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RAPID PUBLICATION

High-Temperature Creep Behavior in $Ni_3(Al, Ta)$ Single Crystals with Different Orientations

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High temperature creep behavior of a nickel-rich $Ni_3(Al, Ta)$ with the $L1_2$ structure is investigated in order to clarify the influence of crystallographic orientation. The single crystals with four different orientations are deformed in compressive creep at the temperatures ranging from 1123 to 1273 K under a constant load with initial shear stresses being from 35 to 120 MPa for the $(111)[\bar{1}01]$ slip system. The results show a distinct orientation dependence of creep strength, although shape of creep curves, stress exponent and the activation energy seem to be independent on orientation. It is shown, however, that the internal stress measured by strain transient dip tests is found to be orientation-dependent and that the creep behavior is independent on orientation if these are analyzed with the effective stress instead of the applied shear stress.

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Keywords: *Ni_3Al, single crystal, creep, orientation, internal stress*

I. Introduction

There have been much less works on high-temperature creep behavior in single crystalline $L1_2$ Ni_3Al as compared to those on the anomalous positive temperature dependence of strength of the compound. Hemker *et al.*[1] have reported the orientation dependence of high-temperature creep strength of Ni-rich Ni_3Al–1Hf–0.24B (at%) single crystals with the orientations near [001] and near $[\bar{1}23]$, in which the shear strain rate for the former orientation was found to be higher than that for the latter. They also have suggested that more than one slip system would be active upon high temperature creep deformation. Caron *et al.*[2] have reported an unusual operation of the $\{110\}\langle 110\rangle$ slip system observed for the stress axis near [001] when single crystals of Ni-rich Ni_3Al–0.33Hf (at%) are crept at 1033 K. The same observation has been reported by Rong *et al.*[3] for stoichiometric Ni_3Al polycrystals under creep deformation even at a much lower temperature. Shah[4] has worked on the creep deformation behavior of single crystalline nickel-rich Ni_3Al with five stress axis orientations, [001], [011], $[\bar{1}23]$, $[\bar{1}11]$ and $[\bar{2}23]$. It was shown that shear strain rates for orientations of [011] and $[\bar{1}23]$ were approximately half that for the [001] orientation, while those for the $[\bar{1}11]$ and $[\bar{2}23]$ orientations were one-fourth that for the [001] orientation. They have proposed that the active slip system was on octahedral planes for the [001] and [011] orientations, whereas it was on cube planes for the near $[\bar{1}11]$ orientation. This finding is similar to what was reported by Lall *et al.*[5] who investigated the flow stress behavior in relation to various stress axis orientations of Ni_3Al+Nb single crystals.

In view of these previous studies, we feel that no rigorous explanation has been made on the deformation mechanism behind creep of Ni_3Al single crystals and its orientation dependence. The purpose of the present investigation is to provide a better understanding on the influence of orientation on the high-temperature creep behavior in $Ni_3(Al, Ta)$ single crystals.

II. Experimental

Single crystals, 18 mm in diameter and 100 mm in length, of single-phase $Ni_3(Al, Ta)$ with a Ni-rich composition of Ni–22Al–2Ta (in at%) were grown from the melt under an argon atmosphere by a modified Bridgeman technique. The single crystal bars were homogenized at 1523 K in a sealed silica tube evacuated to about 10^{-3} Pa for 240 h and then furnace cooled. Compressive creep test specimens, $3 \times 3 \times 6$ mm^3, were cut by an abrasive wheel to obtain various stress axis orientations using a goniometer stage. Growth direction of the single crystals were determined by back-reflection Laue X-ray diffraction prior to cutting. Orientations of the specimen used in the present work are shown in Fig. 1. Specimens were electropolished before the tests for about 50 μm using a solution of 95% acetic acid and 5% perchloric acid (vol%) in order to remove the deformed surfaces.

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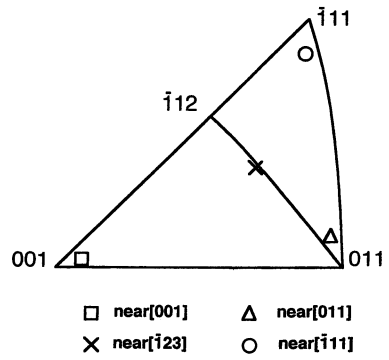

Fig. 1 Unit triangle showing orientations of single crystals used.

Compression creep tests were conducted at temperatures ranging from 1123 to 1273 K in an argon atmosphere at a constant load, giving an initial shear stress ranging from 35 to 120 MPa for the primary octahedral (111)[$\bar{1}$01] slip system. Creep strains were detected by transducers via silica rods whose ends were attached to just above and below the specimen.

III. Results and Discussion

Creep curves are obtained for specimens with four different orientations, namely near [001], near [$\bar{1}$11], near [011], and near [$\bar{1}$23]. Figure 2 shows creep shear strain rate-shear strain curves at 1223 K under an initial shear stress of 57 MPa, in which each curve is drawn for creep deformation up to 100 h. The creep strain rate for each stress axis orientation in the early stage of primary creep appears to increase with creep strain and then decreases till steady-state is achieved, exhibiting a sigmoidal response. During primary creep, the maximum creep strain rate is achieved with less creep strain for near [011] and near [$\bar{1}$23] than those for the near [$\bar{1}$11] and near [001] orientations. Consequently, steady-state is achieved at much less strain for the near [011] and near [$\bar{1}$23] orientations (within less than 10% strain) than for the near [$\bar{1}$11] and near [001] orientations (more than 30% strain). The steady state strain rate is obviously higher for the near [$\bar{1}$11] and near [001] orientations than for near [011] and [$\bar{1}$23] orientations. The results clearly indicate that the high-temperature creep behavior of Ni_3(Al, Ta) single crystals is dependent on crystallographic orientation.

The relations between the steady state shear strain rate and shear stress are summarized in Fig. 3 with the full logarithmic scale. It is found that when compared at the same shear stress the steady state creep rate increases in the order of near [$\bar{1}$23], near [011], near [001], and near [$\bar{1}$11]. Through the linear relations in the figure it is assumed that the creep deformation in all the specimen tested can be expressed by the following Dorn-type equation,

$$\dot{\gamma}=A\tau^n \exp\left(-\frac{Q_1}{RT}\right), \tag{1}$$

where $\dot{\gamma}$ is the steady-state shear creep rate, τ the shear creep stress, n the stress exponent, Q_1 the activation energy, T absolute test temperature, A is a material constant, and R is the gas constant. Analyses of Fig. 3 reveal that the stress exponent for all the orientations are within a range of 3.0 to 3.5. Then the activation energy, Q_1, in eq. (1) can be obtained, where creep tests were performed with initial shear stresses of 57, 77, and 98 MPa at the temperatures between 1123 and 1273 K. The Arrhenius-type plots of steady-state shear strain rates are shown in Fig. 4. The activation energies derived from the figure are found to be independent both on orientations and initial shear stress and fall in a range between 300 and 370 kJ/mol. It seems therefore that although the creep behavior of Ni_3(Al, Ta) single crystals is dependent on crystallographic orientation however, both the stress exponent and the activation energy are independent of it.

In order to seek for the cause for the orientation dependence of high-temperature creep behavior, the internal stress for the steady state deformation is examined by using strain transient dip tests[6]. Equation (1) is rewritten as:

$$\dot{\gamma}=A'\tau_e^{n'} \exp\left(-\frac{Q_2}{RT}\right) \tag{2}$$

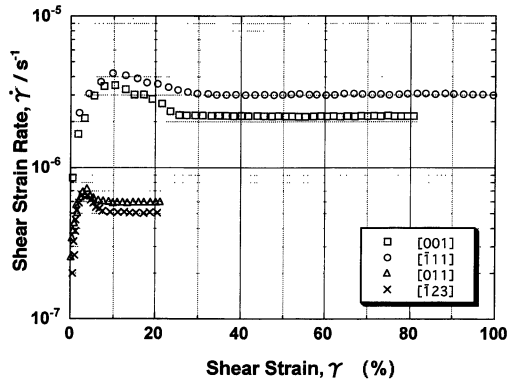

Fig. 2 Creep shear strain rate-shear strain curves of four orientations at 1223 K under a shear stress of 57 MPa. The total creep time was 100 h.

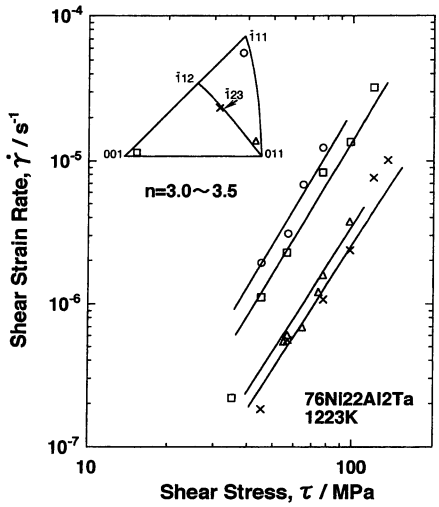

Fig. 3 Steady-state shear strain rate versus shear stress relations in the full logarithmic scale.

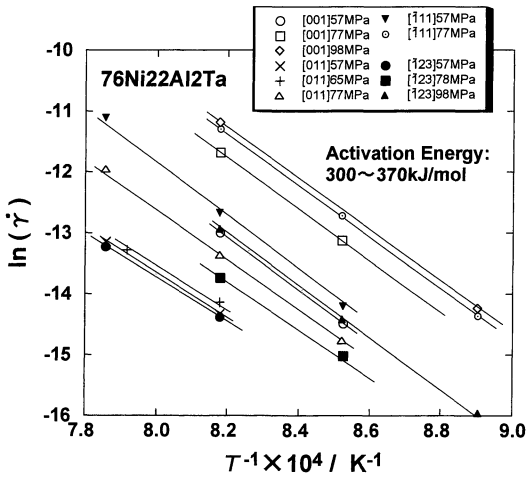

Fig. 4 Arrhenius-type plots steady-state shear strain rates.

and

$$\tau_e=\tau-\tau_i, \tag{3}$$

where τ_e is the effective shear stress, τ_i the internal shear stress, Q_2 the activation energy, n' the stress exponent, A' is a material constant, and $\dot{\gamma}$, τ, R and T are the same meanings as defined in eq. (1). Then we can find a correlation between effective shear stress, τ_e, and steady state shear strain rate according to eq. (2) using measured values of internal stresses under various test conditions. The results are shown in Fig. 5. It is now shown that the orientation dependence vanishes if the effective stress is taken to interpret the creep behavior of single crystalline $Ni_3(Al, Ta)$ and that the stress exponent or n' is about 3.5. This in turn tells us that the cause for the orientation dependence found in the present work is due to the orientation dependence of internal stress in the compound. The Arrhenius-type plots of steady-state shear strain rate according to eq. (2) are shown in Fig. 6. The activation energy, Q_2, derived from the figure are about 420±15 kJ/mol. This value is comparable to a reported activation energy of about 340 kJ/mol[7] for creep deformation

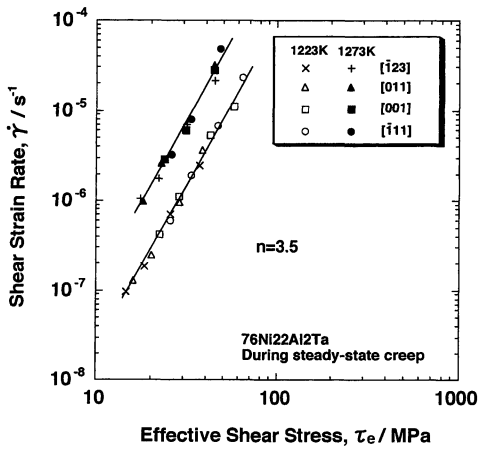

Fig. 5 Steady-state shear strain rate versus effective shear stress relations in the full logarithmic scale.

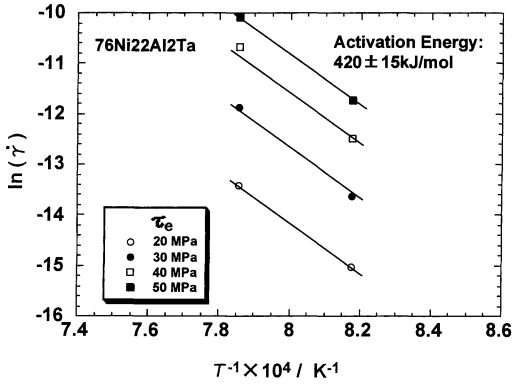

Fig. 6 Arrhenius-type plots of steady-state shear strain rate for effective shear stresses.

of Ni_3Al alloys and an activation energy of volume diffusion in Ni_3Al alloy ranging from 290 to 350 kJ/mol[8]-[10]. Investigations to reveal the reason for the orientation dependence of internal stress are currently underway through observations of the deformation structures and dislocation mechanics involved. The preliminary results indicate that the deformation is mainly through a primary octahedral slip system in all the orientations, but there are indications that some additional slip systems are activated for the orientations with a lower creep strength, although the relevance is unclear.

IV. Conclusions

Orientation dependence of high-temperature creep behavior of $Ni_3(Al, Ta)$ single crystals is investigated and the following conclusions are drawn.

(1) There seems to be the orientation dependence in the creep behavior of $Ni_3(Al, Ta)$ single crystals as discussed in terms of creep strain rate and applied shear stress. However, the orientation dependence vanishes if the creep behavior is interpreted with the effective stress instead of the applied stress.

(2) The creep behavior can be interpreted by the Dorn-type equation for all the orientations and the stress component and activation energy for creep are estimated, with the effective shear stresses, to be 3.5 and 420±15 kJ/mol, respectively.

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