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Effect of Creep on Crystallographic Orientation in Single Crystal Superalloy

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The creep-rupture tests were performed on a single crystal rods made of CMSX-4 superalloy obtained at withdrawal rates of 3 and 5 mm/min. After the rupture the microstructure and fracture surface were examined and correlated with X-ray crystal rotation measurements by the Ω-scan method. The conclusions about the crystal lattice rotation during creep test were provided.

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1. Introduction

High efficiency of modern turbine engines requires high temperature of exhaust gases driving the turbine section [1]. As a result, the conditions to which the turbine components are exposed become much more demanding. Structural components developed to withstand these conditions, such as first stage turbine blades and vanes, are of particular interest to ensure their safe and effective use [2]. Therefore, full characteristic of the materials used in manufacturing of these structural components, mostly single crystal nickel-base superalloys are necessary to predict the exploitation lifetime and evaluate their performance. The key issue with regard to the turbine blades is both their exposure for high temperature and load during service which induce creep fatigue [3]. Therefore, creep characteristics are carefully investigated in high-temperature materials. It is well known that the mechanical properties of single crystals are inherently anisotropic [4]. Turbine blades are produced using the withdrawal process with a selector technique to obtain the well oriented structure, mostly in [001] direction. Studies on the influence of primary and secondary orientation on the creep behavior of the single crystal have been carried out by many researchers [5–7]. However, the exact influence of creep on orientation changes is not well known. Studies on rotation of crystallographic orientation during creep are essential for modelling the creep behavior and the prediction of the engines parts lifetime [8–10]. The main objective of this study is to investigate the effect of creep on the crystallographic orientation behavior of Ni-based single crystal superalloy obtained at different withdrawal rates.

2. Experimental

An industrial Ni-based single crystal CMSX-4 superalloy was used as casting material. The chemical composition of superalloy in wt% is 9.6 Co, 6.4 Cr, 6.4 W, 6.5 Ta, 5.6 Al, 3.0 Re, 1.0 Ti, 0.6 Mo, 0.1 Hf, and balance Ni. The single crystal superalloy was produced in form of cylindrical rods, which were directionally solidified by the Research and Development Laboratory for Aerospace Materials at Rzeszów University of Technology with the use of a vacuum furnace for directional solidification VIM-IC 2 E/DS/SC ALD. The exact orientations of the specimens were determined by the Laue back-reflection technique. The casts were solidified at the withdrawal rates of 3 and 5 mm/min. After the casting process, specimens with a gauge length of 30 mm and a diameter of 3 mm, were prepared by mechanical machining and grinding. These specimens were tested in tensile creep under constant stress at temperature of 982 °C. The applied stress was 248 MPa. After the rupture, longitudinal cross-sections were prepared across the undeformed head part and gauge part for microstructural and orientation studies. Orientation measurements were conducted using X-ray diffraction method invented by the EFG company (Berlin) called Ω-scan [11, 12]. This method with the use of diffractometer design for measuring reflexes of Ni-based superalloys is able to map, point by point, the sample surface and measure crystallographic orientation. Additionally, characterization of microstructure and fracture surface were made with the use of scanning electron microscope JEOL JSM-6480.

3. Results

By applying the Laue back-reflection method it was determined that the misorientation of [001] direction from the samples axis was 6° for samples obtained at withdrawal rate of 3 mm/min and 1° for 5 mm/min. The creep rupture lives of the single crystal CMSX-4 superalloy samples obtained at 3 and 5 mm/min withdrawal rates were 165 h and 151 h, respectively. The microstructures of longitudinal section presented in Fig. 1 show that the primary dendrite arms are well aligned in the head part of the creep samples after rupture. In both samples, dendrites became distorted in the gauge part which

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can be seen by short cross-sections of dendrite cores to appear locally on the sample surface (A, Fig. 1). Microvoids appeared at similar distances from fractured surface (Fig. 1, mv) for both samples. The fractured surfaces of both samples showed the smooth outer ring typical for a creep failure. Both fracture surfaces are clearly showing facets with fourfold symmetry which confirm that deformation occurred on the {111} planes (Fig. 2).

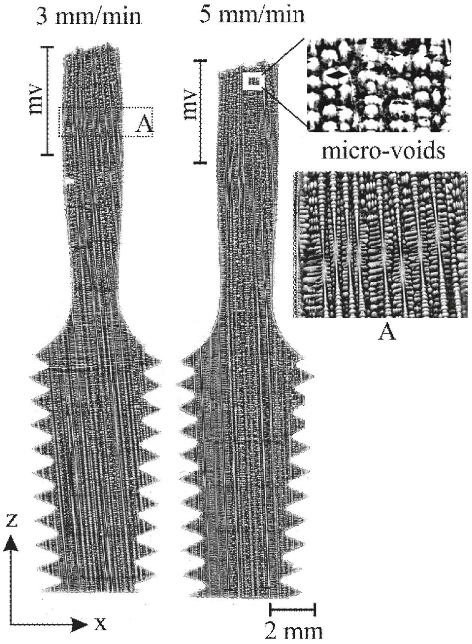

Fig. 1. SEM microstructure of longitudinal sections of creep samples after rupture, mv — micro-voids area.

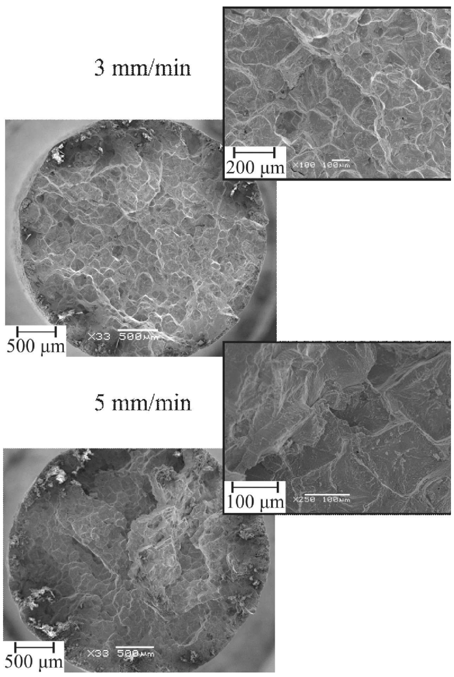

Fig. 2. Fracture surfaces of tested samples obtained at different withdrawal rates.

The crystal orientation maps were determined by applying the Ω-scan method. The maps were obtained by collecting about 350 measuring points with the use of a 1 mm spot size. The step on the surface was set to 0.5 mm. Additionally, it is possible to estimate lattice parameter changes with this technique. Maps of the Euler angles and lattice parameters for samples obtained at withdrawal rates at 3 mm/min and 5 mm/min are shown in Figs. 3 and 4. In both samples, rotation of lattice occurred mostly in the gauge part.

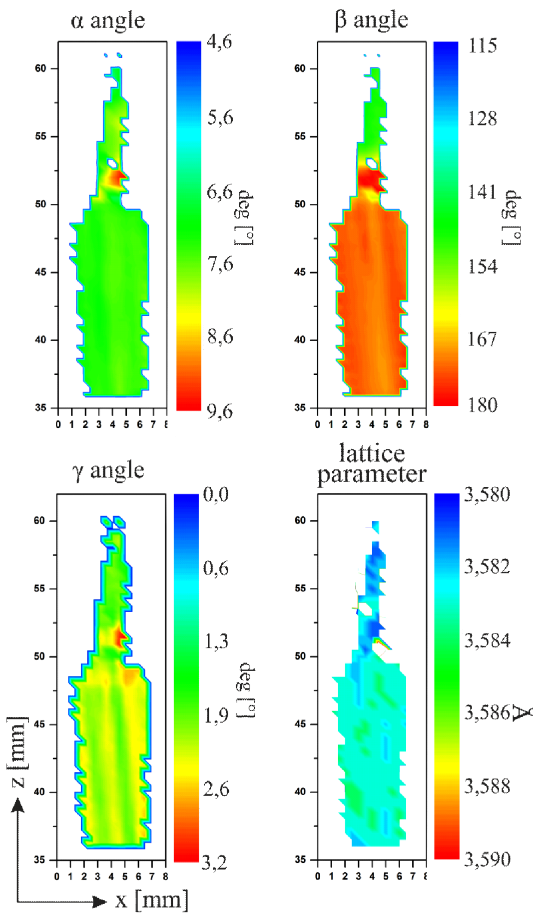

Fig. 3. Orientation maps of Euler angles and lattice parameter changes for sample obtained at withdrawal rate of 3 mm/min.

Non-continuous rotation appeared in the heads of creep samples. However, some low angles boundaries between dendrite cores appeared in the head part of sample obtained at 3 mm/min rate — γ angle rotation shows lines of the same misorientation which correspond to the primary dendrite arms direction. This can be the evidence that in the first stage of creep, dendrite cores keep the orientation and act as strengthening entities, similar to the composite structures. Comparing maps from both samples we can see that higher rotation occurred in the sample obtained with higher withdrawal rate where for β angle gauge part rotates with higher degree (Fig. 4).

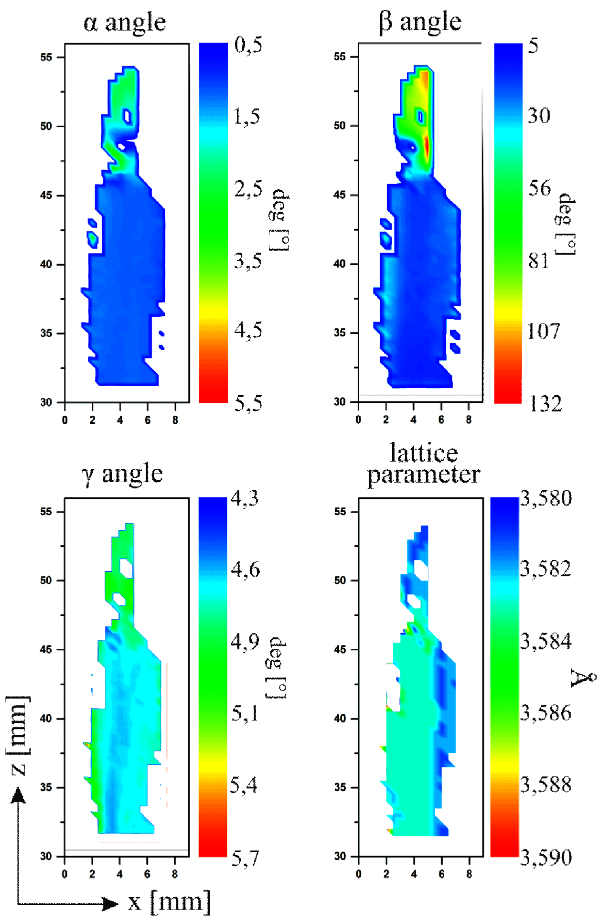

Fig. 4. Orientation maps of Euler angles and lattice parameter changes for sample obtained at withdrawal rate of 5 mm/min.

4. Summary

The microstructure changes and lattice rotation were analyzed on single crystal CMSX-4 superalloy obtained at 3 and 5 mm/min withdrawal rates after creep deformation at 982 °C. The longitudinal cross-sections of samples after rupture show that primary dendrite arms were well aligned in the head part of creep samples. However, some low angle boundaries appear between dendrite cores which is shown by straight lines of misorientation corresponding to primary dendrite cores. This suggests that primary dendrite arms can act as strengthening entities in the first stages of creep. For both samples, the fractured surfaces show similar mechanism of failure with dominant octahedral slip on {111} planes. The rotation of the lattice and dendrite distortion occurring in the gauge part of the creep samples were not uniform with higher rotation near the holders and fracture surface. There was no visible continuing rotation of lattice along the gauge. The higher degree of lattice rotation were observed for the sample obtained at 5 mm/min withdrawal rate, especially on β angle, which is the rotation around load axis.

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