The Deformational Behaviour and Microstructural Evolution of Al-Sc-Zr Alloys with Different Copper Content under High Strain Rate Impact Loading

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Keywords: copper, Al-Sc-Zr alloy, temperature, strain rate effect, dimple, dislocation

ABSTRACT

This study investigates the dynamic mechanical property of three high strength Al-Sc-Zr alloys with different Cu content over a temperature range of −150°C to 300°C, and at strain rates of 2.0×10³ s⁻¹, 4.0×10³ s⁻¹ and 6.0×10³ s⁻¹ using a Split-Hopkinson pressure bar. The effects of strain rate and temperature on the impact behaviour, evolution of the microstructure and fracture properties are studied. The results show that Al-Sc-Zr alloys with higher Cu content have greater strength. Fractographic SEM observations show that the fracture surfaces have a characteristic dimple-like structure. Observations of the microstructure show that the dislocation density increases with increasing strain rate and strain. TEM observations of the microstructure reveal that the presence of Al₃(Sc, Zr) precipitate in the matrix and grain boundaries can retard dislocation movement and result in significant strengthening effect on the mechanical response.

INTRODUCTION

Traditional aluminium alloys have a high strength/weight ratio and are used extensively in the aerospace and automobile industries. The strength of an aluminum alloy is often enhanced by adding small amounts of Copper Magnesium, Zinc, and Manganese. It has recently been shown that the addition of Scandium (Sc) and Zirconium (Zr) yields a remarkable improvement in both the mechanical strength and the weldability of aluminum alloys as a result of a grain refinement effect, an improved resistance to recrystallization and a reduction in the tendency of the alloy towards hot-cracking (Norman et al., 1998). The addition of Sc and Zr allows the aluminum alloy matrix to form ordered L₁₂ structural Al₃(Sc, Zr) phases, which are coherent with the Al matrix. Furthermore, the addition of copper to aluminum alloys can also increase their stress corrosion resistance (Paglia et al., 2006) and gives aluminum alloys high specific strength and fracture toughness. Alloys of this kind find extensive use in commercial aircraft. But the Cu additives in an Al alloy also make it highly susceptible to hot weld cracks and it may become unweldable. However, some previous research has shown that Al₃(Sc, Zr) precipitates can become coherent with the aluminum matrix, and their addition can lead to a significant reduction in hot cracking during welding and inhibition of grain growth. Therefore, in the present study, we investigate the effect of Cu content on the dynamic mechanical properties and microstructural evolution of Al-Sc-Zr alloy.

Structural engineering components are invariably exposed to many different rates of strain and loading in manufacture or subsequent service life. It is necessary to acquire full details of their dynamic mechanical properties and microstructural characteristics under high strain rate conditions. Although there has been much work done on the fundamental properties of Al-(Cu)-Sc-Zr alloys, that includes hardening mechanisms (Torma et al., 1989), tensile properties (Roder et al., 1996), recrystallization (Riddle ey al.,
2004) and weldability (Lukin, 1996) there have not been many studies made of the effect of Cu content on the dynamic mechanical response of Al-Sc-Zr alloys. Accordingly, a Split-Hopkinson pressure bar was used in the current study to investigate the dynamic mechanical property and microstructural evolution of Al-Sc-Zr alloys with three different Cu content at strain rates of $2.0 \times 10^3 \text{s}^{-1}$, $4.0 \times 10^3 \text{s}^{-1}$ and $6.0 \times 10^3 \text{s}^{-1}$ at -150°C, 25°C and 300°C respectively. Finally, based on observations of the microstructural evolution, the relationship between mechanical response and the microstructure of the Al-Sc-Zr alloy with different copper content is determined and discussed.

**EXPERIMENTAL PROCEDURE AND MATERIAL PREPARATION**

Bars of Al-Sc-Zr alloy with different Cu content were provided by the Taiwan Hodaka Technology Co Ltd. The chemical composition of the Al-Sc-Zr-(Cu) alloys was determined by glow discharge spectrometry (GDS) and is shown in Table 1. The dynamic impact deformation experiments were conducted at temperatures of -150°C, 25°C and 300°C under strain rates of $2.0 \times 10^3 \text{s}^{-1}$, $4.0 \times 10^3 \text{s}^{-1}$ and $6.0 \times 10^3 \text{s}^{-1}$ with a Split-Hopkinson compression device. Details of the test configuration and measurement technique used were presented in a previous study by Lee et al. (2006) After dynamic testing, the fracture feature analyses were carried out using a standard metallographic technique and examined using a JEOL TEM-3010 Transmission Electron Microscope (TEM) operating at 15kV. The microstructure of the deformed specimens was examined using a JEOL TEM-3010 Transmission Electron Microscope (TEM) operating at 200kV. The specimens for TEM observation were prepared by cutting 350µm slices from the deformed specimens which were then thinned and twin-jet polished using a solution of 30% nitric acid in 70% methanol at 15V and -30°C.

![Stress-Strain Curve Relationship](image)

**Table 1** Chemical composition of the Al-Sc-Zr alloys with different Cu content.

<table>
<thead>
<tr>
<th>Element (wt.%)</th>
<th>Zn</th>
<th>Mg</th>
<th>Cu</th>
<th>Sc</th>
<th>Zr</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Sc-Zr—1</td>
<td>6.9</td>
<td>2.1</td>
<td>0.13</td>
<td>0.13</td>
<td>Balance</td>
<td></td>
</tr>
<tr>
<td>Al-Sc-Zr—2</td>
<td>6.9</td>
<td>2.1</td>
<td>0.3</td>
<td>0.13</td>
<td>0.13</td>
<td>Balance</td>
</tr>
<tr>
<td>Al-Sc-Zr—3</td>
<td>6.9</td>
<td>2.1</td>
<td>1.2</td>
<td>0.13</td>
<td>0.13</td>
<td>Balance</td>
</tr>
</tbody>
</table>

**Stress-Strain Curve Relationship**

Fig. 1(a) shows the true stress-strain curves for Al-Sc-Zr alloy with 1.2% Cu content deformed at strain rates of $2.0 \times 10^3 \text{s}^{-1}$, $4.0 \times 10^3 \text{s}^{-1}$ and $6.0 \times 10^3 \text{s}^{-1}$ at a temperature of -150°C, 25°C and 300°C respectively. It can be seen that the flow stress of the Al-Sc-Zr-1.2Cu alloy increases with strain rate and strain, but decreases with a rise in temperature. Fracture occurs under all loading conditions except at 300°C. Results obtained for Al-Sc-Zr-0.3Cu and Al-Sc-Zr-0Cu, as shown in Fig. 1(b) and 1(c), respectively. A comparison of the true stress-strain curves for these Al-Sc-Zr alloys deformed at a strain rate of $6.0 \times 10^3 \text{s}^{-1}$ at -150°C, 25°C and 300°C is shown in Fig. 1(d). The alloy with the highest Cu content has the highest flow stress. It is clear that the flow stress of Al-Sc-Zr alloys containing Cu is higher than those without Cu within the same temperature and strain rate range.
strain rate sensitivity decreases as the deformation temperature is increased. However, the activation energy decreases with an increase in flow stress, but increases with a rise in temperature. Fractographic observations have revealed that the fracture surfaces of the three Al-Sc-Zr alloys with and without copper have a characteristic dimpled transgranular structure, which implies that the specimens fail in a ductile model. The TEM observations have revealed that the dislocation density increases with increasing strain rate, but decreases with increasing temperature. At elevated temperature, a rapid annihilation of the dislocations occurs and there is a homogeneous distribution of $\text{Al}_3\text{Sc}$ precipitate within the matrix even under high strain rates. In addition, the coherent precipitate of $\text{Al}_2\text{Cu}$ present in the Al-Sc-Zr alloy with higher Cu concentration can have a significant strengthening effect on the material.

ACKNOWLEDGMENT

This work was supported by National Science Council (NSC) of Taiwan under contract no. NSC 99-2218-E-151-006-MY2, which is gratefully acknowledged.

REFERENCES

應變速率及測試溫度對 Al-Sc-Zr 合金的巨觀機械性質反應及析出物、晶粒細化與差排等顯微結構之影響