Study of microstructure and tensile properties of infrared-heat-treated cast-forged 6082 aluminum alloy

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ABSTRACT
In this study, a cast rod is used as the material for the forging process (without extrusion). The cast forging process is used to ameliorate the coarse grains that form in the follow-up heating process of extrusion-forged materials. Infrared (IR) heating is also used for comparison with conventional heating processes. Experimental results show that the direct forging process (without extrusion) suppress coarse grain formation and that IR heating can improve the mechanical properties of cast- and extrusion-forged materials. IR heating also enhances the tensile properties of forged materials.

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1. Introduction

6082 aluminum alloy is attractive due to its light weight, high strength, and corrosion resistance. It is an Al-Mg-Si alloy with high silicon content. 6082 is widely used for car components to replace steel. For example, Birol reported that the mobile cantilever/suspension hanging parts of a steering system are usually made from 6xxx series aluminum alloys [1].

Most forging processes use an extruded aluminum rod (with a size suitable for the forging process). However, a lot of strain is induced in the material during the extrusion process and coarse grains form during post-heating processes, decreasing the reliability and affecting the characteristics of surface treatment. Birol [2] found that extruded 6082 aluminum alloy after heat treatment formed a coarse-grain ring along the edge of extruded bar. Lee et al. [3] investigated the influence of deformation strain rate on Al6061 aluminum alloy, and found that a higher deformation strain rate led to a higher grain growth rate in the subsequent heat treatment. Kwon et al. [4] reported that some coarse grains formed inside an aluminum alloy after the forging process; these grains influenced reliability. For age-hardening aluminum alloys, heating is used to control the mechanical properties and grain size of the aluminum alloys. The heating process includes solution treatment, water quenching, and an aging process. The main goal of solution treatment is to dissolve the second phases into the matrix and form super-saturated solution solutes. The main strength phase forms in the following heat treatment process. These types of precipitates are discussed extensively in the papers of Zhen et al. [5] and Marioara et al. [6]. Hence, in the present study, an as-cast aluminum rod is
used as the material for the forging process (without extrusion) to avoid coarse grain formation which happened in the subsequent heat treatment.

Atmosphere heating stoves and forced ventilation furnaces are commonly used for heating. These conventional heating methods do not produce uniform temperatures, and thus lead to large variation in mechanical properties. And the local heating design is difficult for the conventional heating methods, too.

The goals of next-generation heating technologies are to reduce emissions and increase heat transfer efficiency. In the present study, infrared (IR) heating is used in addition to conventional heating.

IR heat treatment methods are used for drying and heating aluminum materials. Kadolkar et al. [7] used IR heating to heat an AA2618 billet, and proved the high efficiency of this method. However, the effects of IR heating on cast-forged (CF) and extrusion-forged (EF) materials has not been investigated. In the present study, IR heat treatment was used to study the difference between CF and EF 6082 aluminum alloy, and to clarify the effect of coarse grain formation on material characteristics and to assess the relationship between casting segregation and forging. The results can be used as a reference for industrial applications.

### Table 1 – Chemical composition (wt.%) of 6082 aluminum alloy.

<table>
<thead>
<tr>
<th>Element</th>
<th>Mg</th>
<th>Si</th>
<th>Cu</th>
<th>Mn</th>
<th>Cr</th>
<th>Fe</th>
<th>Al</th>
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</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>0.82</td>
<td>1.2</td>
<td>0.07</td>
<td>0.9</td>
<td>0.16</td>
<td>0.18</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

### Table 2 – Experimental parameters and specimen codes.

<table>
<thead>
<tr>
<th>Sample condition</th>
<th>Heating method</th>
<th>Solution treatment</th>
<th>Artificial aging</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion + forging</td>
<td>Air furnace</td>
<td>560 °C, 2 h</td>
<td>170 °C, 8 h</td>
<td>EF170</td>
</tr>
<tr>
<td>Air furnace</td>
<td>560 °C, 2 h</td>
<td>180 °C, 8 h</td>
<td>EF180</td>
<td></td>
</tr>
<tr>
<td>Air furnace</td>
<td>560 °C, 2 h</td>
<td>190 °C, 8 h</td>
<td>EF190</td>
<td></td>
</tr>
<tr>
<td>Infrared</td>
<td>560 °C, 30 min</td>
<td>180 °C, 6 h</td>
<td>EFIR</td>
<td></td>
</tr>
<tr>
<td>Casting + forging</td>
<td>Air furnace</td>
<td>560 °C, 2 h</td>
<td>170 °C, 8 h</td>
<td>CF170</td>
</tr>
<tr>
<td>Air furnace</td>
<td>560 °C, 2 h</td>
<td>180 °C, 8 h</td>
<td>CF180</td>
<td></td>
</tr>
<tr>
<td>Air furnace</td>
<td>560 °C, 2 h</td>
<td>190 °C, 8 h</td>
<td>CF190</td>
<td></td>
</tr>
<tr>
<td>Infrared</td>
<td>560 °C, 30 min</td>
<td>180 °C, 6 h</td>
<td>CFIR</td>
<td></td>
</tr>
</tbody>
</table>

2. Experiments

The properties of CF and EF specimens after heat treatment were investigated. A 6082 car cantilever was used as the study material. Its chemical composition is shown in Table 1. The forged parts were produced through the 40 mm diameter × 335 mm cylinder extruded bar and cast cylinder.

Forged parts were heat using conventional heat treatment and IR heat treatment, respectively. Conventional heat treatment included air furnace heat treatment at 560 °C for 2 h, followed by water quenching, and then artificial aging heat treatment in the air furnace (180 °C, 8 h). Due to its strong penetration ability, IR heating needed only 30 min for solution heat treatment (at 560 °C), which was followed by water quenching and an aging process (180 °C, 8 h). The experimental parameters and codes are shown in Table 2.

Fig. 1 shows a photograph of forged parts and a diagram of a tensile test rod sample. Microstructures and the distribution of second phases were observed using optical microscopy (OM, OLYMPUS BX41M-LED) and the SEM (HITACHI SU-5000) equipped with an energy dispersive spectrometer (EDS).

The samples were ground using SiC sandpaper, and then polished with 1- and 0.3- μm alumina powder. Each heat-treated sample was etched with Keller’s reagent and KMnO₄ and then observed with an optical microscope.

Rockwell-B hardness (HRB) tests were conducted using a 1.59 × 10⁻³ m steel ball as the test head and a pressure load of
100 kgf. The tensile test was performed using a universal testing machine. A stretching rate of 5 mm/min was used. Fig. 2 shows a photograph of broken specimens after the tensile test.

3. Results

Fig. 3 shows the hardness results of CF and EF specimens after various heat treatments. The hardness values of CF specimens are higher than those of EF specimens. Higher hardness was obtained by IR heat treatment, which means that the segregation of the cast and the dendritic crystals contributed to the hardness. Fig. 4(a) shows the second phase distribution of an EF specimen. The second phase particles are evenly distributed in the matrix. The dark second phases are Al-Mg-Si phases, and the light second phases are Al(FeMnCr)Si phases. Fig. 4(b) shows the second phase distribution of an EF specimen after conventional heat treatment (EF180). The dark second phases are significantly reduced due to the solution treatment effect. Fig. 4(c) shows the second phase distribution of an EF specimen after IR heat treatment (EFIR). The dark second phases are significantly reduced. This shows that with 30 min of IR heat treatment, the Al-Mg-Si second phases dissolved. Fig. 4(d) shows the distribution of the second phases of a CF specimen. The second phase particles are evenly distributed in the matrix. Dendritic crystals, which were originally in the castings, became redistributed and fined during the forging process. Fig. 4(e) shows the second phase distribution of the CF specimen after conventional heat treatment (CF180). The dark second phases are significantly reduced, indicating that the second phase particles not subjected to the extrusion process were solidified into the matrix. Fig. 4(f) shows the second phase distribution of CFIR. The dark second phases are significantly reduced, indicating that the second phases of the CF specimen dissolved into the matrix even with short IR heat treatment.

Fig. 5 and Table 3 show the results of SEM observation and EDX analysis. On the EF and CF specimens (Fig. 5(a) and (b)), there are two kinds of intermetallic compounds that could be distinguished, the gray ones and black ones, according to the EDX analysis, the gray ones are AlFe(MnCr)Si intermetallic compounds and the black ones are Al-Mg-Si intermetallic compounds. On the EF180 and CF180 specimens (Fig. 5(c) and (d)), shows that after the conventional heat treatment, Al-Mg-Si dissolved into the aluminum matrix and AlFe(MnCr)Si remained. On EFIR and CFIR specimens (Fig. 5(e) and (f)), shows that the Al-Mg-Si could also be dissolved into the aluminum matrix after IR heat treatment. Fig. 6(a–f) shows the microstructure features of samples with various heat treatments. Fig. 6(a–f) shows magnified views and the grain size of Fig. 6(a–f). In Fig. 6(a–f), lots of small grains can be observed, and these grains were formed during the hot work process (extrusion and forging), and grain growth in the following heat treatment, which means that these small grains were dynamic recrystallization grains. Fig. 7(a) reveals the microstructure...
Fig. 4 – Microstructure features of various heat-treated specimens.

Fig. 5 – SEM observation results of various heat-treated specimens, the intermetallic compounds of EF and CF could be reduced after air/IR heating treatment.

Table 3 – Energy dispersive spectrometer (EDS) analysis results for examined specimens, as shown in Fig. 5.

<table>
<thead>
<tr>
<th>at.%</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.01</td>
<td>5.01</td>
<td>2.11</td>
<td>4.79</td>
<td>0.01</td>
<td>1.30</td>
<td>3.59</td>
<td>4.58</td>
</tr>
<tr>
<td>Cu</td>
<td>0.12</td>
<td>0.20</td>
<td>0.24</td>
<td>0.70</td>
<td>0.39</td>
<td>0.53</td>
<td>0.24</td>
<td>0.45</td>
</tr>
<tr>
<td>Mg</td>
<td>48.42</td>
<td>0.83</td>
<td>1.87</td>
<td>1.49</td>
<td>16.18</td>
<td>1.46</td>
<td>1.23</td>
<td>1.50</td>
</tr>
<tr>
<td>Al</td>
<td>27.35</td>
<td>71.08</td>
<td>74.37</td>
<td>74.54</td>
<td>62.01</td>
<td>69.49</td>
<td>73.73</td>
<td>68.22</td>
</tr>
<tr>
<td>Cr</td>
<td>1.91</td>
<td>2.92</td>
<td>3.26</td>
<td>1.59</td>
<td>2.44</td>
<td>4.12</td>
<td>3.46</td>
<td>2.25</td>
</tr>
<tr>
<td>Mn</td>
<td>1.22</td>
<td>10.15</td>
<td>10.97</td>
<td>9.27</td>
<td>2.00</td>
<td>12.03</td>
<td>8.61</td>
<td>14.27</td>
</tr>
</tbody>
</table>

feature of EF specimen, fine grains are evenly distributed in the matrix, and the grain size of EF is $d = 6.3 \pm 2.2 \mu m$. Grain growth happened after the conventional heat treatment, and some grain became coarse, the grain size in the EF180 is $d = 8.1 \pm 3.26 \mu m$ and $d = 55.2 \pm 6.2 \mu m$ (Fig. 7(b)). Fig. 7(c) reveals the microstructure feature of EFIR specimen, the grain size of EFIR is $d = 6.8 \pm 2.7 \mu m$, the grain size of EFIR is relatively small to the FE180. Fig. 7(d) shows the microstructural features of a CF specimen. A lot of dynamic recrystallization occurred in the matrix, the grain size of the CF specimen is $d = 5.8 \pm 1.3 \mu m$. After conventional heat treatment, these
fine grains did not become coarse, remaining small (CF180, Fig. 7(e)), and the grain size of the CF180 is $\bar{d} = 7.4 \pm 2.6 \mu m$. Furthermore, after IR heat treatment process (CFIR), dynamic recrystallization grains were still small, the grain size of CFIR is $\bar{d} = 6.3 \pm 2.0 \mu m$. From XRD results (shown in Fig. 8) confirmed the Al-Mg-Si and AlFe(MnCr)Si phases exist on both CF and EF specimens, and after conventional heat treatment and IR heat treatment, Al-Mg-Si phases disappeared.

Fig. 9 shows the tensile curve of EFIR and CFIR specimens. The Young’s modulus values are similar (EFIR: 80.2, CFIR: 74.2), but CFIR showed better ductility. Fig. 10 shows the tensile test results of EFIR and CFIR specimens. The tensile strength of CFIR is close to that of EFIR (>370 MPa). There was little material variability (Fig. 10(a)). The elongation test shows that direct forging (without extrusion) produced samples with better ductility (Fig. 10(b)).
4. Discussion

In this study, the properties of EF and CF (without extrusion) materials were investigated and compared. According to Hu et al. [8], a casting 6082 alloy contains Cr-containing dispersoids, Mn-containing dispersoids, an Al-Mg-Si phase (e.g., β'-Mg-Si), and β-AlFeSi. Lodgaard and Ryum et al. [9] reported that β-AlFeSi converted into α-Al(FeMnCr)Si in the subsequent high-temperature heat treatment (annealing or homogenization), and in this study, comparing the results of OM, SEM, EDS and XRD analysis, AlFe(MnCr)Si and Al-Mg-Si intermetallic compounds can be observed on both CF and EF specimens. Previous reports have confirmed that it is hard to distinguish the specific composition of AlFe(MnCr)Si and Al-Mg-Si of the 6082 aluminum alloy [10–12], and Lise Dons et al. found that both second phases enhanced material strength [13]. In this study, the hardness results show the hardness of CF is higher than EF, therefore, it is suitable to suggest that the direct forging process can reduce the consumption of the intermetallic compounds with enhanced effect. After convention heat treatment and IR heat treatment, the dissolution of Al-Mg-Si intermetallic compounds into the aluminum matrix could be observed. In this study, the results also show that CF specimens had higher tensile ductility than EF specimens, while retaining a small grain size. This can be explained as follows. The CF specimen showed higher hardness as a result of the segregation effect. Birol [1] studied the grain structure of extruded 6082 and found that the addition of chromium to Al-Mg-Si alloy led to grain boundary pinning that suppressed grain growth. Similar effects were found for manganese-containing aluminum alloy [8]. In the present study, CF specimens after conventional heat treatment did not show significant grain growth, so it could be reasonably speculated that chromium and manganese were in a dispersed phase (not Al(FeMnCr)Si), inhibiting grain growth. Based on the above findings, the relationship between forging process and microstructure is plotted in Fig. 11. In the tensile test, CF specimens showed lower fluctuation than EF specimens, and had similar tensile strength and ductility. It is presumed that Mg-Si precipitated to allow uniform nucleation of chromium and manganese during heat treatment, enhancing material strength and increasing uniform deformation. In addition, the low variability and good ductility could improve reliability and increase fatigue resistance [4].
5. Conclusion

In this study, a cast cylinder was directly used as the forging process material (without extrusion) and subjected to IR heat treatment. The following findings were obtained:

1. Comparing with the extrusion-forging 6082 aluminum alloy, using direct forging process (without extrusion) can suppress the grain growth which happened during the solution heat treatment.
2. Using IR heat treatment to dissolve the Al-Mg-Si intermetallic phases into the 6082 aluminum matrix is workable, and maintains the same final hardness as the conventional heat treatment.
3. Cast forging with IR heating process enhanced the elongation of 6082 aluminum alloy.

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Conflicts of interest

The authors declare no conflicts of interest.

References


