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Tensile, creep behavior and microstructure evolution of an as-cast Ni-based K417G polycrystalline superalloy

Beining Du[a], Ziyang Hu[a,c], Liyuan Sheng[a,*], Chuanyong Cui[b,*], Jinxia Yang[b], Yufeng Zheng[a], Xiaofeng Sun[b]

[a] Shenzhen Institute, Peking University, Shenzhen 518057, China
[b] Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China
[c] Shenzhen Yezhan Electronics Co., Ltd., Shenzhen 518110, China

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ABSTRACT

The Ni-based K417G superalloy is extensively applied as aeroengine components for its low cost and good mid-temperature (600–900 °C) properties. Since used in as-cast state, the comprehensive understanding on its mechanical properties and microstructure evolution is necessary. In the present research, the tensile, creep behavior and microstructure evolution of the as-cast K417G superalloy under different conditions were investigated. The results exhibit that tensile cracks tend to initiate at MC carbide and γ/γ′ eutectic structure and then propagate along grain boundary. As the temperature for tensile tests increases from 21 °C to 700 °C, the yield strength and ultimate tensile strength of K417G superalloy decreases slightly, while the elongation to failure decreases greatly because of the intermediate temperature embrittlement. When the temperature rises to 900 °C, the yield strength and ultimate tensile strength would decrease significantly. The creep deformation mechanism varies under different testing conditions. At 760 °C/645 MPa, the creep cracks initiate at MC carbides and γ/γ′ eutectic structures, and propagate transgranularly. While at 900 °C/315 MPa and 950 °C/235 MPa, the creep cracks initiate at grain boundary and propagate intergranularly. As the creep condition changes from 760 °C/645 MPa to 900 °C/315 MPa and 950 °C/235 MPa, the γ′ phase starts to raft, which reduces the creep deformation resistance and increases the steady-state deformation rate.

1. Introduction

Ni-based polycrystalline superalloy is widely used in industrial turbine and aeroengine components which serve at mediate temperature (600–900 °C) for its good mid-temperature properties and relatively low manufacturing cost [1,2]. However, to ensure its long-term service at critical conditions of temperature and stress, a wide range of alloying elements, such as Cr, Mo, B, and C are usually added in the Ni-based polycrystalline superalloy [3,4]. Then the microstructure of the polycrystalline superalloy becomes complicated with the coexistance of γ, γ', carbide, boride, eutectic, topologically close-packed (TCP) phases and so on [5]. Therefore, there would be many factors affecting the mechanical properties of polycrystalline Ni-based superalloy, such as precipitates, grain size, grain boundary, etc.

The recent researches demonstrated that the microstructures could influence the mechanical performance of polycrystalline superalloy in different ways [5,6]. He et al. [7] have investigated the creep property of M963 superalloy and found that the interface of MC carbide and matrix could initiate cracks. The researches of Yang et al. [8] and Liu et al. [9] also confirmed that MC carbide would lead to initiation of tensile and creep cracks in superalloys, and then cause the final fracture. Besides, as a low strength phase, γ/γ′ eutectic structure is also considered as crack initiation site. Wei et al. [10] have found that tensile cracks would form at γ/γ′ eutectic area in CM-681LC superalloy. γ' phase is the major strengthening phase of Ni-based superalloy, which would influence the deformation of superalloy through the interaction with dislocations [11–13]. Grain boundary is an important component of the microstructure in polycrystalline superalloy. The grain boundary strength and precipitates along grain boundary would affect the mechanical properties obviously [14–17]. B and C are simultaneously added in polycrystalline superalloy to strengthen its grain boundary, which would result in precipitates along grain boundary [18]. According to the recent research [19], the evolution of grain boundary structure and

* Corresponding authors.
E-mail addresses: lysheng@yeah.net (L. Sheng), chycui@imr.ac.cn (C. Cui).

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Table 1
Nominal composition of K417G superalloy (wt%).

	Cr	Co	Mo	V	Al	Ti	C	Zr	Ni
0.018	9.00	10.00	3.00	0.75	5.25	4.40	0.18	0.07	Balance

the adjacent precipitate would exert some effects on the mechanical properties by inducing microcracks. In a word, the deformation mechanisms of polycrystalline superalloy at different conditions are intricate. Moreover, the microstructure would evolve during service at high temperature, which would influence the dislocation movement, crack initiation and deformation behavior of superalloy [17,20]. Therefore, it is necessary to analyze the overall microstructure evolution during deformation, which is helpful to clarify the deformation mechanism.

The Ni-based K417G polycrystalline superalloy is developed by the Institute of Metal Research, Chinese Academy of Sciences. It contains less refractory alloying elements compared with other superalloys, so that its elements segregation during solidification is not serious, and it can be used in as-cast state. Accordingly, K417G superalloy is a low cost and density alloy, and has a quite simple manufacturing process, which can be used on gas turbine engine parts, such as turbine blades and vanes [18,21]. Tensile and creep properties are important indexes for evaluating the mechanical properties of superalloys [22–25]. Through tensile test, the strength and ductility of superalloy can be obtained, thus the mechanical performance of superalloy can be evaluated preliminarily. Creep deformation and fracture is one of the main failure modes of superalloys during service [26,27]. Creep test could simulate the deformation of superalloy under actual service conditions of high temperature and stress. The comprehensive analysis on the tensile, creep behavior and microstructure evolution would deeply understand the interaction of microstructure and mechanical properties of superalloys. Therefore, in the present research, the Ni-based K417G polycrystalline superalloy is fabricated, and its tensile properties, creep properties, microstructure evolution and dislocation morphology are investigated to thoroughly understanding its deformation mechanism.

2. Experimental procedures

The nominal composition of K417G superalloy is listed in Table 1. The alloy was melted in vacuum induction furnace at 1500 °C and poured into mold at 1350 °C to obtain as-cast alloy rods with 15 mm in diameter and 220 mm in length. Cylindrical specimen was cut from the as-cast rod to observe its microstructure. After grinded, polished and chemical etched in a solution of 5 g $CuSO_4$ + 20 mL HCl + 25 mL H_2O, the grain distribution and microstructure of the specimen were observed through INSPECT F50 scanning electron microscope (SEM). Image-Pro Plus software was applied to calculate the average grain size of the superalloy and the average size and area fraction of carbide and γ/γ′ eutectic structure.

The as-cast rods were machined into standard tensile and creep specimens without heat treatment, as shown in Fig. 1. The tensile tests were conducted on an INSTRON 5582 testing machine. The testing temperatures were 21 °C, 700 °C and 900 °C. These three temperatures were chosen because at 21 °C, the microstructure of polycrystalline superalloy could keep stable. 900 °C can be considered as the ceiling service temperature of polycrystalline superalloys, and 700 °C is an appropriate service temperature for polycrystalline superalloys. At least three identical specimens were tested at each temperature. The tensile speed is 0.001 mm/s and displacement-controlled tests. The tensile tests at 21 °C are conducted according to the GBT228.1-2010 test standard, and the tensile tests at 700 °C and 900 °C are conducted according to the GBT228.2-2015 test standard.

The creep tests were performed on a CSS3905 testing machine. The testing temperature and stress were 760 °C/645 MPa, 900 °C/315 MPa and 950 °C/235 MPa. These three test conditions were chosen to clarify the creep behavior of K417G superalloy at low temperature/high stress, moderate temperature/moderate stress and high temperature/low stress conditions, respectively. The creep tests in this paper are according to the GBT2039-2012 test standard.

After tensile and creep tests, longitudinal sections were cut from the fractured specimens. After grinding, polishing and chemical etching, the longitudinal sections were observed on SEM to observe the crack propagation path and microstructure evolution. 2 mm thick samples were cut near the tensile and creep crack surfaces. After grinding and electropolishing in a 10% $HClO_4$ + 90% C_2H_5OH solution, Electron Back-Scattered Diffraction (EBSD) was used to observe the plastic deformation distribution after tensile and creep tests. Samples for transmission electron microscope (TEM) observation were obtained from thin slice cut at a distance of 5 mm away from the fracture surfaces. Thin foils were prepared by twin-jet thinning in a solution of 10% perchloric acid and 90% alcohol at −20 °C, and the twin-jet current is maintained at 40 mA. TEM observation was performed on JEM2100.

3. Results

3.1. Microstructure of the as-cast K417G superalloy

The microstructure of as-cast K417G superalloy before tensile and creep tests was observed through SEM and the results are

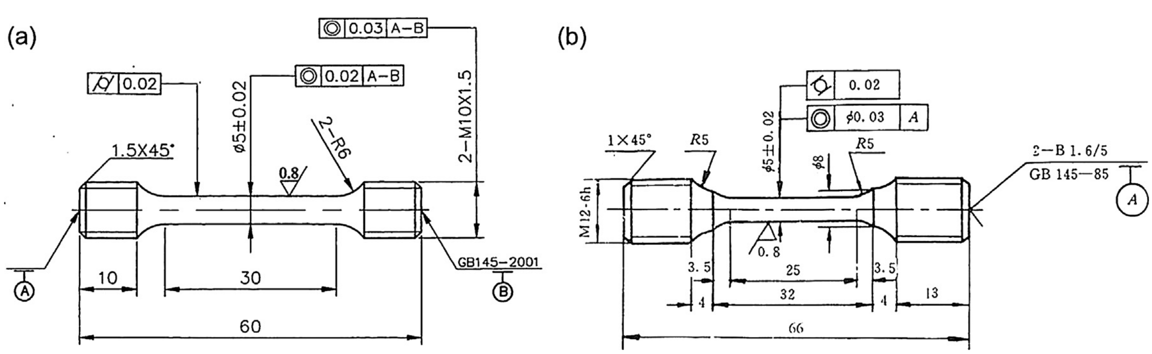

Fig. 1. Schematic diagram of standard tensile (a) and creep (b) specimen.