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The creep deformation mechanisms of a newly designed nickel-base superalloy

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ABSTRACT

The influences of applied stress (120–760 MPa) and temperature (700–1000 °C) on the creep deformation mechanisms of the newly developed nickel-base superalloy M951G have been studied. The dominant deformation mechanisms of M951G alloy after different creep tests were systematically investigated and the reasons for their transition were well discussed. A creep mechanism map at various creep conditions was summarized and the theoretical critical resolved shear stresses (CRSSs) of various creep mechanisms under different temperatures were also calculated. Results show that the CRSSs of different creep mechanisms display different dependencies of temperature and the favorable deformation mechanisms at different creep conditions are different. τ_{APB}, τ_{OB} and τ_{CL} are decreased to varying degrees with the temperature increasing; on the contrary, there is a positive correlation between τ_{SF} and temperature. At low temperature region, the favorable deformation mechanism is shearing of γ′ precipitates by stacking faults. However, it changes to antiphase boundaries (APBs) coupled dislocation pairs shearing in the γ′ precipitates and dislocation climbing in the γ matrix channel at high temperatures. At intermediate temperatures, both stacking faults and APBs are observed owing to the alternate leading of the CRSSs for APBs and stacking faults shearing in γ′ precipitates.

1. Introduction

Nickel-base superalloys are widely applied as the turbine blades and vanes in the aircraft engines and industries gas engines owing to their outstanding mechanical properties and good corrosion resistance at elevated temperatures [1]. The unique microstructure, which consists of plenty of ordered γ′ precipitates with $L1_2$ structure coherently embedded in γ matrix, is responsible for the excellent properties of superalloy [1].

With the development of the engines, the high temperature creep resistance of superalloy becomes one of the major standard for the engineers to evaluate the mechanical properties of a newly designed superalloy. Extensive researches have been conducted to study the creep deformation mechanisms of superalloys previously [2–5]. Similar dislocation substructures, including isolated stacking faults, continuous stacking faults and microtwinning, were observed for a newly designed power metallurgy disk superalloy at 700 °C from 670 MPa to 897 MPa [5]. Tian studied the creep behaviors of a 4.2%-Re containing superalloy in the temperature ranges 1040–1100 °C, results showed that the dominant deformation mechanism changed from dislocation climbing over the rafted γ′ phase to super-dislocation shearing into the γ′ precipitates with the creep stage from steady-state to accelerated [3]. Results from Wang demonstrated that for a nickel-base superalloy tensile creep at 1000 °C, only the long dislocations with ⟨110⟩ line direction were observed in the γ′ precipitates; however, at 1140 °C, both the long and zigzag dislocations were present in the microstructure [4]. In addition, with the increase of creep strain from 0.1% to 27%, the dominant deformation mechanism of U720Li disk superalloy varied from dislocations bypassing the γ′ precipitates via Orowan loops to occurrence of grain boundary sliding at 725 °C/630 MPa [2].

As mentioned above, although the creep deformation mechanisms of superalloys have been widely studied, previous studies mainly focus on a certain or a small range of temperatures and stresses. The influences of temperatures and applied stresses over a wide range on the creep mechanisms of nickel-base superalloys have rarely been reported, which will certainly be helpful for better understanding of their creep mechanisms. On the other hand, most of the previous researchers put their attention on the dominant deformation mechanisms (several ones may operate simultaneously) during creep tests. However, the papers on the favorable deformation mechanism, which has more priority over others to occur under a certain creep condition, have seldom been published until now.

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Table 1
Nominal compositions of M951G alloy (wt%).

W	Mo	Nb	Co	Cr	Al	Hf	Others	Ni
6.5	3	2.2	5	9	6	1.5	0.091	Bal

In present study, the newly designed nickel-base superalloy M951G alloy [6], which is used as a potential vane material in the gas turbine engines, is chosen to systematically investigate the creep behaviors within the temperature range of 700 °C to 1000 °C and stress from 120 to 760 MPa. The purpose of this work is to elucidate the variation of the dominant and favorable deformation mechanisms with the changes of creep conditions.

2. Experimental procedure

The nominal chemical compositions of M951G alloy are listed in the Table 1. And the related heat treatment was conducted on M951G alloy as follow: 1210 °C × 4 h, AC→1100 °C × 4 h, AC→870 °C × 24 h, AC (AC: air cooling).

The specimens for creep tests were machined from the heat-treated bars with a diameter of 5 mm and a gauge length of 25 mm. The tensile creep tests were conducted over a wide stress range of 120–760 MPa under temperatures from 700 °C to 1000 °C in air, as listed in Table 2. During all creep tests, the temperature was controlled within ± 2 °C using three thermocouples. All of the samples were run to failure and at least two identical specimens were tested at each creep condition. The specimens for transmission electron microscope (TEM) observation were cut perpendicularly to the loading axis and mechanically ground down to approximately 50 µm, and then electrochemically thinned by twin-jet polisher with a solution of 10% perchloric acid and 90% alcohol, at a voltage of 17.5 V, current of 52 mA and temperature below −20 °C. All of the resulting foils after creep tests were systematically examined using a JEM 2100 TEM operating at 200 kV.

3. Results

3.1. Creep properties

The creep curves and apparent stress exponent (n) of M951G alloy at different test conditions are shown in Fig. 1. It can be clearly seen that the shape of the creep curves displays strong stress dependence. For all the temperatures in this work, under low applied stress region, the curves consist of an obvious primary stage and a dominant steady-state stage, which is followed by a limited accelerated stage. However, when creep at higher stress, the length of the primary and steady-state stages significantly decreases, while the accelerated stage becomes the dominant one.

For nickel-base superalloy creep deformation at high temperatures, the relationship between steady-state creep rate ($\dot{\varepsilon}_{ss}$) and applied stress (σ_a) at the same testing temperature (T) can be expressed as follow [7]:

$$\dot{\varepsilon}_{ss} = A\sigma_a^n \exp(-\frac{Q}{RT}) \tag{1}$$

where A being a constant related to the material, R being the gas constant, Q is the apparent creep activation energy. n is the apparent stress exponent, which is between 4 and 6 for simple alloys. In present study, as shown in Fig. 1e, different values of n are obtained at low (700–800 °C) and high temperatures (1000 °C), which indicates that different deformation behaviors occur at different temperature regions. On the other hand, the apparent stress exponent at 900 °C under higher applied stress (10.699) is nearly the same as that of 700 °C (11.582) and 800 °C (11.112). Meanwhile, similar apparent stress exponents also have been obtained during creep deformation at 900 °C under low applied stress and at 1000 °C, as shown in Fig. 1e. This phenomenon may relate with the deformation mechanisms and microstructures of M951G alloy and will be systematically discussed in Section 4.1.

3.2. Deformation structures

3.2.1. Microstructures after creep tests at 700 °C

Similar deformation microstructures are obtained after creep tests at 700 °C/650 MPa and 700 °C/700 MPa, as shown in Fig. 2a-d. Large numbers of isolated stacking faults (Fig. 2a and d) shearing in the γ′ precipitates as well as the continuous stacking faults (Fig. 2b and c) cutting through the γ′ and γ phases are observed. Compared with the microstructures at 700 °C/650 MPa, the density of isolated stacking faults is higher after creep deformation at 700 °C/700 MPa, which indicates that the external applied stress promotes the formation of isolated stacking faults. Apart from these fault features, only a small number of dislocations present in γ matrix channel, so the local stress along the γ/γ′ interface should be extremely low. Thus, the favorable way for M951G alloy plastic deformation at 700 °C under relatively lower stress is shearing of the γ′ precipitates by stacking faults.

The deformed microstructures and corresponding deformation mechanisms of M951G alloy after creep at 700 °C under higher applied stress (760 MPa) are displayed in Fig. 2e-f, which are similar to that of 700 °C/650 MPa and 700 °C/700 MPa. However, there are also some differences in the deformed microstructures. Compared with the microstructures obtained under low applied stress at 700 °C (Fig. 2a-d), much high density of tangled dislocations are piled up in the γ matrix channel (Fig. 2e), which indicates that the local stress along the γ/γ′ interface is sufficient large. Aside from that, other remarkable discrepancy can be observed that a number of antiphase boundaries (APBs) shear into the γ′ precipitates, as shown in Fig. 2e and f. Consequently, with the increase of applied stress, the shearing of the γ′ precipitates by dislocations (including stacking faults and APBs) and tangled dislocations in the γ matrix become the dominant modes for plastic deformation under higher applied stress at 700 °C. The deformation mechanisms of M951G alloy after creep deformation at 700 °C under different applied stresses are schematically illustrated in Fig. 2.

3.2.2. Microstructures after creep tests at 800 °C

Fig. 3a and b illustrate the microstructures of M951G after tensile creep at 800 °C/650 MPa. It can be observed that a considerable number of tangled dislocations are piled up in the γ matrix channel and plenty of isolated stacking faults as well as APBs shear into the γ′ precipitates, but no continuous stacking fault present in the

Table 2
Creep life (hour) of M951G alloy at various conditions in present study.

Temperature/°C	Loading Stress/MPa											
	120	150	160	**200**	250	300	360	**450**	550	**650**	700	**760**
700										**693**	273	**155**
800								**757**	121	**20**		
900				**787**	333	125	37	**10**				
1000	**294**	134	74	**20**								