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Effect of γ′ precipitation during hot isostatic pressing on the mechanical property of a nickel-based superalloy

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Abstract

The effect of the precipitation of γ′ phase during hot isostatic pressing (HIPing) on the mechanical property of a nickel-based superalloy, GTD-111, was evaluated by conducting tensile and creep-rupture tests at 871 °C. In the 4-h two-step HIP process, the coupons were isostatically compressed (at 120 MPa) and heated to 1230 °C, well above the dissolution temperature of γ′ precipitates into the γ matrix, for the first 2 h, and cooled down to a temperature to induce the precipitation of γ′ phase and held for the last 2 h at 120 MPa or at ambient pressure. The precipitates were controlled in size by varying the temperature for the last half of the process. According to the result of the tensile test, the mechanical properties of the alloy were varied upon the microstructural evolution, and improved more than 40%, compared to those of the untreated ones. The precipitation of γ′ phase under high pressure further improved in the properties, suggesting that the precipitation of γ′ phase at high pressure provides an advantage for the rigidity of the structure. Based on these findings, a 6-h three-step HIP process was tried, and proved to be an effective substitute for the normal heat treatment, especially in terms of creep properties. This feature was mostly attributed to the homogenized microstructure of HIPed ones, as evidenced by the X-ray diffraction patterns.

Keywords: Nickel-based superalloy; Hot isostatic press; Microstructure; Gas turbine; Mechanical properties

1. Introduction

Hot isostatic pressing (HIPing) is a well adopted technology for the manufacture, and, since recently, for the rejuvenation, of hot gas components of land-based gas turbines made of nickel-based superalloys. The elimination of casting microporosity through HIP at high temperatures by the creep diffusion process reduces the scatter of mechanical properties [1]. These alloys are but strengthened by means of the precipitation of γ′ phase, $Ni_3(Al, Ti)$, in the γ-Ni matrix. As the size, shape and fraction of γ′ precipitates in the matrix are not fully controlled during the HIP process, the resultant mechanical properties of the alloy are inappropriate for use in the gas turbine at the service temperature. A recent work on the microstructure and the room temperature tensile properties of the HIP treated IN738 alloy revealed such an inappropriateness [2,3]. Though the ultimate tensile strength (UTS) and the ductility of HIP treated material were comparable to those of the wrought (forged and heat treated) IN 718, its yield strength (YS) was found to be lower, being attributed to the low volume fraction of γ′ precipitates due to the lack of post-HIP heat treatment. In a study on the effect of the HIP process on the mechanical properties of a nickel-based single crystal superalloy, CMSX-4, it was also noticed that a heat treatment after HIPing gave rise to a full recovery of the normally heat-treated microstructure [4]. Hence a post-HIP heat treatment is usually recommended to maximize the mechanical properties of the alloy [5–10].

In a recent work of our group on the microstructure of HIPed nickel-based superalloy with a directionally solidified grain structure designed for land-based gas turbines, feasibility for the integration of the conventional post-HIP heat treatment into a HIP cycle is examined. It was reported that the size and morphology of γ′ precipitates are dependent on the specific HIP process, and discussed in the light of the retarded diffusion of the alloying elements under high pressure and the volume difference between the precipitates and the γ matrix [11]. As the process temperature adapted in our previous work was not however enough to dissolve all the precipitates, the

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Table 1
The nominal chemical composition of the specimens (wt.%)

Ni	Balance
Cr	14
Co	9.5
Ti	4.9
Al	3.0
W	3.8
Mo	1.5
Ta	2.8
C	0.08
Zr	0.03
B	0.01

effect of pressure on the precipitation of γ′ was not fully surveyed.

In this succeeding work the feasibility for the integration is further examined in which the process temperature is first raised enough to dissolve all γ′ precipitates, and lowered for them to reprecipitate by using a multi-step temperature program. The effect of the precipitation of γ′ phase during HIPing on the mechanical property of the nickel-based alloy is then evaluated by conducting tensile and creep-rupture tests at an elevated temperature.

2. Experimental procedure

A nickel-based superalloy, GTD-111, with a directionally solidified grain structure was investigated in this work, as was done in our previous work [11]. This alloy is being applied to the first stage turbine blade for 1300 °C-class GE 7FA gas turbines and has nominal chemical compositions as listed in Table 1. This alloy was invest-cast as a 120 mm × 60 mm × 30 mm plate for the first set of experiment by company "A", and as a cylindrical rod with the length of 200 mm and the diameter of 15 mm for the second set of experiment by company "B". These plates and rods were heat treated at 1190 °C for 4 h, 1120 °C for 2 h and subsequently at 845 °C for 24 h. The resulting microstructure consists of directionally oriented grains with dendrite arm spacing around 300 μm.

For the first set of experiment all six kinds of test specimens, including four kinds of HIP treated ones, were fabricated into the form of cylindrical bars for the tensile test at 871 °C (strain rate = 1 mm/min), as shown in Fig. 1. For the second set of experiment all five kinds of test specimens, including three kinds of

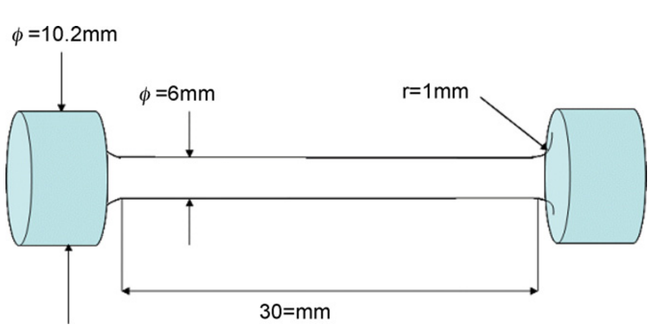

Fig. 1. Tensile test specimen for the first set of experiment.

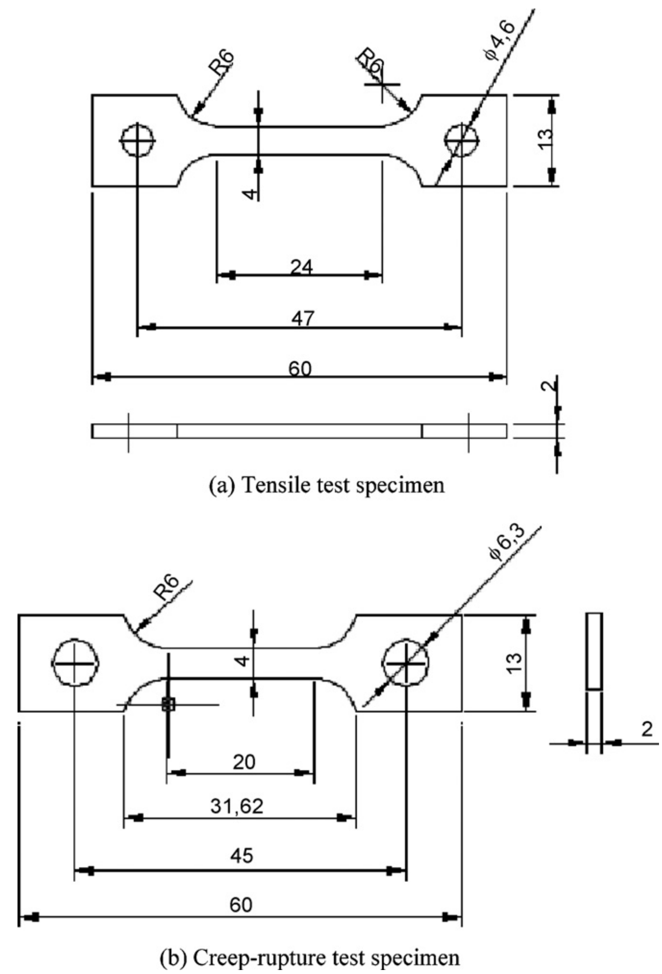

Fig. 2. Tensile and creep-rupture test specimens for the second set of experiment.

HIP treated ones, were fabricated into a plate form for the tensile and creep-rupture tests at 871 °C, as shown in Fig. 2. The stain rate for the tensile test was chosen to be 1 mm/min, and the load (tensile) for the creep-rupture test to be 372 MPa. Total 11 kinds of specimens were prepared for the investigation. Detailed procedures for the treatment for each specimen are listed in Table 2. Four of these are as-cast-and-heat-treated (AR1 and AR2) and subsequently aged or degraded (AG1 and AG2) at a temperature of 1100 °C for 70 h, respectively. Seven other specimens were treated in a HIP (ABB, Quintus) after being degraded at 1100 °C for 70 h. (The heating rate was 0.25 °C/s, and cooling rate 0.17 °C/s for the HIP treatment.)

Our experimental process (HIP process) is designed to reproduce conventional heat treatment for GTD-111, but under high pressure (isostatic condition), in order to merge two different processes, namely conventional heat and HIP treatment, into one advanced HIP process. The conventional process of heat treatment for nickel-based superalloy consists of solutionizing (dissolving γ′ into gamma matrix), precipitation hardening (precipitation of gamma prime in the homogenized or solution-treated matrix) and normalizing (or precipitation of secondary gamma prime) to maximize the mechanical properties. 1230 °C is chosen for solutionizing, because it lies well above the γ′ precipitation temperature, but well below the (incipient) tem-