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Influences of ruthenium and crystallographic orientation on creep behavior of aluminized nickel-base single crystal superalloys

F.H. Latief [a,*], K. Kakehi [a], H. An-Chou Yeh [b], H. Murakami [c]

[a] Department of Mechanical Engineering, Tokyo Metropolitan University, 1-1 Minami-osawa, Hachioji-shi, Tokyo 192-0397, Japan
[b] Department of Materials Science and Engineering, National TsingHua University, 101, Section 2, Kuang-Fu Road, Hsinchu 30013, Taiwan
[c] Hybrid Materials Center, National Institute for Materials Science (NIMS), 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan

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ABSTRACT

The influences of ruthenium and surface orientation on creep behavior of aluminized Ni-base single crystal superalloys were investigated by comparing two different types of NKH superalloys. The aluminized coated specimens were then subjected to creep rupture tests at a temperature of 900 °C and a stress of 392 MPa. The coating treatment resulted in a significant decrease in creep rupture lives for both superalloys. The diffusion zones between the coating and substrate led to changes in microstructure, which diminished the creep behavior of the aluminized superalloys. Because of the interdiffusion of Ru, Al and Ni, the solubility of some of the refractory elements, such as W, Re. Mo, Co and Cr decreased in the diffusion zone; the precipitation of topologically close-packed (TCP) phases was thus inevitable. In the present study, the addition of Ru increased the degree of Re and Cr supersaturation in the γ matrix. Consequently, the addition of Ru indirectly promoted the precipitation of TCP phases in aluminized Ni-base single crystal superalloys. Furthermore, the growth of TCP precipitates was greatly influenced by the specific surface orientations of the Ni-base single crystal superalloys. In conclusion, the {110} specimens showed shorter creep rupture life than the {100} specimens, this was due to the difference in the crystallographic geometry of {111}⟨101⟩ slip system and TCP precipitates between the two side-surface orientations of the specimens.

1. Introduction

Aluminide coatings have been applied to Ni-base single crystal superalloys used for turbine components in order to protect them from oxidation and corrosion during their service lives. Details of these coatings have been reported [1–5]. Problems have arisen with these coated superalloys, leading to the loss of the coating. These problems include the precipitation of topologically close-packed (TCP) phases, the formation of Secondary Reaction Zones (SRZs) and the ‘rumpling’ of the coating caused by thermal cycling. Such problems degrade the properties of coated Ni-based superalloys, and are potentially life-limiting to turbine blades. In particular, TCP phase precipitation and SRZ formation are regarded as serious problems in both coated and uncoated Ni-base superalloys. As is well known, topologically close-packed (TCP) phase is a collective designation for several intermetallic compounds rich in the elements W, Mo, Re and Cr precipitated in Ni-base single crystal superalloys [6]. TCP phases form during service at elevated temperatures in such superalloys with high concentrations of these elements added to promote strength the loss of these elements from the matrix impairs the mechanical properties of the blade. Precipitation of the TCP phases [7–9] deteriorates the ductility and creep resistance of Ni-base superalloys. However, the damage mechanisms by aluminide coatings are not yet well understood. In the present study, we investigated the influence of crystallographic orientation on creep behavior of aluminized Ni-base single crystal superalloys, one Ru-free and the other Ru-containing.

2. Experimental materials and procedures

Fully heat-treated (solution and aging) Ni-base single crystal superalloys NKH-304 and NKH-510 were used as substrate materials in this study. The details of chemical composition and heat treatment route for each superalloy are given in Table 1. NKH-304 is the base alloy, and NKH-510 is a 3 mass% Ru-addition alloy, where 3% Ru is substituted for Ni. The creep specimens with {100} and {110} side-surfaces (Fig. 1) were prepared by electric discharge machining (EDM), and had cross-section areas of 2.8 mm × 2.8 mm and gauge length of 19.6 mm. The specimens were mechanically polished with emery paper prior to the aluminizing process.

* Corresponding author. Tel./fax: +81 42 6772709.
E-mail address: fahamsyah78@gmail.com (F.H. Latief).

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Table 1
Chemical composition and heat treatment of alloys.

Alloy	Chemical composition (mass%)	Heat treatment
NKH-304	11Co, 6Cr, 6W, 5.4Al, 1.4Ti, 6.8Ta, 4.8Re, 0.12Hf and bal. Ni	Solution heat treatment: 1310 °C/10 h + 1320 °C/12 h + 1325 °C/12 h + gas furnace cooling and followed by aging treatment: 1180 °C/4 h + 870 °C/20 h + air cooling
NKH-510	11Co, 6Cr, 6W, 5.4Al, 1.4Ti, 6.8Ta, 4.8Re, 0.12Hf, 3Ru and bal. Ni	Solution heat treatment: 1310 °C/10 h + 1320 °C/12 h + gas furnace cooling and followed by aging treatment: 1160 °C/4 h + 870 °C/20 h + air cooling

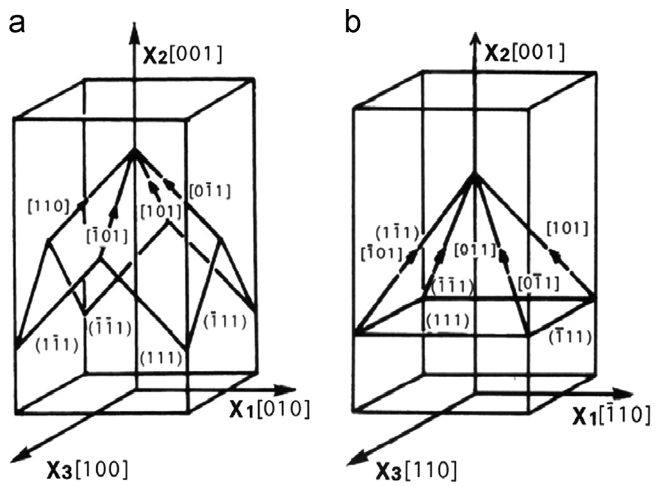

Fig. 1. Arrangement of {111}⟨101⟩ slip systems for two kinds of creep specimens with (a) {100} and (b) {110} side-surface orientations.

The specimens were then embedded in an Al_2O_3 retort containing a mixture of 24.5 mass% Al, 24.5 mass% Cr, 49 mass% Al_2O_3 and 2 mass% NH_4Cl powders, and heated at 1000 °C for 5 h in flowing argon for the aluminizing treatment called the pack cementation process. The coated superalloys were then subjected to creep test with a temperature of 900 °C and a stress of 392 MPa with a parallel load ⟨001⟩ direction. For comparison, the creep test was also conducted on uncoated specimen under same conditions in order to determine the effect of the aluminide coating on the creep behavior of Ni-base single crystal superalloys. The microstructural changes before and after the creep rupture tests were observed by scanning electron microscopy (SEM). The compositional profiles through the cross section of samples were analyzed by electron probe microanalysis (EPMA). The orientation of crystal grain was identified by a TSL-OIM electron back scattered diffraction (EBSD) analyzer.

3. Results

3.1. Microstructures after heat treatment and coating

The microstructures of the γ' precipitates after aging heat treatment are shown in Fig. 2. No obvious differences in the morphology of γ′ precipitates were observed between the two alloys. The mean γ′ precipitate lengths were 345 nm and 310 nm in the alloys NKH-304 and NKH-510 respectively. The γ′ precipitate size of the Ru-containing alloy NKH-510 was a little smaller than that of the base alloy. SEM micrographs of as-aluminized Ni-base single crystal superalloys NKH are shown in Fig. 3. Three distinctive layers can be distinguished from the micrographs: (i) the coating as an outer protective layer, (ii) an interdiffusion zone (abbreviated as IDZ), and (iii) a substrate. IDZ was derived from the reaction between the inward diffusion of Al, produced by the coating powders mixture and the outward diffusion of Ni from the substrate at the interface area, which was composed of β-NiAl due to the heat treatment. The thickness of the IDZ seemed to vary in both side-surface orientations as shown in Fig. 3. The IDZ thickness of the aluminized NKH-304 was about 3.0 μm on the {100} side-surface and 4.7 μm on the {110} side-surface; meanwhile, the IDZ thickness of aluminized NKH-510 was about 2.3 μm on the {100} side-surface and 3.9 μm on the {110} side-surface. In other words, differences in IDZ thickness ensued in all specimens. This means that the presence of the coating rendered the changes in the effective cross-section area that affects the creep behavior of Ni-base superalloys.

3.2. Creep behavior

Fig. 4 shows the variation in creep rupture lives performed at a temperature of 900 °C and a stress of 392 MPa. The two superalloys exhibited similar trends, while the bare specimens with the {100} side-surface orientation demonstrated higher creep rupture life than the {110} side-surface orientation. It was clear that the coating treatment resulted in a significant decrease in creep rupture life in both superalloys. Furthermore, the difference in creep rupture life between the two orientations indicated that anisotropy in creep had occurred. In general, the aluminized NKH-510 had a higher creep rupture life than the aluminized NKH-304, in both the {100} and {110} side-surface specimens. The creep rupture lives of aluminized NKH-304 were 311 h for the {100} side-surface specimen and 253 h for the {110} side-surface specimen, while the measures for aluminized NKH-510 were 641 h for the {100} side-surface specimen and 539 h for the {110} side-surface specimen. The differences in creep rupture lives for both side-surface orientations were 58 h (19%) for the aluminized NKH-304 and 102 h (16%) for the aluminized NKH-510.

3.3. Microstructures after creep rupture test

The SEM micrographs of aluminized specimens after creep rupture test are presented in Fig. 5. An additional zone formed beneath the IDZ in all specimens; this additional zone is called the substrate diffusion zone (SDZ). The SDZ must be differentiated from the IDZ in that it remains particularly γ′ and retains the orientation of the single crystal substrate. However, the secondary reaction zone (SRZ) could not be observed in the two superalloys, as the localized recrystallization had not yet occurred at this stage. The diffusion layer thickness was approximately 23.3 μm on the {100} side-surface specimen and 32.9 μm on the {110} side-surface specimen in the aluminized NKH-304 (Fig. 5a and b). Meanwhile the diffusion layer thickness was approximately 21.6 μm on the {100} side-surface specimen and 33.1 μm on the {110} side-surface specimen in the aluminized NKH-510 (Fig. 5c and d). In addition, the TCP phase was precipitated in the {100} and {110} side-surface specimens for both superalloys, but in differing amounts. The aluminized NKH-510 contained much more TCP phase than the aluminized NKH-304. As crystallographic orientation affected the growth of TCP phases, the formation of these phases was different in the two orientations. The TCP phase showed a