The precipitation microstructure of Mg$_2$Si during aging for AA 6061-T6 alloys is well documented in the literature [20–22]. The number of intermetallic particles increases with the increase of the aging time. Equiaxed grains with fine grain size were formed and increased with the increase of the time of aging for the PWHT.

3.2. SEM, EDS observations
SEM-EDS was used to evaluate the impact of the CDSA on the FSW AA6061-T6 alloy samples. Examination of the chemical contents of the FSW AA6061-T6 alloy samples indicated the dominance of Al (parent material), whereas CDSA was somewhat detected. The tests were performed for the base metal BM (left region), BM (right region), and the SZ zone (middle region). Figure 4 shows EDS plots of the 20% and 60% CDSA, solution treated (ST), and 6 hours heat treated (HT) FSW AA6061-T6 alloy samples taken at several points at the SZ. Figures 3 (a) and (b) represent the 20% and 60% ST samples, while Figs. 3 (c) and (d) represent the 20% and 60% 6-hour HT samples. Tables 3 (a-d) list elements’ composition percentages at each point referenced in Fig. 3. Al is the major element, while other elements such as C, Fe, Mg, Mn, O, and Si exist in a small percentage. It is evident from the EDS images and the listing of the chemical elements at the SZ that the absence of the Cu element of the CDSA material is anticipated. EDS plots of FSW samples with 20% and 60% CDSA ST and 6 hours CDSA HT samples at the SZ and BM regions are shown in Fig. 4, respectively. The plot unequivocally depicts Al as the major element in all samples. Al was also found to be the major element in the SEM-EDS analysis performed for a nanoindentation imprint in the SZ, as seen in Fig. 5. As we reported, other elements also existed but in very small percentages.

Table 3
(a) Weight % of the elements for the 20% ST CDSA at the SZ

<table>
<thead>
<tr>
<th>Location</th>
<th>C</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-M 20%(1)_pt1</td>
<td>7.03</td>
<td>ND</td>
<td>ND</td>
<td>73.36</td>
<td>4.99</td>
<td>1.29</td>
<td>13.33</td>
</tr>
<tr>
<td>ST-M 20%(1)_pt2</td>
<td>9.73</td>
<td>1.23</td>
<td>ND</td>
<td>83.80</td>
<td>1.28</td>
<td>ND</td>
<td>3.96</td>
</tr>
<tr>
<td>ST-M 20%(1)_pt3</td>
<td>10.36</td>
<td>ND</td>
<td>6.41</td>
<td>75.99</td>
<td>4.39</td>
<td>ND</td>
<td>2.84</td>
</tr>
<tr>
<td>ST-M 20%(1)_pt4</td>
<td>11.38</td>
<td>0.76</td>
<td>1.33</td>
<td>85.66</td>
<td>0.87</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST-M 20%(1)_pt5</td>
<td>11.42</td>
<td>1.59</td>
<td>ND</td>
<td>86.99</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>ST-M 20%(1)_pt6</td>
<td>11.87</td>
<td>ND</td>
<td>ND</td>
<td>88.13</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

Table 3
(b) Weight % of the elements for the 60% ST CDSA at the SZ

<table>
<thead>
<tr>
<th>Location</th>
<th>C</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST-M 60%(1)_pt1</td>
<td>9.01</td>
<td>2.08</td>
<td>1.16</td>
<td>68.15</td>
<td>6.89</td>
<td>12.72</td>
<td></td>
</tr>
<tr>
<td>ST-M 60%(1)_pt2</td>
<td>8.99</td>
<td>2.98</td>
<td>0.26</td>
<td>67.82</td>
<td>6.45</td>
<td>13.50</td>
<td></td>
</tr>
<tr>
<td>ST-M 60%(1)_pt3</td>
<td>7.27</td>
<td>2.18</td>
<td>0.34</td>
<td>81.11</td>
<td>2.86</td>
<td>6.24</td>
<td></td>
</tr>
<tr>
<td>ST-M 60%(1)_pt4</td>
<td>7.42</td>
<td>9.79</td>
<td>0.46</td>
<td>79.01</td>
<td>3.32</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>ST-M 60%(1)_pt5</td>
<td>7.96</td>
<td>2.83</td>
<td>0.45</td>
<td>88.76</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
</tbody>
</table>

Table 3
(c) Weight % of the elements for the 20% 6-hour HT CDSA at the SZ
### Table 3

(d) Weight % of the elements for the 60% 6-hour HT CDSA at the SZ

<table>
<thead>
<tr>
<th>Location</th>
<th>C</th>
<th>O</th>
<th>F</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT6-M 20%(1)_pt1</td>
<td>7.66</td>
<td>ND</td>
<td>ND</td>
<td>1.88</td>
<td>70.01</td>
<td>5.79</td>
<td>1.48</td>
<td>13.19</td>
</tr>
<tr>
<td>HT6-M 20%(1)_pt2</td>
<td>6.83</td>
<td>1.33</td>
<td>ND</td>
<td>0.40</td>
<td>82.21</td>
<td>2.79</td>
<td>ND</td>
<td>6.43</td>
</tr>
<tr>
<td>HT6-M 20%(1)_pt3</td>
<td>6.84</td>
<td>ND</td>
<td>ND</td>
<td>0.79</td>
<td>86.84</td>
<td>1.67</td>
<td>ND</td>
<td>3.86</td>
</tr>
<tr>
<td>HT6-M 20%(1)_pt4</td>
<td>6.49</td>
<td>19.79</td>
<td>0.83</td>
<td>ND</td>
<td>52.25</td>
<td>20.64</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>HT6-M 20%(1)_pt5</td>
<td>5.42</td>
<td>0.90</td>
<td>ND</td>
<td>0.61</td>
<td>93.06</td>
<td>0.00</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

ND* - not detectable.

### 3.3. XRD analysis

The XRD results are presented in the plot of Fig. 6. The plot includes 20%, 60% DCSA zero hours ST, 6 hours HT, and BM samples. In addition to the presence of Al at several peaks \([2\theta(\degree) = 37.50, 64.07, 77.32, \text{and} 81.55]\), other elements such as \(\text{Al}_2\text{O}_3, \text{Mg}_2\text{Si}, \text{Al}_5\text{Fe}_2\text{Si}, \text{Al(FeMnCr)}\text{Si}, \text{and} \text{Al+Al}_2\text{O}_3\) existed with smaller amounts at peaks of \(2\theta(\degree) = 36.14, 39.54, 41.56, 42.35\text{and} 43.51\), respectively.

Figure 7 shows the XRD patterns of the 20%, 60% DCSA zero hours ST, 6 hours HT, and BM samples. Again, the diffraction peaks are labeled in the Figure. It is also observed that the samples depicted aluminum cubic and Al, Fe, and Si systems of hexagonal crystal structure.

### 3.5. Nanohardness measurements

The nanoindentation plot of Fig. 8 indicated the softening effect in SZ of the 20% Cu 6 hours heat treated samples. The hardness at the SZ was measured as 0.55 GPa compared to a hardness of 0.63 GPa for the BM fat, with a depth of indentation of 4.75 \(\mu\text{m}\).

### 3.6. Fractography

Figure 9 (a-d) and Fig. 10 (a-b) show fracture surfaces of the 1400 rpm and 1 mm/s of as welded and 6 hours heat treated samples. These fractographic images include crack initiation, spherical and broken dimples, secondary cracks, tear ridges, and particles. It is noted that crack initiation occurs in the vicinity of the TMAZ/HAZ retreating side following the PWHT, Fig. 10a. The fracture surface presents many small spherical dimples with layered distribution, which often indicates a ductile fracture. The 20% CDSA AW samples exhibited intergranular cracking with coarser dimples. The dimples were becoming finer for the PWHT welded samples, and the emerging grains were getting smaller than the AW's grain when the aging time was increased, Fig. 10b.
3.7. Conclusions

The present research aims to investigate the microstructure, crystal structure, chemical composition, and mechanical properties of the welded joints of 20% and 60% CDSA PWHT samples. Optical microscopy, scanning electron microscopy, X-ray diffraction, and nanoindentation techniques were utilized. The results are as follows:

1. The SZ and the TMAZ, predominantly composed of equiaxed grains, experienced complete dynamic recrystallization. The grain size in the SZ became finer after PWHT, followed by 6 hours artificial aging process. A significant amount of strengthening intermetallic particles of Mg$_2$Si was observed after PWHT, which changed the structure of the AA6061-T6 alloy.

2. After the PWHT, there was a sudden increase in the hardness at the center of the weld. The SZ is softer than the BM from the nanoindentation hardness results.

3. Fractography of the AW tensile testing fractured samples exhibited intergranular cracking with large dimples. The fractured surface for the PWHT samples exhibited a ductile-like fracture with a large number of fine dimples. These dimples emerged in the ductile fractured surfaces, which only correspond to voids. For the PWHT joint, the dimples were becoming finer, and the grains that emerged were smaller than the AW when the aging time was increased.

Declarations

1. What is your main contribution to the field?

The primary contribution of this research, entitled "Post Weld Heat Treatment Effects on Microstructure, Crystal Structure, and Mechanical Properties of Cu Donor Stir Assisted Friction Stir Welding Material of AA6061-T6 Alloy," is the analysis of the effects of post weld heat treatment on the microstructure, crystal structure, chemical composition, and mechanical properties of AA6061-T6 alloy welded joints produced using Cu donor stir assisted friction stir welding. In this research, we concluded that the stir zone exhibited grain refinement after the heat treatment and artificial aging process, which led to the formation of strengthening intermetallic particles of Mg$_2$Si. In addition, nanoindentation test results showed that the hardness results of the base metal (BM), which is represented by the left and right regions are consistent with the hardness of the AA6061-T6 hardness results. Furthermore, the stir zone experienced softening as compared to the base metal. These findings offer important insights and guidelines for optimizing welding processes and post-weld heat treatments to enhance the performance and durability of welded structures made from the AA6061-T6 alloy.

2. What is novel? In theory, in experimental techniques, or a combination of both?

In our research on "Post Weld Heat Treatment Effects on Microstructure, Crystal Structure, and Mechanical Properties of Cu Donor Stir Assisted Friction Stir Welding Material of AA6061-T6 Alloy," The novelty lies in using high characterization techniques to identify post weld heat treatment and how it impacts the crystal structure, microstructure, chemical composition, and mechanical properties of the welded AA6061-T6 joints.

Our research revealed that the stir zone exhibited grain refinement after the heat treatment and artificial aging process, leading to the formation of strengthening intermetallic particles of Mg$_2$Si. We measured the hardness of the base metal (BM), left and right regions as ~ 6.5 GPa, whereas at the SZ, the hardness is ~ 5.5 GPa at a depth of indentation of 4.7 µm.

3. Does your paper have industrial applications? If yes, who are the likely user?

The research findings and recommendations could be advantageous to industries such as transportation, aviation, maritime, and civil engineering by providing insights to enhance welding processes and post-weld heat treatment procedures. This, in turn, could contribute to the improvement of performance and longevity of welded joints made from AA6061-T6 and other
alloys. As a result, the intended users of this research include materials engineers, industrial specialists, and fabrication professionals working across these various sectors.

Acknowledgments

The authors express their gratitude for the funding support from NASA (grant ID: 80NSSC20M0015). ZW appreciates the support from ONR (grant ID: N00014-19-1-2728). This document’s perspectives, discoveries, deductions, or suggestions belong to the author(s) and do not necessarily represent NASA and ONR’s viewpoints. The authors acknowledge the Commonwealth Center for Advanced Manufacturing (CCAM) and Amsted Rail for making available the infrastructure required for specimen evaluation. Finally, the valuable contribution of Mr. Geoff Widman in carrying out the experiments is acknowledged and appreciated.

a. Funding: The authors would like to acknowledge support from NASA (award number: 80NSSC20M0015). The author ZW also acknowledges support from ONR (award number: N00014-19-1-2728). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NASA and ONR.

b. Competing Interests: The authors have no relevant financial/non-financial interest neither conflict of interest to disclose.

c. Author Contributions: Mr. A. H. Al-Allaq performed XRD characterization and wrote/revised the manuscript. Dr. S. Bhukya carried out experimentation and data analysis for the CDSA and revised the manuscript. Dr. A.A. Elmustafa conceptualized the research and wrote/revised the manuscript. Dr. Z. Wu secured the funding. Mr. M. Ojha performed the SEM-EDS and Dr. Y. Mohammed performed the nanoindentation testing.

References


Figures
Figure 1

Optical microstructure images after PWHT at SZ of joints made at 20% Cu, 1400 rpm, and one mm/s, a) 20% Cu A, b) ST+AA 0Hr, and c) ST+ AA 6 Hr
Figure 2

Typical SEM images of a) as welded and b) PWHT samples, with 20% Cu donor material assisted FSW at a rotational rate of 1400 rpm and a welding speed of 1 mm/s.
Figure 3

(a) and (b) SEM EDS images of the 20 and 60% solution treated (ST). (c) and (d) 20 and 60% 6 hours heat treated (HT) taken at the SZ.
Figure 4
EDS plot of FSW samples with 20% and 60% Cu ST and 6 hours HT samples at SZ (Left) and BM(Right) respectively.

Figure 5
Nanoindentation at the SZ of FSW 20% Cu 6 hours HT sample (left).
EDS line spectrum of 20 points along the
Figure 6

XRD Spectra of the AA6066-T6 FSW samples under different heat treatment conditions and Chemical Structure
Figure 7

The FSW Samples Phases Composition
Figure 8

Nanoindentation hardness versus depth of indentation in the BM (left) SZ (middle), and BM (right) of the 20% Cu 6 HT AW sample.
Figure 9

Typical tensile-tested fracture surface images of PWHTed samples with 20% Cu donor material at a rotational rate of 1400 rpm and a welding speed of 1 mm/s. (a and b) 20% Cu as-welded, (c and d) ST+AA 0 Hr.
Figure 10

Typical tensile tested fracture surface images of PWHTed samples with 20% Cu donor material at a rotational rate of 1400 rpm and a welding speed of 1 mm/s. (a and b) ST+AA 6 Hr welded