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Distinctive role of plastic and creep strain in directional coarsening of a Ni-base single crystal superalloy

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ABSTRACT

The distinctive role of plastic and creep strain in directional coarsening of a single crystal Ni-base superalloy, CMSX-4, was experimentally and analytically investigated. First, solid cylindrical samples were subjected to uniaxial tensile plastic strain at 900 °C followed by thermal aging at 1080 °C. Microstructural observation revealed that the extent of directional coarsening became more pronounced with increasing plastic strain until it reached 0.2%; no further coarsening was induced with the introduction of additional plastic strain. Second, several combinations of plastic and creep strain were applied to the samples. The magnitude of the compressive creep strain at 1080 °C was varied with the plastic strain fixed at 1.5% at 900 °C. The results indicated that the effect of 0.15% creep strain was completely balanced with that of the 1.5% plastic strain; hence, the effects of the plastic and creep strain on the morphological changes differed quantitatively. Finally, elastic-plastic and creep finite element analyses were conducted to rationalize the experimental results. The analytical investigations suggested that the directional coarsening was dependent on the inelastic strain gap between the γ and γ' phases, which was attributed to an inhomogeneous relaxation of the local misfit stress field. The difference in the roles of plastic and creep strain in the coarsening was observed to quantitatively correspond to the difference in the localized inelastic deformations.

1. Introduction

Single crystal Ni-base superalloys are widely used as blade materials for industrial gas turbines and aircraft engines, because they exhibit superior strength at elevated temperature [1]. The typical microstructure of single crystal superalloys consists of cuboidal γ' precipitates surrounded by narrow channels of γ matrix. Many researchers have noted that this unique γ /γ' microstructure substantially affects the mechanical behavior of single crystal superalloys [1–3]. During the operation of a gas turbine, severe directional coarsening, so-called rafting phenomenon, of the initially cuboidal γ' precipitates into the plate-like (normal to the stress axis) or needle-like (parallel to the stress axis) structure can occur locally in hot sections because of the creep stress [2–5]. The plate-like structure, which is developed perpendicular to the uniaxial applied stress, is usually associated with negative-misfit superalloys stressed in tension or positive-misfit ones stressed in compression [2–5]. In contrast, the needle-like structure, which is developed parallel to the stress direction, is associated with positive-misfit superalloys stressed in tension, and negative-misfit ones stressed in compression. The coarsening process and its mechanism have been extensively investigated both experimentally and theoretically [2–8].

In addition to the rafting phenomenon resulting from the creep stress, some experiments have revealed that directional coarsening can be induced by simple plastic straining and subsequent aging [9,10]. Here, the term *plastic* strain is defined as an inelastic strain that cannot induce microstructural evolution if the subsequent aging treatment is not performed. This *plastic* strain should be distinguished from the *creep* strain that can cause directional coarsening during a straining process, as in the rafting phenomenon [9,10]. Véron and Bastie [9] experimentally demonstrated that plastic pre-strain at 850 °C and subsequent aging at 1100 °C led to directional coarsening and kinetically showed that these findings were the result of an inhomogeneous misfit relaxation by the slip dislocation at the γ /γ' interfaces. In addition, we [10] also showed that the extent of directional coarsening was dependent on the temperature during the plastic straining, which was mainly attributed to temperature-dependent plastic deformation in the single crystal superalloy. Here, we performed plastic straining tests for ring-shaped samples, in which the loading generated a non-uniform plastic strain and built up a residual stress field after the unloading [10]. The microstructure in this ring-shaped sample after the subsequent aging treatment at 1080 °C revealed that the directional coarsening mainly

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depended on the direction and magnitude of the creep strain due to the relaxation of residual stress during the subsequent aging treatment [10]. The plastic strain had a less pronounced effect on the morphological changes than the creep strain. However, the quantitative role of plastic strain in the directional coarsening and its difference from that of creep strain have not yet been clarified. This information is important to attain a comprehensive understanding of the microstructural evolution in actual superalloys components. They have to experience various plastic deformations associated with severe thermal stresses during the start-up and shut-down period during operation. Interpretation on the phenomena with fully understanding to the effect of strains history composed of plastic and creep strain will provide a useful information to estimate the actual stress state and access the remaining life of the superalloys component.

The objective of this work was to quantitatively clarify the roles of plastic and creep strain in directional coarsening. First, uniaxial plastic strains were introduced to solid cylindrical samples at 900 ˚C to clarify the relationship between the magnitude of plastic strain and the extent of the directional coarsening. Next, several combinations of tensile plastic strain at 900 ˚C and compressive creep strain at 1080 ˚C were applied to compare the effect of plastic and creep strains on the directional coarsening. Then, the roles of the plastic and creep strain were quantified using finite element analysis considering several microstructural factors such as the misfit stress field and inhomogeneous inelastic deformation behaviors of the γ and γ' phases.

2. Experimental procedure

2.1. Material and sample preparation

A second-generation single crystal superalloy, CMSX-4, was used in this work. The chemical composition of CMSX-4 is 6.4Cr, 9.7Co, 0.6Mo, 6.4 W, 1.0Ti, 6.5Ta, 2.9Re, 0.1Hf, 5.7Al, and bal. Ni in weight percent. For this alloy, the heat treatments were conducted as follows: an 8-stage solution treatment of 1277 ˚C × 2 h + 1288 ˚C × 2 h + 1296 ˚C × 3 h + 1304 ˚C × 3 h +1313 ˚C × 2 h + 1316 ˚C × 2 h + 1318 ˚C × 2 h + 870 ˚C × 2 h in an argon atmosphere followed by two stages of aging treatment of 1140 ˚C × 6 h + 870 ˚C × 20 h in air. After the heat treatment, the CMSX-4 exhibited a regular γ/γ' microstructure consisting of cubic γ' precipitates embedded in a narrow γ matrix, as shown in Fig. 1. The volume fraction and size of γ' were 68% and 0.55 µm, respectively. The average γ/γ' lattice misfit of this alloy was −0.17% when the temperature increased to 900 ˚C [11]. From the casting rod of CMSX-4, solid cylindrical samples, for which gauge section was 5.0 mm in diameter and 15 mm in length (see Fig. 2), were machined for plastic and creep straining tests. The main axis lied within 5 ° from the [001] crystallographic orientation.

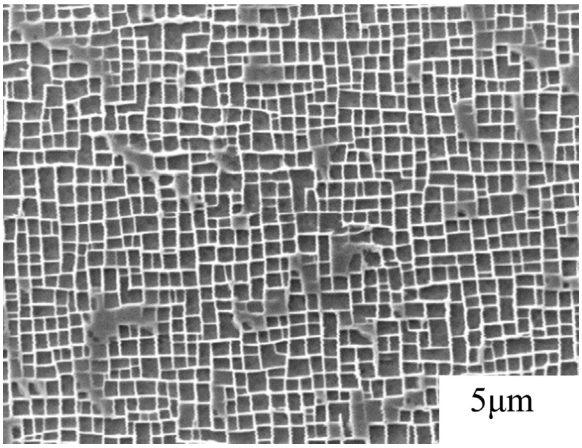

Fig. 1. Initial γ/γ' microstructure of CMSX-4.

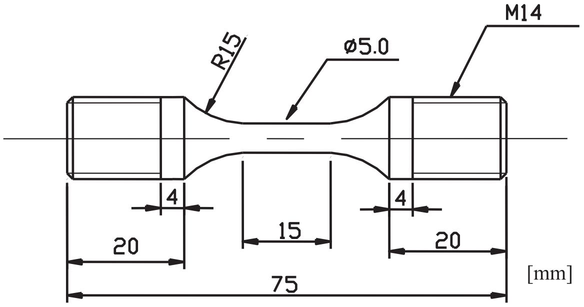

Fig. 2. Geometry of solid cylindrical sample.

2.2. Conditions of plastic and creep straining tests

The primary objective of this work was to clarify the quantitative difference between *plastic* and *creep* strains as driving forces in directional coarsening. According to previous work [10], no microstructural changes were observed directly after the plastic straining process, in which the plastic strain was applied under a strain rate of 3.0×10^{-5}(1/s) at 900 ˚C. The directional coarsening was only observed after the subsequent aging at 1080 ˚C for 20 h. This condition of the subsequent aging is sufficient to complete a kinetic process of the directional coarsening [10]. Therefore, the strain rate and temperature were set at the same conditions for plastic straining in this study.

First, four samples were plastically strained in tension at 900 ˚C, where the magnitudes of the applied strains were changed from 0.05% to 1.5% (see Table 1; Samples 1–4). Second, three samples were subjected to compressive creep strains at 1080 ˚C followed by 1.5% plastic tensile strain at 900 ˚C, where the magnitude of the compressive creep strain was changed from −0.1% to −0.3% fixing the tensile plastic strain at 1.5% (see Table 1; Samples 5–7). The plastic strains were applied at a constant strain rate of 3.0×10^{-5} /s under the strain controlled condition, whereas the creep strains were applied under the constant stress condition of −120 MPa. The axial strains were measured and controlled by a push-on-type strain extensometer. The samples were heated using a high frequency induction heating system, where the temperature was controlled by thermocouples in direct contact with the gauge section. A preliminary test confirmed that the temperature distribution in the gauge section was within 5 ˚C when the sample was heated to 1080 ˚C.

2.3. Quantitative analysis of γ/γ' morphological changes

After the plastic and creep straining tests, all seven samples were sectioned in the axial direction on the (100) plane and subjected to subsequent aging at 1080 ˚C for 20 h, which served to reconstruct the γ/γ' microstructures through the effect of plastic pre-strains [10]. The morphological changes before and after the subsequent aging were examined using scanning electron microscopy (SEM, JEOL 5400). Because the lattice misfit of CMSX-4 is strongly dependent on the position in the dendrite structure, the morphological changes in the inter-dendrite regions were not considered.

Table 1
Summary of plastic and creep straining tests employed in this study.

Sample	Plastic strain, ε_p (900 ˚C)	Creep strain, ε_c (−120 MPa/1080 ˚C)
Sample 1	0.05%	–
Sample 2	0.2%	–
Sample 3	0.8%	–
Sample 4	1.5%	–
Sample 5	1.5%	− 0.1%
Sample 6	1.5%	− 0.15%
Sample 7	1.5%	− 0.3%