Materials Science and Engineering A 527 (2010) 5383–5390

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Anisotropic stress rupture properties of the nickel-base single crystal superalloy SRR99

G.M. Han [a,b], J.J. Yu [a,*], Y.L. Sun [a], X.F. Sun [a], Z.Q. Hu [a]

[a] Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China
[b] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 8 December 2009
Received in revised form 6 April 2010
Accepted 20 May 2010

Keywords:
Single crystal superalloy
Stress rupture
Anisotropy
Deformation mechanism

ABSTRACT

The influence of orientation on the stress rupture properties of a single crystal superalloy SRR99 was investigated at temperatures of 760 and 1040 °C. It is found that the creep anisotropic behaviour is pronounced at the lower temperature of 760 °C and the stress rupture life ranks in the order [0 0 1] > [1 1 1] > [0 1 1]. Despite the anisotropy of stress rupture life is evidently reduced at the higher temperature, the [1 1 1] orientation exhibits the longest life. At 760 °C, EBSD (electron back scattered diffraction) was adopted to measure the lattice rotation and the deduced results indicate that the dominant slip systems are ⟨1 1 2⟩ {1 1 1} during stress rupture test. At 1040 °C, the ranking order of the stress rupture life is [1 1 1] > [0 0 1] > [0 1 1] and the single crystal close to [0 1 1] orientation still shows the poorest life. In the [0 0 1] and [1 1 1] samples, regular γ′ raft structure is formed compared with [0 1 1] samples. Further observations made by TEM investigations reveal the underlying deformation mechanisms for crystals with orientations near [0 0 1], [0 1 1] and [1 1 1] under two test conditions.

1. Introduction

Single crystal nickel-base superalloys, which are widely used in gas turbine blades, have significantly raised operating temperature and efficiency due to their excellent properties in service. However, it is well known that the creep deformation of single crystal superalloy is inherently anisotropic and gas turbine blades with complex shape and cooling channels usually experience a range of stress levels and thermal gradients, it is therefore necessary to investigate the orientation and temperature dependence of the creep properties of nickel-base superalloy single crystals [1]. Although there have been several experimental studies of the anisotropic creep behaviour of single crystal superalloy [2–4], there are still some apparently contradictory results.

MacKay and Maier [3] have reported that samples oriented close to [1 1 1] show the longest lifetimes for MAR-M247 at 774 °C and 724 MPa. But Caron et al. [5] investigated the anisotropic creep behaviour of some advanced superalloys in the temperature ranging from 760 to 1050 °C and have shown that the γ′ particle size and morphology can have a strong influence on both the magnitude and order of different orientations at intermediate temperatures (760–850 °C). They found that for a γ′ edge length of about 0.5 μm, the creep strength of [0 0 1] orientation was optimum while the creep life of [1 1 1] orientation drastically reduced. For smaller γ′ particle the reversal result is true. At higher temperatures (950–1050 °C), the effect of orientation and the particle size on creep strength is considerably reduced. In the later study Sass et al. [6] investigated the influence of orientation on creep behaviour for small strain of single crystal superalloy CMSX-4 at temperatures of 1123 and 1253 K and indicated that [1 1 1] orientation exhibits the poorest creep strength because of poor strain hardening and the activation of additional deformation mechanism. Nevertheless, there is a consensus that the degree of anisotropy of creep behaviour decreases with increasing temperature.

Early work by Winstone [7] on the first generation single crystal superalloy SRR99 has shown that the creep strength of [0 0 1] orientation was stronger than that of [1 1 1] at the lower temperature and this trend of anisotropy was reversed with increasing temperature. Even though the deformation mechanisms for different orientations in various stages of creep have been extensively investigated through TEM analysis for some single crystal superalloys such as CMSX-4 and MAR-M200, notably in the low temperature creep regime, it is not easy to completely elucidate the deformation mechanisms operating in different single crystal superalloys under various conditions of stress, temperature, and orientation. Therefore, it is necessary to further investigate anisotropic stress rupture properties of single crystal in detail and rationalize deformation mechanisms and their temperature and stress dependence. This is the purpose of the present paper.

* Corresponding author. Tel.: +86 24 23971713; fax: +86 24 23906722.
E-mail address: jjyu@imr.ac.cn (J.J. Yu).

0921-5093/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2010.05.051

Table 1
Nominal composition of SRR99 alloy (wt%).

Al	Ti	Cr	Co	Ta	W	C	Ni
5.5	2.2	8.5	5.0	2.8	9.5	0.015	Bal.

2. Experimental procedure

The material used in this study was SRR99 single crystal superalloy. The nominal chemical composition of this alloy is shown in Table 1. The ⟨0 0 1⟩ single crystal rods were produced by the withdrawn process with a selector technique while the directions close to ⟨0 1 1⟩ and ⟨1 1 1⟩ single crystals were grown on a pre-fabricated seed of the desired orientation. Crystallographic orientation of the cast rods was determined by EBSD technique. All specimens received a standard heat treatment including a step solution treatment at 1300 °C for 4 h, followed by a two-step ageing treatment at 1100 °C for 4 h and at 870 °C for 16 h. After this heat treatment, a mean particle size of cubical γ′ was about 0.45 μm and the volume fraction of γ′ phase was about 70%.

The crystals were machined into tensile specimens and the gauge of cylindrical samples had a length of 25 mm and a diameter of 5 mm. The tensile stress rupture tests were performed in air at the temperatures of 760 and 1040 °C using constant-load machines. A series of specimens B, K and P oriented close to three principal orientations were used to do interrupted creep tests in different creep stages before rupture. The specimens were cooled under load in order to preserve the typical microstructure for further investigations. The samples for scanning electron microscopy (SEM) were sectioned along longitudinal section and then prepared by grinding, polishing and electro-etching using a solution of 5 ml HNO_3 + 10 ml CH_3COOH + 85 ml H_2O to reveal γ′. Thin foils for transmission electron microscopy (TEM) observation were cut parallel to low indexed crystallographic planes, then mechanically ground to 50 μm and finally electron-polished at −25 °C in a solution of 8% perchloric acid + 92% ethanol. The TECNAI20, operated at 200 kV, was used for TEM investigations.

3. Experimental results

3.1. Results of creep tests at T = 760 °C

The general results of SRR99 single crystals which were stress rupture tested at 760 °C are summarized in Table 2. Stress rupture lives as a function of orientation are shown in Fig. 1 and the letter in parentheses is the specimen identification. It is clear that the creep behaviour of SRR99 at 760 °C and 790 MPa is highly anisotropic. Extremely low lives are exhibited close to the [0 1 1] and [$\bar{1}$ 1 1], and the longest lives are associated with the [0 0 1] orientation. It also indicates that crystal M with orientation towards the right-hand side of the triangle has higher creep rate and particularly poor creep property. A few representative creep curves are illustrated in Fig. 2. It is clear that the creep curve of crystal B near [0 0 1] orientation shows the lowest primary creep rate at low strains followed by hardening and the transition into secondary creep. For the [0 1 1] orientation, the specimen K tested at 790 MPa failed in less than 5 h. Compared to specimens with [0 0 1] and [0 1 1] orientations, specimen P oriented to [$\bar{1}$ 1 1] exhibits the highest creep rate and largest elongations to rupture at 790 MPa.

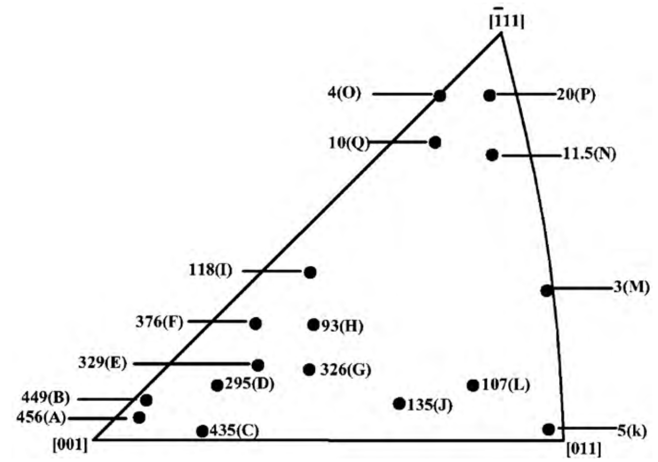

Fig. 1. Stress rupture lives shown as a function of orientation for SRR99 single crystals tested at 760 °C and 790 MPa. The number associated with each orientation is the life of the crystal in hours; the corresponding letter in parentheses is the specimen identification.

3.2. Lattice rotation at T = 760 °C

For single crystals, plastic deformation results in the movement of the specimen axis towards the slip direction. In order to obtain further information on the deformation mechanisms prevailing during creep deformation, the lattice rotations which were determined in the present study by EBSD measurement for some selected specimens under stress rupture test at 760 °C and 790 MPa are illustrated in Fig. 3. It can be seen that the crystals K and M initially near

Table 2
Rupture life data of SRR99 single crystals tested at 760 °C and 790 MPa.

Specimen	T (°C)	Stress (MPa)	Life (h)	Elongation (%)	$\dot{\varepsilon}_p$ (%)	$\dot{\varepsilon}_m$ ($\times 10^{-8}$ S^{-1})	Orientation degrees from	
							[0 0 1]	[0 1 1]
A	760	790	456	16	1	4.8	3.85	41.78
B			449	14.56	1.2	5.2	5.85	40.53
C			435	13.44	1.1	5.4	9.43	35.31
D			295	12.24	1.2	5.7	12.53	34.75
E			329	16	1.8	5.7	15.79	31.23
F			376	9.04	1.4	5	18.39	31.38
G			326	7.04	0.5	6.5	21.36	25.36
H			93	10.24	0.8	20	23.93	26.09
I			118	6.64	1.3	10	25.73	27.82
J			135	3.44	0.7	9.8	29.22	15.7
K			4.7	4.08	1.5	100	43.40	2.41
L			107	3.28	0.6	7	35.57	10.66
M			3	37.44			45.87	13.53
N			11.5	24.48	2.5	360	42.30	24.35
O			4	22.64			45.97	31.43
P			20	40.16	2	244	49.26	29.73
Q			10	35.13			42.08	29.03