Deformation-Induced Large Ductility of Super Saturated Solid Solution Fe-Cu Alloy

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ABSTRACT

The mechanical properties of super saturated solid solution Fe_{60}Cu_{40} alloy have been investigated using compression test. The results show that the grain precipitation and phase transformation occurs during compressive deformation resulting in large work-hardening ability, high strength and large ductility. Our results demonstrate that this novel architecture offers a design pathway towards a new generation of strong materials with large ductility.

Keywords: Fe-Cu Alloy, Super Solid Solution, Precipitation, Phase Transform, Ductility

1. Introduction

Strength and ductility are of the most important mechanical properties of structural materials. However, they are often difficult to obtain the high strong and large ductility simultaneously [1,2]. Generally, the low ductility of materials is attributed to the lack of work hardening caused by their inability to accumulate dislocations [3]. Therefore, the basic idea to improve the ductility of materials is to regain the work hardening (dislocation accumulation capability), which is often accompanied with sacrifice of strength. Classical methods for strengthening materials contain solid solution, dislocation, grain boundary and so on [4]. The solid solution strength metals are to alloy them with elements that are dissolved in the crystal lattice and form a solid solution. Such atoms elastically distort the crystal and can thus interact with the stress field of a dislocation and impede its movement, which results in high strength [5]. On the other hand, large numbers of reports indicated precipitate and phase transformation are also beneficial to improve the ductility during deformation of alloys. Kim showed that certain size of precipitate can improve the hardness and work hardening ability of the materials [6]. Their excellent mechanical properties result from the martensitic transformation of metastable retained austenite, induced by thermomechanical loading [7,8].

Dendrite composite immiscible Fe_{60}Cu_{40} alloy has been prepared successfully by combustion synthesis technique (CS) [9]. By controlling the applied pressure, the different super saturated solid solution Fe_{60}Cu_{40} alloys have been obtained. Especially, there are not large composite segregation both in dendrite and matrix. In this paper, we examined the mechanical properties of this special alloy under compression test. The results show that the nano-scale precipitation and phase transformation occurs during compressive deformation resulting in large work-hardening ability and high strength. Our results demonstrate that this novel architecture offers a design pathway towards both strong and ductility materials.

2. Experimental

The Fe_{60}Cu_{40} alloy has been prepared successfully by CS [9]. In this paper, the Fe_{60}Cu_{40} alloys with different microstructure have been produced by CS under different applied pressure with 8, 6 and 4 MPa of argon gas, which indicated as FC_{8}, FC_{6} and FC_{4}, respectively. Morphologies and compositions of the Fe_{60}Cu_{40} alloys were examined using a JSM-5600LV scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDS, Kevek, USA). Cylindrical compressive specimens with length of 4.5 mm and a diameter of 2.8 mm were cut using an electro-discharging machine, and both ends of the compressive specimens were polished to mirror surfaces, and coated with graphite before tests to reduce the interfacial friction. Quasi-static uniaxial compression test were performed at room temperature using a testing machine with a crosshead speed of 3.5 × 10^{-3} s^{-1}. The before and after compression test samples were in-
investigated with X-ray diffractometry (XRD, Philips X'pert) using CuKα radiation. The cross sections of fractured Fe₆₀Cu₄₀ alloys were also analyzed by the SEM.

3. Results

The typical compressive engineering stress-strain curves of the Fe₆₀Cu₄₀ alloys are compared in Figure 1. The yield strength $\sigma_y$, ultimate fracture strength $\sigma_{\text{max}}$, fractured strain $\varepsilon_f$ are also given in table inset of Figure 1. The yield strengths of the FC₈, FC₆, and FC₄ samples are 520 MPa, 900 MPa, and 790 MPa, respectively, which are higher than that of commercial crystalline Cu-Fe alloys [10]. The highest yield strength is obtained with applied pressure 6 MPa. As shown, the uniform elongation of the FC₈ and FC₄ are only 4% to 5%. In contrast, the uniform elongation of the FC₆ reaches about 20%. It is more than fourfold that of the nanostructured sample and above the critical ductility required for many structural applications. The ductility of the FC₆ enhances because of an improved work-hardening rate. The strong working hardening allows uniform deformation, and leads to a fast climbing curve in the compression test, which is different with most nanos-structured metals and alloys that show plunging curves peaking very early in plastic deformation [1]. So, the strain to failure reaches 30% in the compression.

![Stress-strain curve](image)

Figure 1. Compressive engineering stress-strain curves of the Fe₆₀Cu₄₀ alloy. Table of inset is the yield strength $\sigma_y$, ultimate fracture strength $\sigma_{\text{max}}$, fractured strain $\varepsilon_f$ of the Fe₆₀Cu₄₀ alloys.

<table>
<thead>
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<th></th>
<th>FC₈</th>
<th>FC₆</th>
<th>FC₄</th>
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<tbody>
<tr>
<td>dendrite</td>
<td>520</td>
<td>740</td>
<td>1100</td>
</tr>
<tr>
<td>matrix</td>
<td>900</td>
<td>1330</td>
<td>1100</td>
</tr>
<tr>
<td>$\varepsilon_f$ (%)</td>
<td>12</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 1. Composition of the Fe₆₀Cu₄₀ alloys.

<table>
<thead>
<tr>
<th></th>
<th>FC₈</th>
<th>FC₆</th>
<th>FC₄</th>
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<tbody>
<tr>
<td>dendrite</td>
<td>15.4</td>
<td>16.1</td>
<td>20.0</td>
</tr>
<tr>
<td>matrix</td>
<td>75.5</td>
<td>64.4</td>
<td>56.6</td>
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<tr>
<td>Cu</td>
<td>84.6</td>
<td>83.9</td>
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<tr>
<td>Fe</td>
<td>24.5</td>
<td>35.6</td>
<td>43.4</td>
</tr>
</tbody>
</table>

Figure 2. SEM images of the Fe₆₀Cu₄₀ alloys, (a) 8 MPa, (b) 6 MPa, (c) 4 MPa.
Figure 3 shows the XRD pattern of Fe₆₀Cu₄₀ alloys before and after compressive deformation. All the FC₆, FC₄, and FC₈ before and after compressive deformation contain the ε-Cu-rich and the α-Fe-rich phases. The diffraction peak γ-Fe-rich phase changes weak as the applied pressure decreases, and the γ-Fe-rich phase has not been examined using XRD when the applied pressure decreases to 4 MPa. However, the γ-Fe structure occurs after FC₄ deformation. Another impressively characterization is that the diffraction peaks of the ε-Cu-rich structure shift towards higher angles and γ-Fe-rich towards lower angle after Fe₆₀Cu₄₀ alloys deformation. It means that the solid solution of the ε-Cu-rich and γ-Fe-rich in Fe₆₀Cu₄₀ alloys decreases after the compressive deformation. It is to be noted that FC₆ has the highest ratio of ε-Cu-rich to γ-Fe-rich (defined as ratio of diffraction peaks).

The fractography of the Fe₆₀Cu₄₀ alloys is shown in Figure 4. The intergranular fracture feature has been observed in the fractured surface of the FC₆ (Figure 4(a)). The crack occurs along the dendrite axis because of the stress concentration in soft matrix in the compressive deformation. Some of the dendrite axis cracked when the stress concentration increases to the critical value, such as the zone of III. The Figure 4(b), (c) and (d) are magnification of the I, II and III of the Figure 4(a), respectively. Far from the fractured dendrite axis (II), more precipitations occur, and lots of dimples has been observed with grain size of ultrafine scale comparing with the precipitation. The visible melt traces (Figure 4(d)) are regarded as matrix (melt pointing is about 1000°C) because the local temperature maybe is higher 1000°C the local stress concentration as the sample fractures. The dimples indicate good working harden of the FC₆. The super saturated solid solution of the FC₄ with Cu(Fe) and Fe(Cu) is close to the FC₆. Thus, the yield strength reaches 790 MPa, is near the yield strength of the FC₆ (900 MPa). However, the local stress concentration of the FC₄ is smaller than that of the FC₆, because the dendrite axis of the FC₄ is coarse and short compared with the FC₆. So, the working harden is decreases even the negative value. For the FC₈, owing to the smaller dendrite axis and smaller solid solution, the strength and ductility are smaller than that of the FC₆.

4. Conclusions

In this paper, the bulk immiscible Fe₆₀Cu₄₀ alloy is successfully prepared by a combustion synthesis technique. The Fe₆₀Cu₄₀ alloy is composed of Fe-rich dendritic embedded in Cu-rich matrix uniformly. The content of the dendrite and matrix are 34.5% and 65.5%, respectively. The grain size of matrix is about 30 nm. Owing to the very high superheating (4700°C) of combustion synthesis, the deeply undercooling is obtained, resulting there no large-scaled phase separation into Cu-rich and Fe-rich phases.
REFERENCES


