Features and Effect Factors of Creep of Single-Crystal Nickel-Base Superalloys

SUGUI TIAN, JINGHUA ZHANG, XIN WU, HONGCAI YANG, YONGBO XU, and ZHUANGQI HU

The creep behavior of two single-crystal nickel-base superalloys with [001] orientation has been studied by measuring the creep curves, internal friction stress of dislocation motion, transmission electron microscopy (TEM) observation and energy-dispersive X-ray analysis (EDAX) composition analysis. The results show that over the stress and temperature range, there are different creep activation energies, time exponents, and effective stress exponents in two alloys at different creep stages. The size and volume fraction of the γ' phase in the tantalum-free alloy is obviously decreased with the elevated temperature. This results in the decrease of the internal friction stress during steady-state creep. Higher levels of tungsten in the alloy result in a smaller strain value and lower directional-coarsening rate during primary creep. During steady-state creep, the primary reason for the better creep resistance of the other alloy is that it contains more Al and also Ta, which maintains a high volume fraction of γ' phase. The dislocation climb over the γ' rafts is the major deformation mechanisms during steady-state tensile creep. The fact that the strain rate is decreased with the increase of the size and volume fraction of the γ' rafts may be described by a modified constitutive equation that is based on a model of the rate of dislocation motion.

I. INTRODUCTION

SINGLE-CRYSTAL nickel-base superalloys have been widely used because they possess a high fraction of γ' strengthening phase and good high-temperature properties. Some experimental results show that the deformation behavior of single-crystal nickel-base superalloys depends on their chemical composition as well as on microstructure, such as the average size and the distribution of γ' precipitates.[1±4] Better mechanical properties may be obtained when the γ' phase occupies a higher volume fraction, and the cuboidal γ' precipitates (about 0.5 μm in edge size) are coherently embedded in the γ matrix. It is recognized that refractory metal additions can also have significant effects on the mechanical properties of superalloys.[1±4] The creep lives at 980 °C and 234 MPa exhibit a steep peak as a function of Mo content with the maximum in life occurring at about 14 wt pct Mo.[4] According to a matrix of compositions based on MAR-M247, substitution of Ni for Ta causes large decrease in γ'-solvus temperature, γ'-volume fraction, and γ'-γ lattice mismatch, whereas, substitution of W for Ta results in smaller decreases in these features.[5] Substitution of 2 wt pct W for 3 wt pct Ta results in decreased creep life at high stress but improved life at low stress,[6] Murakami et al.[12] investigated the Ni-base superalloys containing 2 at. pct Ir and indicated that Ir atoms are expected to act as solid-solution hardeners of both the γ' and γ phases without reducing the microstructural stability. The reason that the refractory metal additions affect the creep features and resistance of superalloys is that they have the potential of influencing a number of properties, such as solid-solution hardening, γ'-γ lattice mismatch, γ'-volume fraction, and diffusion rate. However, knowledge of the relative effectiveness of refractory elements W and Ta on the creep resistance of alloys separately and the mechanisms responsible for their effects is lacking.

In addition, it may be considered that the creep resistance of alloys depends on the volume fraction of γ' precipitates and the internal friction stress of dislocation motion. The internal friction stress (σ0/MPa) is the average internal stress due to neighboring dislocations and other obstacles determining the behavior of mobile dislocations, which is expressed as the difference between the applied stress (σa) and the effective stress (σe): σ0 = σa - σe, and suggests the deformation resistance of the alloy during steady-state creep. Rouault-Rogez et al.[13] considered that the internal stress associated with creep was related to the temperature and the applied stress. The internal friction stresses and creep activation energies vary in alloys under different conditions. This affects the creep mechanism. So far, only a few articles on the influence of the alloying elements on the creep mechanism and resistance of the alloys have been reported. Combined with microstructural observations of the deformed alloy, the measurement of the internal friction stress during steady-state creep can be valuable in order to explore the nature of the deformation resistance and creep mechanism of the alloy.

In this article, the creep curves and internal friction stresses associated with creep in two superalloys were measured, together with transmission electron microscopy (TEM) observation and energy-dispersive X-ray analysis (EDAX) composition analysis, to provide evidence of the microstructural phenomena and to discuss the influence of some factors on the creep features of the alloys. Finally, a model of
Table I. Nominal Compositions of Experimental Superalloys (Weight Percent)

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Ti</th>
<th>Ta</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>Co</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy 1</td>
<td>6.0</td>
<td>—</td>
<td>6.5</td>
<td>6.5</td>
<td>8.5</td>
<td>—</td>
<td>bal</td>
<td></td>
</tr>
<tr>
<td>Alloy 2</td>
<td>4.0</td>
<td>4.0</td>
<td>—</td>
<td>16.0</td>
<td>—</td>
<td>6.0</td>
<td>8.5</td>
<td>bal</td>
</tr>
</tbody>
</table>

creep, based on the rate of dislocation motion, is proposed to account for the deformation mechanism during steady-state creep.

II. EXPERIMENTAL PROCEDURE

Two kinds of single-crystal nickel-base superalloys of [001] orientation have been produced by means of the crystal selection method in a directional-solidification vacuum furnace under a high thermal gradient. Longitudinal orientations of all specimens were within 7 deg deviating from [001]. The nominal compositions of the superalloys are listed in Table I. The heat treatments were as follows:

- 1280 °C, 6 hours, AC + 1310 °C, 4 hours, AC + 1040 °C, 4 hours, AC + 870 °C, 20 hours, AC (alloy 1)
- 1100 °C, 8 hours, AC + 1240 °C, 4 hours, AC + 1090 °C, 2 hours, AC + 850 °C, 24 hours, AC (alloy 2)

AC is defined as air cooling.

For the alloys in the present study, alloy 1 possesses a negative misfit (δ, about −0.248 pct), while the tantalum-free alloy 2 has a higher negative lattice mismatch. This may be achieved by comparing the spacing of misfit dislocations in alloy 1 (\(D_1 = 0.033 \, \mu m\) measured in Figure 12(c)) with that of tantalum-free alloy 2 (\(D_2 = 0.021 \, \mu m\) measured from Figure 14) because of smaller spacing of misfit dislocations corresponding to higher lattice mismatch.

III. EXPERIMENTAL RESULTS AND ANALYSIS

A. Comparison of the Mean Internal Friction Stresses in Two Alloys

During creep, dislocations pile up and multiply in matrix channels under the applied stress. Dislocation slip and climb may occur owing to the thermal activation, relaxing the stress concentration in local regions. Ahlquist and Nix\(^{[14]}\) considered that the dislocation movement is driven by an effective stress (\(\sigma_e\)). The internal friction stress (\(\sigma_0\)) is an inherent property of the materials and reflects the deformation resistance of the alloy. The mean internal friction stresses (\(\sigma_0\)) of alloy 2 were measured by means of transient strain-dip tests\(^{[14]}\), as shown in Figure 1 (the value of internal friction stress of alloy 1 shown in Figure 1 in literature\(^{[15]}\)). A separate sample was used for each steady-state rate determination at any particular stress and temperature. Internal-friction stress measurement was made at least twice for each \(\sigma_0\) during steady-state creep.

It may be understood from Figure 1 that the values of the mean internal friction stress decrease with increasing temperature and slightly increase with the increase in applied stress (\(\sigma\)) due to the effect of strain hardening in obstructing dislocation motion. But, the values of the relative internal friction stress (\(\sigma_0/\sigma\)) decrease with the increase of temperature and applied stress. The differences between the relative internal friction stresses under different applied stresses are lessened with the increase of temperature. This is attributed to the recovery role increased by dislocation annihilation and rearrangements during high-temperature creep to weaken the effect of strain hardening.

Comparing the internal friction stresses of alloy 1 with

![Fig. 1—Relationship among the internal friction stress (\(\sigma_0\)), applied stress, and temperature for alloy 2: (a) the internal friction stress as a function of temperature under the different stress and (b) the relative internal friction stress as a function of temperature under the different stress.](image-url)