I. INTRODUCTION

Nickel-based superalloys have been the principal high-temperature structural materials for gas turbine engines for the past 5 decades. Significant improvements in their properties have been made by alloy additions and directional solidification and through the use of single crystals. However, the development of superalloys has advanced to the point where the operating temperatures in gas turbine engines now approach the melting temperatures of these alloys. Thus, new high-temperature structural materials are being sought. Because superalloys derive their strength from Ni₃Al intermetallic precipitates, it is not surprising that these intermetallics have been pursued as the next generation of high-temperature materials. Work on intermetallic alloys began with the development of ductile Ni₃Al alloys and has grown rapidly to include TiAl, Ti₃Al, FeAl, CoAl, NiAl, and other intermetallics. The potential of these intermetallics has been comprehensively reviewed.[1-4]

The intermetallic alloy NiAl, which is the subject of this study, offers many advantages over superalloys. NiAl is less dense than current superalloys. It also has excellent oxidation resistance and very high thermal conductivity. Strong bonding between nickel and aluminum results in a high melting temperature and the potential for good high-temperature strength. However, the use of NiAl as a high-temperature structural material is currently hindered by limited ductility at low temperatures. Although the low creep strength of stoichiometric NiAl currently limits its application, strengthening with precipitates and solid solu-
tion alloying is promising and developmental efforts are continuing.

This study was conducted to establish a basic data set for high-temperature creep of stoichiometric NiAl single crystals and to explore the characteristics of high-temperature deformation of this material. Previous studies have described the dislocations in deformed NiAl single crystals\(^{11-14}\) and the steady-state creep rates at high temperature.\(^{11,12,13}\) However, results from these studies sometimes disagree, and there is still little description of the differences in mechanical response between “hard” and “soft” oriented crystals, besides the increased strength of hard oriented crystals. Thus, a comprehensive investigation of high-temperature deformation was undertaken to describe characteristics of deformation in more detail and to provide means for inferring the underlying creep deformation mechanisms in NiAl.

The deformation properties of single-crystal NiAl were studied using constant stress tension creep, constant stress or constant strain rate compression tests, and transient tests. Results are presented for crystals oriented along various soft orientations, \([223]\), \([111]\), and \([110]\), and along the hard \([001]\) orientation. Interested readers may refer to Reference 14 for a complete description of all of the results of this study. We begin the article with a description of the mechanical testing methods and procedures used in this work. This is followed by a presentation and discussion of the deformation properties of crystals oriented along the soft directions. The mechanical properties of hard oriented crystals are then described and compared with those of crystals deformed along soft orientations. Dramatic differences in the deformation properties of hard and soft oriented crystals are further shown in tests wherein the stress is abruptly changed and the resulting strain rate transient is recorded. All of these deformation characteristics provide a basis for determining the mechanisms that control high-temperature creep of NiAl single crystals. These controlling mechanisms are explored in a forthcoming article.

### II. PREPARATION AND ORIENTATION OF SINGLE-CRYSTAL SAMPLES

Single crystals of stoichiometric NiAl were prepared at the Engineering Materials Technology Laboratories, GE Aircraft Engines (Cincinnati, OH). The crystals were nominally \(25 \times 38 \times 100\) mm, with the long axis oriented about 10 deg from \([001]\). Crystals were grown in argon by the Bridgman method and then homogenized in an argon atmosphere at 1316 °C for 50 hours. The composition of similarly prepared crystals measured by GE Aircraft Engines is shown in Table I. The compositions of the crystals used in this study were not measured but are expected to fall within the range in this table.

The orientation of each of the uncut crystals was determined by Laue X-ray diffraction along two perpendicular axes. Laue X-ray diffraction of only one crystal axis is sufficient to determine the orientation; the second Laue photograph was used to validate the orientation. The error in the Laue analysis is on the order of 2 deg. The crystals could be set up to cut samples with an accuracy near 1 deg. Each sample was X-rayed after being cut, and the loading axis was found to be within 3 deg of the desired orientation.

Loading orientations were chosen to study both the \([010]/[001]\) and \([110]/[001]\) slip systems. In crystals oriented near the \([011]\) axis, slip of \(b = [001]\) dislocations occurs on \([010]\) planes; in crystals oriented near the \([111]\) axis, \(b = [001]\) slip occurs on \([110]\) planes.\(^{8,9,10}\) Results for crystals oriented along the \([001]\) axis are especially interesting, since \(b = [001]\) glide is inhibited with this loading; instead, \(b = [101]\) glide occurs, as shown previously\(^{15}\) and discussed in more detail in a forthcoming article. The high strength of these hard \([001]\) oriented crystals is in sharp contrast to the strength of soft non-[001] loading orientations.

### III. MECHANICAL TEST PROCEDURES

Both tension and compression samples were electrode discharge machined (EDM) from the oriented crystals. Compression samples were cut 7.62-mm long with a 3.81 × 3.81-mm cross section. Sheet tension samples were cut with a nominal gage length of 20.3 mm and a cross section of 3.10 × 3.10 mm. All specimens were low stress ground to remove the polycrystalline, recast layer resulting from the EDM cutting. Specimens were mechanically polished to 25 μm and then electropolished. The specimens were polished at −10 °C and 25 V for about 3 minutes in a stirred electrolytic solution of 10 vol pct perchloric acid in methanol.

Test temperatures ranged from 850 °C (0.58 \(T_m\)) to 1200 °C (0.77 \(T_m\)). Strain rates could be controlled and measured as low as \(10^{-7}\) s\(^{-1}\) and as high as \(10^{-3}\) s\(^{-1}\). These test conditions span the entire power law creep regime for NiAl.

#### A. Tension Creep Tests

Tension samples were tested under constant stress maintained by an Andrade–Chalmers arm with a 3:1 mechanical advantage between the sample and the applied load. The samples were held with TZM molybdenum grips contacting with the 2.38-mm-radius shoulders on the specimen. In order to protect these grips from oxidation, tension tests were done under a vacuum of about 10\(^{-5}\) torr, maintained with a Leybold model 150/360 VH turbo molecular pump. The vacuum chamber containing the sample was heated by an ATS Super Kanthal furnace with MoSi\(_2\) heating elements. Care was taken to position the test specimen within this area in order to avoid temperature gradients along the gage length.

The possibility of compositional changes associated with