The Mechanical Response of the Ni-Ni$_3$Nb Eutectic Composite: Part I. Monotonic Behavior

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To understand the mechanical behavior of the Ni-Ni$_3$Nb eutectic composite, it was necessary to determine the operative deformation and fracture mechanisms in the Ni$_3$Nb intermetallic phase. It was found that Ni$_3$Nb deforms primarily by twinning along {112} planes and {011} planes when tension and compression, respectively, are applied parallel to the [100] growth direction. The {112} twins were observed to serve as crack nucleation sites with cracks forming along the twin boundaries. The monotonic response of the Ni-Ni$_3$Nb eutectic composite was investigated with tension and compression tests, metallography, and electron fractography. Room temperature tensile testing of the Ni-Ni$_3$Nb composite revealed this material to be capable of sustaining tensile strains in excess of 11 pct. This large composite ductility was associated with extensive {112} twinning of the Ni$_3$Nb lamellae and subsequent twin boundary cracking. When amassed in sufficient numbers in a given cross-section, these {112} twin boundary fissures initiated composite rupture. The room temperature ultimate tensile and compressive strengths of the alloy were found to be 109 and 235 ksi, respectively.

The potential of eutectic composites as high strength structural members is well documented. However, most eutectic composite research has dealt with systems reinforced by ultrahigh-strength intermetallic phases which exhibit limited ductility. Since it would be desirable to develop composite systems with good ductility and toughness in addition to high strength levels, it is of interest to gain additional insight into the mechanical characteristics of the Ni-Ni$_3$Nb eutectic composite with its plastically deformable Ni$_3$Nb reinforcing phase.

In earlier studies, Quinn, Kraft and Hertzberg achieved high strength levels in the unidirectionally solidified Ni-Ni$_3$Nb eutectic alloy which contains 68 vol. pct Ni and 32 vol. pct Ni$_3$Nb lamellae. They tentatively identified the formation of {112} twins in the Ni$_3$Nb phase of the Ni-Ni$_3$Nb eutectic when tension was applied parallel to the growth direction ([100] Ni$_3$Nb) and noted that cracks formed in the intermetallic near these {112} twins. In addition, the Ni$_3$Nb phase, an ordered orthorhombic intermetallic of type $D_{2d}^3$ with lattice parameters of $a = 5.07\,\text{Å}$, $b = 4.57\,\text{Å}$ and $c = 4.23\,\text{Å}$, has been reported to slip at room temperature on two planes, one of which is the (010) plane—the other slip plane has not been identified.

The objective of this investigation will be to more completely characterize the monotonic mechanical response of the Ni-Ni$_3$Nb eutectic composite. A study of Ni$_3$Nb deformation and fracture mechanisms will provide needed information of constituent phase behavior and lead to a more complete understanding of the static behavior of the eutectic composite.

EXPERIMENTAL PROCEDURES

Ni$_3$Nb

Using a composition of Ni-24 at. pct to simulate the room temperature composition of the Ni$_3$Nb in the Ni-Ni$_3$Nb eutectic alloy, ingots of Ni$_3$Nb were produced by alloying a eutectic alloy with appropriate amounts of niobium. The ingots were then zone-refined at slow growth rates (~5 cm per hr) to produce a large grained structure. Subsequent X-ray orientation studies revealed that the growth direction of the columnar grains produced in this manner was [100] ± 5 deg which is essentially coincident with the [100] growth direction of the Ni$_3$Nb platelets in the Ni-Ni$_3$Nb eutectic composite. To facilitate trace analysis of the operative deformation mechanisms, prepolished compression, bend, and hardness specimens were prepared and appropriate grains oriented with standard Laue X-ray techniques. After straining, the deformation surface relief and underlying structure, as revealed by subsequent polishing, were analyzed with standard one surface and two surface trace analysis techniques. Two-surface trace analysis was conducted whenever possible; however, in some instances trace analysis was confined to one surface. It should be noted that, due to the low symmetry of an orthorhombic lattice, one surface trace analysis in orthorhombic materials is statistically more meaningful than one-surface trace analysis in cubic materials.

Ni-Ni$_3$Nb Eutectic Alloy

Master heats of Ni-23.3 wt pct Nb using high purity materials (99.97 pct Ni and 99.7 pct Nb) were induction melted in an argon atmosphere and cast into steel chill molds. The cast ingots, contained in Al$_2$O$_3$ crucibles and protected by an argon atmosphere, were then unidirectionally solidified vertically with induction melting. All specimens were grown at 4.7 cm per hr which
Fig. 1—Micrograph revealing the transverse structure of the Ni-Ni$_3$Nb eutectic composite (4.7 cm per hr). Magnification 255 times.

Table I. Monotonic Properties of the Ni-Ni$_3$Nb Composite

<table>
<thead>
<tr>
<th>Properties</th>
<th>Average Results</th>
<th>Range of Results</th>
<th>No. of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength, ksi</td>
<td>108.7</td>
<td>104.7 to 115.0</td>
<td>9</td>
</tr>
<tr>
<td>Strain at tensile fracture, pct</td>
<td>12.4</td>
<td>11.2 to 15</td>
<td>4</td>
</tr>
<tr>
<td>Reduction in area, pct</td>
<td>13.4</td>
<td>11.7 to 16.8</td>
<td>3</td>
</tr>
<tr>
<td>Notched tensile strength, ksi</td>
<td>139.8</td>
<td>138.0 to 143.4</td>
<td>3</td>
</tr>
<tr>
<td>Ultimate compressive strength, ksi</td>
<td>234.7</td>
<td>222.3 to 254.1</td>
<td>7</td>
</tr>
<tr>
<td>Compressive strain at ultimate, pct</td>
<td>6.03</td>
<td>4.96 to 6.89</td>
<td>7</td>
</tr>
</tbody>
</table>

produced an average lamellar spacing of approximately 9.4 μ. The transverse microstructure is shown in Fig. 1.

Tensile testing with standard $\frac{1}{2}$ in. diam tensile specimens was conducted with a strain gage extensometer measuring the strain over the 1 in. gage length. In addition, notched tensile tests were performed with standard $\frac{1}{2}$ in. diam tensile samples containing a 60 deg notch in the center of the gage section which reduced the cross-sectional area by 45 pet. (The measured notch root radius was less than 0.003 in.) Compression tests were conducted with 0.200 in. diam by 0.500 in. high cylinders of the eutectic alloy. In all tests, the load was applied parallel to the growth direction on an Instron testing machine at a cross-head speed of 0.02 in. per min. A summary of the results of this testing program is given in Table I.

After testing, appropriate specimens were nickel-plated and sectioned longitudinally for metallographic examination of the fracture profile. Two different metallographic techniques were employed. When excessive final polishing with MgO was used, etching with a modified Marbles Reagent [20g CuSO$_4$, 100 ml HCl (conc.), 100 ml H$_2$O, and 200 ml ethyl alcohol] produced microstructures which revealed the Ni$_3$Nb twins under white light. This technique was limited to low magnification observations because of excessive surface relief and edge rounding. Therefore, for high magnification micrographs (all micrographs in this paper except Fig. 8), final polishing was conducted with Al$_2$O$_3$ which produced a high quality metallographic polish. However, subsequent etching with the modified Marbles Reagent delineated the Ni$_3$Nb twins only under polarized light.

Two-stage carbon replicas were made of appropriate fracture surfaces and examined in an electron microscope with an accelerating potential of 50 kv.

RESULTS AND DISCUSSION

Ni$_3$Nb TWINNING

Two distinct types of twins, {011} and {112}, were observed and identified by trace analysis, Fig. 2. The {011} twins were typically of a lenticular shape and were observed to be wide regardless of sectioning angle, Fig. 3. It was found that the {011} twins formed when compressive stresses were developed parallel to the