Fracture Behavior of a B2 Ni-30Al-20Fe-0.05Zr Intermetallic Alloy in the Temperature Range 300 to 1300 K

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Tensile tests were conducted on a Ni-30 (at. pct) Al-20Fe-0.05Zr intermetallic alloy in the temperature range 300 to 1300 K. The alloy did not exhibit any room-temperature ductility and failed at an average stress of about 180 MPa. The brittle-to-ductile transition temperature (BDTT), which was higher than those for Ni-50Al and Ni-50Al-0.05Zr, was relatively insensitive to strain rate and varied between about 960 K at a nominal strain rate of 1.4 × 10^{-5} s^{-1} to about 990 K at a strain rate of 1.4 × 10^{-3} s^{-1}. Detailed observations of the fracture surfaces revealed that cleavage failure had originated at a pre-existing defect in all instances, where the fracture stress, σ_f, correlated extremely well with the square root of the average defect size, 2c, in accordance with linear elastic fracture mechanics. The average value of the critical stress intensity factor estimated from the σ_f - 2c data varied between 4 to 7 MPa m^{1/2}. A comparison of the fracture map for this intermetallic alloy with those for face-centered cubic (fcc) and refractory body-centered cubic (bcc) metals, alkali halides, refractory oxides, and covalent-bonded ceramics indicated that the low-temperature brittleness of the alloy is, in part, due to mixed atomic bonding.

I. INTRODUCTION

The stoichiometric Ni-50Al* intermetallic compound has several attractive properties in comparison to currently available commercial superalloys. These include a B2 crystal structure, excellent oxidation resistance, high thermal conductivity, a high melting point (1911 K), and a relatively low density (6 Mg m^{-3}) so that NiAl is presently being considered as a candidate material to replace superalloys in aircraft engine applications. Despite this attractive combination of properties, polycrystalline NiAl has little or no low-temperature ductility and poor high-temperature strength which presently restrict its use as a turbine blade material. As a result, there is a considerable amount of effort being made at present to improve these mechanical properties. Although the creep properties of NiAl have been demonstrably improved by well-established techniques, such as solid solution alloying and precipitate, dispersion, particulate, and long fiber strengthening methods, improving the low-temperature ductility of this alloy poses a considerable challenge for alloy development.

As a result of several earlier investigations, it is now known that {110} (001) is generally the favored slip system in NiAl. Thus, only three independent slip systems can operate in this alloy, which are insufficient to satisfy the von Mises criterion for generalized plasticity in a polycrystalline material. While the operation of additional slip systems, such as those involving {110} {111} slip on the {110} planes, can potentially satisfy the von Mises criterion and maintain grain boundary compatibility in a polycrystalline material, it is important to note that this is only a necessary, but not a sufficient, condition for improving the ductility of many polycrystalline intermetallic alloys. This fact is borne out by two important observations. First, recent studies on Ni-50Al single crystals tested along the (001) direction and favorably oriented to induce (111) slip showed little or no tensile ductility at temperatures below about 590 K. Second, polycrystalline Fe-50Al does not exhibit significant room-temperature ductility, although (110) (111) is the favored slip system in this alloy.

Clearly, other factors must be satisfied to ensure that σ_f < σ_p, where σ_p and σ_f are the macroscopic yield and fracture strengths of the alloy, respectively, in order to attain significant improvements in low-temperature ductility. These include intrinsic processes, such as the nature of the atomic bond, the ease of dislocation nucleation and mobility in the lattice, grain boundary embrittlement by impurity elements, insufficient slip systems to permit slip transfer from one grain to another, and the presence of grain boundary microvoids due to long-range ordering. Some or all of these mechanisms are largely responsible for the poor low-temperature ductility of many intermetallic alloys through their influence on σ_p, σ_f, or both. In addition, extrinsic factors, such as environmental effects, surface flaws, and processing conditions, also affect ductility.

Current research aimed at improving the low-temperature ductility of NiAl has concentrated on developing micro- and macroalloying techniques and improved processing capabilities. Recent observations have demonstrated that the room-temperature tensile ductility of (110) oriented NiAl single crystals can be increased to as much as 6 pct with small additions (typically, about 0.1 to 0.25 pct) of Fe, Ga, and Mo. In contrast, as stated earlier, macroalloying techniques have not generally resulted in a significant enhancement of the room-temperature ductility of single phase, polycrystalline NiAl. However, an earlier investigation on a melt-spun Ni-30Al-20Fe wire revealed a room-temperature...
tensile ductility of about 5 pct.\textsuperscript{[22]} This relatively high value has not yet been duplicated by other investigators\textsuperscript{[17, 23–29]} in alloys of similar composition, although it was demonstrated recently that a cast and double-extruded specimen exhibited a tensile ductility of about 2 pct.\textsuperscript{[27, 28]}

The present investigation was undertaken to characterize the low- and high-temperature tensile fracture properties of a Ni-30Al-20Fe-0.05Zr alloy for which preliminary results have been reported\textsuperscript{[17, 24, 25]}\textsuperscript{[29]}\textsuperscript{[29]} The deformation characteristics of the alloy are reported elsewhere.\textsuperscript{[30]} Previous studies on Ni-30Al-20Fe both with\textsuperscript{[17, 24, 25]} and without Zr\textsuperscript{[23, 27, 28]} were conducted at room temperature, and the brittle-to-ductile transition temperature (BDTT) of these alloys was not determined. The choice of this composition was governed, in part, by the relatively large room-temperature ductility reported for Ni-30Al-20Fe melt-spun wire\textsuperscript{[22]} and, in part, by the substantial improvement in the oxidation resistance of NiAl due to the addition of 0.05 pct Zr.\textsuperscript{[31]} The present article is divided into three parts. First, the effect of strain rate on the BDTT of the alloy is examined. Second, the fracture characteristics of the alloy between 300 and 1300 K are presented with a view of developing an experimental fracture mechanism map. It was felt that this map would provide valuable insights into the nature of the failure mechanisms occurring in this alloy over a wide range of normalized stresses and homologous temperatures. Third, the fracture map is compared with those for other classes of materials in order to qualitatively understand the role of atomic bonding on the low-temperature ductility of NiAl-based alloys.

**II. EXPERIMENTAL**

Table I gives the characteristics and composition of the vacuum-atomized Ni-30Al-20Fe-0.05Zr prealloyed powders procured from Homogeneous Metals, Inc., Clayville, NY. The levels of carbon, nitrogen, and oxygen represent the average values of those reported by three different testing laboratories. The powders were vacuum sealed in mild steel cans and extruded at 1400 K using a 16:1 reduction ratio. Recrystallized and equiaxed grains were observed in both the longitudinal (Figure 1(a)) and transverse (Figure 1(b)) directions of the extruded alloy, where the average grain size, \( d \), determined from several linear intercept measurements was 26.3 ± 1.3 \( \mu \text{m} \) at the 95 pct confidence limit. Tensile buttonhead specimens having gage lengths of 30.5 mm and gage diameters of 3.0 mm were centerless ground from the extruded rods and electropolished in a 10 pct perchloric acid-90 pct methanol bath prior to testing. Tensile tests were conducted to fracture at constant initial strain rates, \( \dot{\varepsilon} \), varying between \( 10^{-6} \) and \( 2 \times 10^{-3} \text{ s}^{-1} \) in the temperature range 300 to 1300 K. The true stresses and true plastic strains reported in this article were calculated from the load-time chart recordings assuming constant volume conditions without incorporating additional corrections for specimen necking. The fracture surfaces were examined by scanning electron microscopy (SEM) after cleaning them ultrasonically in an ethanol bath and sputter coating them with a thin layer of Au-Pd alloy. In addition, longitudinal polished sections of the fractured specimens were examined under an optical microscope to compliment the SEM observations.

![DIC optical micrographs of (a) longitudinal and (b) transverse microstructures of the extruded alloy showing recrystallized equiaxed grains.](image)

**Table 1. Characteristics and Composition of Ni-30Al-20Fe-0.05Zr Powders**

<table>
<thead>
<tr>
<th>Fabrication Technique</th>
<th>Morphology, Mesh (Particle Size)</th>
<th>Composition (At. Pct)</th>
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<tbody>
<tr>
<td>Vacuum atomization</td>
<td>spherical, -60/+100 mesh (149 to 250 ( \mu \text{m} ))</td>
<td>30.7 20.1 bal. 0.06 0.018 &lt;10(^{-3}) 0.007 &lt;10(^{-4})</td>
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