INTRODUCTION

The aluminium alloy AA2024 is a member of the heat-treatable aluminium series. Al-Cu precipitation is the main strengthening mechanism in the Aluminium 2xxx series. AA2024 has good fracture toughness, high corrosion resistance and specific strength. This alloy is generally employed in lightweight applications to save weight such as in airplanes, spacecraft, and high-speed trains.

Since the 2xxx series has a high thermal conductivity, a high thermal expansion coefficient and a low melting point, they are hard to weld with traditional welding methods. Therefore, solid-state welding techniques to weld aluminium alloys is of high importance. Among the solid-state welding techniques, rotation friction welding (RFC) is a promising method, especially for the parts with cylindrical cross-section Department of Machinery and Metal Technologies, s. 7–9. In RFC, two cylindrical cross-section materials are forced to rotate to generate heat with the pressure applied by axial forces. This technique can be regarded as a relatively quick technique that generally lasts for tens of seconds.

Since the principles of friction welding are the same, there are some variants of this welding method such as friction stir welding (FSW), linear friction welding (LFW), and rotary friction welding (RFW). There are also various studies regarding friction welding in the literature. Prashanth and others studied RFW of Al–12Si parts manufactured with the selective laser melting method. The shape and size of the Si phase increased in the weld zone. This variation has resulted in significant changes to the mechanical properties of the weld joint. Rafi and others investigated the mechanical and microstructural properties of RFW applied to a AA7075-T6 joint. They found that the spindle speed, friction pressure, and burn-off length affect the joint strength with 89% joint efficiency.
investigated high-frequency LFW of 5052 and 6063 aluminium alloys. Material flow during welding was affected by the thermal conductivity at elevated temperatures. They also noted that the grains are refined and the hardness was increased at the interface of the Al 6063 alloy. The joints with low heat inputs yielded higher joint strengths.

In this work AA2024-T6 aluminium rod materials were welded with a rotary-friction-welding technique. The effect of forging pressure under constant parameters were investigated. Tensile tests were applied to rotary-friction-welded specimens. Failure energies, elongations and tensile results were evaluated in terms of different forging pressures. The microstructure was characterized by optical microscope, SEM, SEM/EDS devices. Phase formations was evaluated and supported by the literature.

2 MATERIALS AND METHOD

In this study, AA2024-T6 with an 18-mm diameter was employed. The specimens were machined to 12-mm. The tensile tests were performed on a SHIMADZU AGS-50kN Universal testing device according to the ATSM E8 standard. The crosshead speed was adjusted to 5 mm·min⁻¹. The tensile strength and maximum strength are measured at room temperature as 354 MPa and 522 MPa, respectively. The elongation at break was 23 %. There are no specific applications on the surface of the specimens. The chemical composition of the AA2024-T6 is presented in the Table 1.

<table>
<thead>
<tr>
<th>Element (w/%)</th>
<th>Cu</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Cr</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>(w/%)</td>
<td>3.7</td>
<td>1.22</td>
<td>0.5</td>
<td>0.5</td>
<td>0.15</td>
<td>0.32</td>
<td>0.03</td>
<td>0.05</td>
<td>Balance</td>
</tr>
</tbody>
</table>

The specimens were welded with rotary-friction-welding machine. Table 2 shows the welding parameters used in RFW tests for all experiments, the spindle speed and friction pressure were 1200 min⁻¹, 60 MPa, respectively. The total friction time was adjusted to 8 s, whereas the duration of the forging time was 4 s.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Forging pressure (MPa)</th>
<th>Friction pressure (MPa)</th>
<th>Forging time (s)</th>
<th>Friction time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>60</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The specimens were cut from a plane that is parallel to the axis of rotation for metallographic explorations. Conventional metallographic procedures were applied to the joined specimens. The microstructure specimens were etched with Keller solution with an application time of 8 s. A Nikon Eclipse L150A light optical microscope was employed for micro and macrostructural investigations. Also, FEI Quanta 200 FESEM scanning electron microscope (SEM) with energy dispersive spectroscopy (EDS) device was employed for metallurgical exploration. A Wilson hardness tester was used for microhardness measurements. Hardness measurements were taken with 0.25-mm intervals with a 10-gF load.

3 RESULTS AND DISCUSSION

The effect of the friction pressure on tensile-elongation behaviour of the rotary-friction-welded AA2024-T6 aluminium joints is shown in Figure 1. According to the figure, the tensile strength of the base metal exhibited the best tensile performance among all tensile tests with 472.26 MPa maximum tensile bearing capacity. None of the rotary-friction-welded specimens has achieved the tensile strength of the base metal. Changing the forging pressure during welding has an effect on the tensile strength. The tensile strengths increases as the forging pressure is decreased. The maximum tensile strength is obtained at a forging pressure of 80 MPa. The tensile strengths for forging pressures of (120, 100 and 80) MPa were obtained as 345.37, 359.10, and 366.22, respectively.

The elongations represent the degree of ductility for the material being tested. The elongation has similar characteristics compared to tensile behaviour of the joints. Figure 2 shows the effect of forging pressures on the elongation at break and failure energies. The elongations were decreased as the forging pressure increases. On the other hand, the base metal has an elongation of 19.21 % that is similar to the elongation at a forging pressure of 80 MPa, achieving 19.28 % elongation. The lowest elongation was obtained in forging pressure of 120 MPa as 15.37 %. There was an approximately 20 % loss in elongation compared to the application pressure of 80 MPa. Namely, there is an important ductility loss in the experiment that has forging pressure of 120 MPa.

The failure energy is another important aspect for evaluating toughness and the energy-absorption capacity.
of the joint. Therefore, measuring the failure energy is of great importance. The failure energy was measured with an integration of the area under the tensile-elongation curve. According to the failure-energy results, the maximum failure energy was obtained in the base metal. The failure energy has an inverse relation to the forging pressure. Since the elongation and tensile strength were decreased with an increase in the forging pressure, the failure energies were decreased as the forging pressure increases.

A rotary welded and trimmed microstructure specimen with 80 MPa forging pressure is presented in Figure 3a and 3b. On the other hand, light optical microscope microstructure images from the cross-section of this specimen are presented in Figures 3c to 3e. The microstructure of the rotary-friction-welded AA2024 can be divided into four section for both jointing side; i) base metal (BM), ii) heat-affected zone (HAZ), iii) thermomechanically affected zone (TMAZ) and iv) dynamically recrystallized zone (DRZ).

Given the grain size and distribution, BM has a coarse grain size in the microstructure between 10 μm and 240 μm. These grains are not equiaxed and elongated through the rotation axis. Due to the tempering effect, the grains in the HAZ are coarsened as well. With a combination of forging and friction force that is parallel to the rotation axis, the grains are enforced to extend outside. Namely, the elongation axis was deflected 90° due to these effects. The friction heat and dynamic stirring of both friction surfaces causes both recrystallization and mechanical deflection of the grains simultaneously. Therefore, elongated grains perpendicular to the rotation axis and finer grains compared to HAZ are obtained. As for DRZ, this region represents the fusion and solidified zone. Since each side of the specimen is cold, the DRZ underwent quick solidification. Thereby, a finer grain size in the weld joint is obtained.

Line hardness measurement from the cross-section of the rotary-friction-welded joint is illustrated in Figure 4. The BM has 117 ± 5 HV hardness. In the HAZ, the hardness increases up to 130 HV due to the tempering effect. Then, the hardness reaches the maximum point in the TMAZ due to the combined effect of strain hardening and tempering. However, as we move into the DRZ, the hardness decreases. Partial recrystallization affects the
strain hardening. As the recrystallization effect increases due to friction heating, the hardness decreases at the same time. This recrystallization ratio reaches a maximum in the DRZ. For this reason, the finer grains were obtained in the DRZ. Although the DRZ has finer grains, the hardness of this region is the lowest. The recrystallized grains had the lowest hardness since these grains are free of strain hardening and tempering effects.

Energy dispersive x-ray spectroscopy (EDS) is a useful technique to characterize the phases in the microstructure. Figure 5 and Table 3 show line and point EDS measurements from the TMAZ. The line EDS measurements were taken from intergranular formations. As seen from the figure, there are some Mg, Cu and Si responses. While the first EDS measurement point exhibited a Si response, 0.04% of the Si from the second EDS measurement was obtained. The content of the first EDS point can be attributed to the presence of $\text{Al}_2\text{Cu} + \text{Al}_2\text{Mg}_3 + \text{Mg}_2\text{Si}$ or $\text{Al(CuMgSi)}$ phases. On the other hand, the second EDS result reflects a clear indication of $\text{Al}_2\text{CuMg}$ (S phase) phase. The S-phase existed the intergranular regions in TMAZ and HAZ. As well as the coarse S phase, the solid-solution clusters that converted into the GPB zones increase the hardness of the HAZ. Due to severe plastic flow and heating, the S phases and GBP zones are coarsened in the TMAZ. The natural aging is the main driving force for the coarsening effect. However, the hardness near the DRZ and in the DRZ decreased since the S-phases and GBP zones are dissolved in the microstructure due to the recrystallization effect. Similar results were also obtained by various researchers. It was reported that the S phases are generally at intergranular locations in the TMAZ. Due to the recrystallization effect stemmed from friction heating, the S phase is dissolved in the grains.

Geng noted that the $\text{Al}_2\text{CuMg}$ (S) and $\text{Al}_2\text{Cu}$ phases are present in the HAZ and TMAZ. These phases are dissolved in the Al matrix of the DMZ due to the heating effect.

4 CONCLUSIONS

In this work, AA2024 aluminium rods were successfully welded with the rotary-friction-welding technique. According to the results, following conclusions can be drawn:

- Friction increased the severity of the heat input in the HAZ and TMAZ, causing wide, brittle regions. These wide HAZ and TMAZ resulted in less tensile strength. Therefore, the forging pressure has an adverse effect on the tensile strength of the RFW specimens.
- Increasing the friction pressure elevated the hardness, especially in the TMAZ region. Brittleness in the DRZ, HAZ and TMAZ caused a local loss of ductility. For this reason, the elongation at break and the failure energy tend to decrease at high friction pressures.
- The $\text{Al}_2\text{CuMgSi}$ and $\text{Al}_2\text{CuMg}$ phases are present in the microstructure. $\text{Al}_2\text{CuMg}$ plays an important role in the strengthening mechanism. These phases precipitated at intergranular locations.
- The amount of $\text{Al}_2\text{CuMg}$ and other natural aging phases tend to increase near to the DRZ due to the heating effect. Also, the maximum hardness is generally obtained in the TMAZ. However, the hardness is suddenly decreased due to the recrystallization effect induced by welding heat. During recrystallization, the secondary phases are dissolved in the solid solution.
- Since the newly recrystallized grains have a minimum amount of precipitation phases, the lowest hardness is obtained at the DRZ. The main reason for fail-
ure from the DRZ in tensile specimens can be attributed to this softening effect.

5 REFERENCES


