



Microstructural degradation and its corresponding mechanical property of wrought superalloy GH4037 caused by very high temperature



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ABSTRACT

Overheating exposures of turbine blades during service increased the risk of service safety in aircraft engines. Nevertheless, limited investigations about microstructural degradation induced by the overheating temperature and the effects on mechanical property of wrought superalloys were reported. In this paper, wrought superalloy GH4037 sectioned from an un-used 1st stage turbine blade of an aircraft engine was adopted to investigate the microstructural degradation caused by short-time thermal exposure at very high temperature (higher than normal service temperature) and the microstructural evolution during the mechanical tests after the short-time thermal exposures. The effects of microstructural degradation on mechanical properties including hardness, high temperature tensile properties and creep properties were also analyzed. The results indicate that gradual dissolutions of γ' phase and grain boundary (GB) carbides were the typical manifestation of microstructural degradation in GH4037 alloy during the short-time thermal exposures at 1000–1140 °C for 3 min and 5 min. The dissolved γ' phase and GB carbides re-precipitated in a very short time (less than 12 min) as ultra-fine particles and continuous/cellular GB carbides during 850 °C tensile tests and creep tests at 850 °C/196 MPa. Due to the re-precipitated ultra-fine γ' phase, the tensile strength at 850 °C after exposing to 1140 °C for 3 min was analogous to those of specimens without the thermal exposure. But the re-precipitated continuous/cellular GB carbides would cause the significant decrease of tensile ductility at 850 °C and the creep elongation at 850 °C/196 MPa. On the other hand, the dissolution of γ' phase and GB carbides during the short-time thermal exposures reduced the creep properties at 700 °C/471 MPa significantly, as it took much longer time (more than 18.1 h) for the re-precipitation of γ' phase when the overheated alloys were exposed at 700 °C/471 MPa. The work provides the guidance for overheating-inspection and diagnosis of service safety for blades made of wrought superalloys.

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1. Introduction

Ni-based superalloys are widely used as turbine blades for aviation and power plant applications, which are expected to withstand aggressive service conditions, such as high temperature, complex stress combination and oxidation environment [1,2]. The deformation induced by creep is one of the dominant failure modes in turbine blades [3,4]. For the sake of safety and economy, the diagnosis of service-induced damage and the prognosis of service life are of interests to users, manufacturers and designers. Since

mechanical properties of superalloys are dependent on the microstructure, the remaining life of blades is associated with microstructural degradation, which is primarily affected by service temperature and stress [1,4,5].

Under some abnormal circumstances, such as the emergency regimes of One Engine Inoperative (OEI) and the blocking of cooling passages, the turbine blades in turbine engines would be exposed to the excessive elevated temperature by over 150 °C higher than the designed service temperature of the alloy, resulting in the so-called overheating exposure [6,7]. The overheating exposure of turbine blades was strictly controlled to limited time periods during service [2]. The corresponding microstructural degradation of turbine blades could be introduced instantly in terms of the

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coarsening and dissolution of γ' precipitates as well as the dissolution of carbides, even local incipient melting [8–12]. Li et al. reported that the coarsening and the dissolution of γ' precipitates occurred in the 1st stage turbine blades during overheating service, which were made of DZ22 alloy, and caused the significant reduction of creep strength [13]. When the service temperature exceeded the solidus temperature of blade alloys, the incipient melting was introduced and catastrophically decreased the creep strength, resulting in cracks in the serviced blades [11].

In the late 1950s', a research program about the effects of overheating exposure on creep properties of polycrystalline superalloys was implemented by University of Michigan and NASA [14,15]. It was indicated that the creep properties were unaffected or increased by overheating exposures, and the resistance to overheating exposures increased with the volume fraction of γ' phase. Nevertheless, investigations about overheating exposures to superalloys were limitedly published after this program. Recently, a specific test bench (STB) has been established for overheating simulation of in-flight conditions by Cormier et al. [7,16]. The influence of overheating exposure on the creep behavior of single crystal Ni-based superalloy was investigated by using this STB [17,18]. In previous researches on polycrystalline superalloys, the overheating exposures were introduced during creep and the attention was mainly paid on creep properties. The microstructural degradation was not characterized in detail due to the limitation of microstructural characterization techniques at that time. As a consequence, the impacts of overheating temperature on microstructural degradation in polycrystalline superalloys during overheating exposure may not be revealed, and the influence of microstructural degradation on mechanical properties during and after overheating exposure has not been elucidated, either.

In this study, GH4037 wrought superalloy was sectioned from an un-used 1st stage turbine blade for an aircraft engine. Special short-time thermal exposures were carried out at temperatures much higher than the normal service temperatures of this alloy to simulate the temperature environment during overheating service condition. The objectives of this paper are: 1) to study the effects of temperature and time on microstructural degradation during short-time thermal exposures; 2) to investigate the microstructural evolution in the thermal-exposed alloy during mechanical tests; 3) to understand the influence of microstructural degradation on mechanical properties of the alloy.

2. Experimental

2.1. Materials and heat treatment

The microstructures of GH4037 alloy bar and blades made of GH4037 alloy might differ from each other due to the manufacture processes. To avoid this difference, materials in this research was obtained from an un-used forged 1st stage turbine blade for an aircraft engine, which was made of GH4037 wrought superalloy (Ni-13.5Cr-6W-3Mo-2Al-2Ti-0.3V-0.06C, in weight percent). The blade had been subjected to a standard heat treatment (SHT, 1180°C/2 h/air cooling (AC) + 1050 °C/4 h/AC + 800°C/16 h/AC) [19]. The specimens without short-time thermal exposure were hereafter referred as SHT alloy, which contained 20.2 wt% γ' precipitates, 0.5 wt% Cr₂₃C₆, 0.3 wt% TiC and M₃B₂ borides based on the physicochemical phase analyses by NCS Testing Technology Co., Ltd.. The grain boundaries were mainly filled with Cr₂₃C₆ carbides [20]. The solvus temperature of γ' phase in SHT alloy was determined to be about 935 °C by DSC using the heating curve.

To simulate microstructural evolution caused by overheating temperature and its effect on mechanical properties of the blades, specimens for microstructural observation, tensile and creep tests

were sectioned from the blade. Special short-time thermal exposures listed in Table 1 were conducted in laboratory and followed by water-quenching. The specimens exposed to the short-time thermal exposures at 1000–1140 °C for 3 min and 5 min are named as A1–A4 and B1–B4, respectively, as shown in Table 1.

2.2. Mechanical property tests

To gain insight into the strength of γ' - γ matrix within the grains, the micro-hardness was measured at locations away from grain boundaries. A Vickers indenter with a load of 3 kg was adopted to measure the micro-hardness at 6 locations for each specimen.

Because of the complex geometry of turbine blades [20], plate-type specimens were sectioned from the blade for the investigation of tensile and creep properties. The geometry and dimensions of the plate-type specimens are shown in Fig. 1(a). Tensile tests were carried out to gain the tensile strength of SHT alloy at 850 °C, 1000 °C and 1100 °C. To understand the influence of microstructural degradation caused by the short-time thermal exposures on the strength of the alloy at normal service temperature range, an A4 specimen was also subjected to the tensile test at 850 °C. The tensile test procedure was modified based on Chinese Standard GB/T 4338-2006 (ISO 783: 1999, MOD) to gain the microstructure in the samples at 850 °C, 1000 °C and 1100 °C for 5 min. It took about 30 min to heat the specimens rapidly from room temperature to test temperatures, and then the specimens were hold for 5 min before loading. The tests were strain controlled by a strain rate of 3.3E-4 per second. The ruptured specimens were water quenched to room temperature.

To investigate the effects of the short-time thermal exposures on creep properties of GH4037 alloy, creep tests were conducted in air at 700°C/471 MPa and 850°C/196 MPa. Extra stress rupture tests at 850°C/196 MPa were conducted. One creep test was carried out for each microstructure condition, while at least 2 stress rupture test were carried out for each microstructure condition. The creep/stress rupture test conditions were selected with the consideration of Chinese Aeronautical Industry Standard HB/Z 91–1985. The testing procedures were compliant with Chinese Standard GB/T 2039-2009, which is similar to International Standard ISO 204: 2009. It took about 3 h to heat the specimens from room temperature to the test temperatures. The specimens were hold for 2 h before loading during creep tests. The creep elongations were monitored continuously by using an extensometer attached to the ridges of special fixtures, which were made of single crystal Ni-based superalloy and designed to hold the non-standard plate-type specimen during creep tests, as shown in Fig. 1(b). To get the microstructural evolution of the specimens (SHT alloy and B4 specimens) during creep tests at 850°C/196 MPa, creep tests were interrupted after holding at 850 °C for 2 h before loading and at strains ranging from 0.8% to 1.0%. Then the specimens were water quenched to observe the microstructure.

2.3. Microstructural observation and characterization

The metallographic samples were mechanically polished and then etched with different solutions. A solution of 10% C₂H₂O₄ and 90% H₂O was employed for the observation of grain microstructure.

Table 1

Short-time thermal exposure conditions (temperature and time) in this study.

	1000 °C	1050 °C	1100 °C	1140 °C
3 min	A1	A2	A3	A4
5 min	B1	B2	B3	B4

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