Mechanical properties of recrystallized L1<sub>2</sub>-type Ni<sub>3</sub>(Si, Ti) intermetallics

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The mechanical properties of the Ni<sub>3</sub>(Si, Ti) alloys undoped and doped with 50 p.p.m. boron, both of which were polycrystalline specimens prepared by recrystallization, were investigated by tensile testing. The yield stress was found to increase with increasing test temperature to a maximum at 800 K, followed by a decrease. The tensile elongation was highest at room temperature and tended to decrease with increasing temperature for both alloys, but was consistently higher in the boron-doped Ni<sub>3</sub>(Si, Ti) alloys than in the undoped ones over all the test temperatures. The change in the ultimate tensile stress (UTS) with temperature was similar to that of tensile elongation. The transgranular fracture became dominant as the elongation increased, regardless of the alloys and the testing temperature. Thus, this work again verified that the alloying method proposed by the present authors is useful for improving the grain-boundary cohesion of L1<sub>2</sub>-type ordered alloys.

1. Introduction

The Ni<sub>3</sub>Si alloy is known to increase its strength with increasing temperature [1], and has excellent corrosion and oxidation resistance at ambient and elevated temperatures. However, this alloy suffers from grain-boundary brittleness similar to the Ni<sub>3</sub>A1 alloy. The addition of boron to improve the ductility of this alloy has been unsuccessful.

In a previous paper [2] in which the metallographic and structural analyses for L1<sub>2</sub>-type Ni-Si-Ti ternary alloy were performed, it was found that the alloying element, titanium, substitutes for elemental silicon and also was greatly soluble in the Ni<sub>3</sub>Si alloy. The mechanical properties of the Ni<sub>3</sub>Si alloyed with elemental titanium were investigated in their polycrystalline form [3]. Consequently, some useful results were introduced by this alloying [3]; the yield stress increased with increasing titanium concentration at all testing temperatures. Also, the peak temperature in the yield stress–temperature curve increased with increasing titanium concentration. The most striking result was that the ductility was established by the addition of elemental titanium. The higher elongation values were observed in the alloys consisting of higher titanium and higher nickel concentrations. Further improvement of the tensile elongation was found by the addition of a small amount of boron. The variation of the elongation with temperature showed a peak at intermediate temperatures. The ductility of the Ni<sub>3</sub>Si alloys observed in the previous work [3] verified the alloying principle to improve the grain-boundary cohesion of L1<sub>2</sub>-type ordered alloys which has recently been proposed by the present authors [4–7]; it was demonstrated that a replacement of X (= b sub-group element in the periodic table) with T (= mostly transition metals) in the Ni<sub>3</sub>X alloy reduces the difference in the electrochemical bonding nature, resulting in a lowering of the propensity for grain-boundary fracture and improving the ductility in the Ni<sub>3</sub>X alloys.

The main purpose of this work was to determine whether the change in the mechanical properties of Ni<sub>3</sub>Si alloys on the addition of elemental titanium was due to the microstructural effect or to the alloying effect itself. For this purpose, the Ni<sub>3</sub>(Si, Ti) alloys and the Ni<sub>3</sub>(Si, Ti) alloys doped with a small amount of boron were prepared in the recrystallized form. Their mechanical properties were observed by tensile test over a wide range of test temperatures, and also correlated with the fractographic observation.

2. Experimental procedure

The alloys were prepared by nonconsumable arc melting in an argon atmosphere. Nickel, 99.9 wt % purity, silicon, 99.999 wt % purity, and titanium sponge, 99.8 wt % purity, were used as starting materials. The nominal and analysed chemical compositions of the alloys used in this work are shown in Table I and the agreement between the two values was fairly good; the selected composition was 79.5 at. % Ni, 11 at. % Si and 9.5 at. % Ti (denoted Ni<sub>3</sub>(Si, Ti) alloy) and located in a single-phase region of the L1<sub>2</sub> structure as shown in Fig. 1 at which marked strengthening and ductility are expected [3]. Also, to improve the ductility further, the alloy consisting of this composition was doped with 50 p.p.m. boron using an Ni–10 wt % boron master alloy. The alloy buttons with dimensions approximately 15 mm × 15 mm × 80 mm were homogenized.
TABLE I Nominal and analysed values of chemical compositions for the alloys used in this work

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Nominal (analysed) chemical compositions</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Ni</td>
</tr>
<tr>
<td></td>
<td>(at. %)</td>
</tr>
<tr>
<td>Ni$_3$(Si, Ti)</td>
<td>79.5</td>
</tr>
<tr>
<td>Ni$_3$(Si, Ti) + 50 p.p.m. B</td>
<td>79.5</td>
</tr>
</tbody>
</table>

3. Results and discussion

3.1. Microstructure

Fig. 2 shows the optical microstructures of the Ni$_3$(Si, Ti) alloy (Fig. 2a) and the boron-doped Ni$_3$(Si, Ti) alloy (Fig. 2b). Both alloys exhibit apparently single-phase structure with the average grain size of approximately 50 μm. Figs 3 and 4 show the TEM bright-field images of both alloys. The Ni$_3$(Si, Ti) alloy again showed no second phases and relatively straight grain boundaries, as seen in a bright-field image (Fig. 3a), and also an indication of the ordered structure; i.e. the ordered spots as indicated in a selected-area diffraction pattern (Fig. 3b). On the other hand, the boron-doped Ni$_3$(Si, Ti) alloy showed second phases at the grain-boundary planes and/or at triple junctions of grain boundaries (Fig. 4a). Although structural and chemical analyses were not performed for these particles, it is likely that they are boride combined with the constituent atoms. Thus, it appears that the solubility limit of boron in the ternary Ni$_3$(Si, Ti) alloys is very low, i.e. below 50 p.p.m. (~ 0.03 at. %). This value is extremely low in comparison with that of the Ni$_3$Al alloy (i.e. between 1.5 and 2.0 at. % [8]).