Research Article

Investigation on Mechanical Properties of GH4720Li at High Strain Rates at Wider Temperature Range

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In this paper, the dynamic mechanical properties of GH4720Li nickel-base alloy under a large temperature range and high and low strain rates were studied by the hot compression test. The difference of mechanical properties of GH4720Li alloy under high and low strain rates was analyzed from the perspective of microstructure. The hot compression test experimental results showed that the true stress of GH4720Li alloy decreased at a low strain rate as the trial temperature elevated. Nevertheless, it was abnormal that the true stress increased at high strain rate condition as temperature elevated. By comparing the microstructure under high and low strain rates, it was found that the precipitates under low strain conditions contained a large amount of Cr (Mo). However, the content of Cr (Mo) in the precipitates at a high strain rate decreased, while the content of Fe increased. It would be concluded that Cr (Mo) would reduce the compressive strength and plasticity of GH4720Li alloy, while Fe would increase the compressive strength and plasticity of GH4720Li alloy. In addition, under the condition of a low strain rate, the shape of Cr (Mo) precipitates obtained at 20°C was lamellar, but it was spherical at 800°C. The compressive strength of GH4720Li composites with lamellar precipitates was higher than that of spherical precipitates.

1. Introduction

GH4720Li was a kind of advanced high-strength wrought Ni-matrix superalloy, which was developed for application in high-integrity rotating components of gas turbine engines such as discs and turbine blades [1–3]. Over the past few years, a great deal of efforts had been made with regard to GH4720Li alloys [4–9]. Wan et al. had investigated the high-temperature deformation behavior of an U720ULi alloy by the hot compression test at a temperature of 1060°C~1080°C and strain rates of 0.001~10 s⁻¹. It demonstrated that high activation energy for $\gamma + \gamma'$ dual-phase microstructures was mainly attributed to the precipitation hardening effect of γ' (Ni₃ (Al, Ti)) particles [4]. Zhao et al. have studied fine-grain ingot casting technology of a Ni-base superalloy 720Li by the hot compression test at a temperature of 1110°C~1150°C and strain rates of 0.001-0.1 s⁻¹, and they found that a hot die forged pancake was produced

with an ASTM 7 fine grain structure, which demonstrated the potential of GH720Li alloy disk to meet the component technical requirement [5]. Liu et al. had inspected the hot deformation behavior of U720Li alloy with fine, coarse, and mixed grains by the hot compression test in the range of 1040°C~1190°C and strain rates of 0.01~0.5 s⁻¹. In the single-phase region, dynamic recrystallization (DRX) mainly occurred along the boundaries, while a decrease in the grain size accelerated DRX kinetics. In the two-phase region, DRX on grain boundaries of coarse grain was limited [6]. Yu et al. had identified a relationship between the dynamic recrystallization (DRX) and presence of γ' precipitates for Udimet720Li by the hot compression test at a temperature of 1070°C~1190°C and strain rates of 0.01~0.5 s⁻¹. For coarse grain, the nucleation of DRX grains was influenced by the γ' interparticle spacing [7]. Qu et al. had established a constitutive equation and processing map of GH4720Li alloy based on the flow stress

during the hot compression test at a temperature of 1100°C~1170°C and strain rates of $0.01\sim 1\text{ s}^{-1}$ [8]. Monajati et al. had investigated the hot temperature deformation behavior of nickel-base superalloy UDIMET720 by the hot compression test at 1000°C~1175°C at strain rates of $10^{-3}\sim 1\text{ s}^{-1}$, and it applied the power-law, the Sellars-Tegart, and an empirical equation to thermomechanical behavior [9]. The mechanical properties of GH4720Li alloy were mainly concentrated in a low strain rate and high-temperature section, but few studies on the mechanical properties of high strain and medium-low-temperature section. It was also of great practical significance to study the mechanical properties of GH4720Li alloy in the medium- and low-temperature section and high strain rate.

In general, turbine blades were small components, which were wholly exposed to a narrow range of high temperatures. But the turbine discs were relatively larger components. Hence, in the process of actuation, there existed a wide range of temperature gradient conditions on the surface of the turbine disk. In other words, there existed a wide range of temperature difference between different parts such as the interior and edges of a turbine disc. For example, the service temperature of the inner diameter part was relatively low, while the temperature of the web part was relatively medium. At the same time, the temperature of the rim part was the highest.

Therefore, in addition to high-temperature mechanical properties of GH4720Li alloy, it was necessary to investigate the mechanical properties at low and intermediate temperatures. Besides, the turbine discs suffered the scour by high-temperature and high-pressure gas and may be impact by a foreign object; in other words, the turbine discs got damaged not only by creep and fatigue but also impact, which would lead to the failure of an engine [10]. Thus, it was important to research mechanical properties of GH4720Li alloy at the high strain rate. In the open literature, there were few reports on the high strain rate dynamic mechanical properties of GH4720Li alloy at a wide range of temperatures. Therefore, the high strain rate mechanical properties of GH4720Li alloy were investigated under a wide range of temperature changes. In the same temperature range, the mechanical properties of GH4720Li alloys with high strain rate and low strain rate showed different trends. The differentiation of mechanical properties between high strain rate and low strain rate was explained in detail.

2. Experimental Details

The chemical compositions of GH4720Li superalloys were measured as C, Cr, Al, Mo, B, Ti, Mn, Si, Nb, Ni, and Fe. The size of specimen at a strain rate of 10 s^{-1} is $\varnothing 6\text{ mm} \times 9\text{ mm}$, and the size of specimen at a strain rate of 1000 s^{-1} and 5000 s^{-1} is $\varnothing 5\text{ mm} \times 5\text{ mm}$. Hot compression tests were conducted at a temperature of 20°C, 200°C, 400°C, 800°C, and 1000°C, and the strain rates were set to be 10 s^{-1} , 1000 s^{-1} , and 5000 s^{-1} , respectively. Uniaxial compression tests of the nickel-base superalloy GH4720Li were conducted, and three duplicate tests were carried out at each temperature and strain rate. Low strain rate isothermal compression experiments were carried out on a Gleeble-3500 mechanical simulator. The simulator was equipped with a control system to impose

exponential decay of the actuator speed to obtain a constant strain rate. The deformation temperature was measured by thermocouples that were welded to the center region of the specimen surface. The strain, deformation temperature, and strain rate were automatically controlled and recorded. However, high strain rate compression experiments were carried out on an enhanced split Hopkinson bar system. The enhanced split Hopkinson bar technique was originally developed by Wang et al. for the experiments at elevated temperatures [10]. When the specimen was sandwiched between the bars in the traditional way, a temperature gradient developed in the elastic bars during the specimen preheating. Such a temperature gradient could cause an unwanted change in the elastic constants, and thus the mechanical impedance of the bars. As a result, the state of the stress wave propagation in the elastic bars could be affected. To avoid such influence, the incident and transmit bars of the split Hopkinson bar system were left outside the furnace with an environment temperature. A synchronous bar-moving system was utilized to make sure that the incident and transmitted bars were in full contact with the specimen microseconds before the stress wave arrived at the far end of the incident bar. To reduce the end friction during compression tests, the specimen ends were first polished by waterproof SiC paper and then greased in the tests. Prior to the hot compression, the specimens were heated to deformation temperature at a rate of 10°C/s and hold for 5 min to eliminate thermal gradients as well as to ensure uniform temperature of the specimens. Then, the specimens were compressed with a specified strain rate and quenched in water immediately to retain the microstructures at elevated temperature. Finally, the specimens were after polished and etched in the corrosive solution. The microstructure and chemical composition of the phases were observed by a Scanning Electron Microscope (SEM) with energy dispersive spectrometry (EDS). X-ray diffraction meter (XRD) was applied to determine the phase composition.

3. Result and Discussions

3.1. The True Stress-Strain Curves. The true stress-strain curves of hot compression of GH4720Li alloys under different conditions are shown in Figure 1. It can be seen from Figure 1(a) that the flow stress decreased gradually as the temperature increased at the low strain rate (10 s^{-1}). However, the abnormal mechanical properties of GH4720Li alloy appeared at a high strain rate ($1000\text{ s}^{-1}/5000\text{ s}^{-1}$). When the strain rate was $1000\text{ s}^{-1}/5000\text{ s}^{-1}$, the flow stress did not decrease with an increase of deformation temperatures; on the contrary, when the temperature reached 200°C, the true stress value of GH4720Li alloy reached the maximum, followed by the stress value at 800°C. Under the condition of a high strain rate, the stress values of GH4720Li alloy from large to small were 200°C, 800°C, 400°C, 20°C, and 1000°C, as shown in Figures 1(b) and 1(c). Therefore, GH4720Li exhibited completely different mechanical properties at high and low strain rates. To further understand the anomalous phenomenon about flow stress of GH4720Li alloy at high strain rates (1000 s^{-1} and 5000 s^{-1}), the flow stress-deformation temperature relationship is plotted in Figure 2.

FIGURE 1: The true stress-strain curve of GH4720Li alloy under the different conditions (a) 10 s^{-1} , (b) 1000 s^{-1} , and (c) 5000 s^{-1} .

Figure 2 showed the flow stress vs. deformation temperature with various strain rates and strains. Generally, plastic deformation produced a lot of heat. For the loading at a high strain rate, there was no sufficient time for this heat to dissipate into the surroundings. The actual temperature in consideration of a significant increase in temperature with a specimen would be estimated by [10, 11]

$$T = T_0 + \Delta T = T_0 + \int_0^\varepsilon \frac{\eta}{\rho C_v} \sigma d\varepsilon, \quad (1)$$

where T_0 is the initial temperature in compressive experiments, ΔT is the increment in temperature within specimen caused by the adiabatic process under high-rate loading, C_v is the heat capacity, ρ is the density of the material, ε is the plastic strain, σ is the flow stress, and η is the fraction of the heat generated by the plastic work that applies to the sample.

As seen in Figures 2(a)–2(c), for the studied range of temperatures (20°C – 1000°C) and the selected strain rates (10, 1000, and 5000 s^{-1}), when the strain rate was 10 s^{-1} , the true stress decreased with the increase of temperature; when the strain rate increased to 1000 s^{-1} / 5000 s^{-1} , the true stress increased with the increase of temperature (20°C – 200°C); when the temperature continued to increase to 400°C , the stress decreased gradually; when the temperature reached 800°C , the stress began to increase with the increase of temperature; when the temperature increased to 1000°C , the stress was weakened.

3.2. Microstructures of Deformed Specimens. There was no precipitate in the microstructure of GH4720Li alloy before the hot compression test, as shown in Figure 3. However, during the low strain rate test (10 s^{-1}), a large number of precipitates were produced in the microstructure of GH4720Li alloy, as shown in Figures 4(a) and 4(b), and the precipitates produced contained a large amount of Cr (Mo) elements, as

FIGURE 2: The flow stress VS. Temperature relations with strain rate of (a) 10/s, (b) 1000/s, and (c) 5000/s.

shown in Figures 5(a) and 5(b). The toughness of precipitates could effectively inhibit the crack growth [12]. When the toughness strength of precipitates exceeded the limit value of local stress, the precipitates could prevent the crack from expanding [13, 14]. For the precipitates with a layered structure, the crack front could not surround the tough precipitates and could renucleate in the adjacent material. Therefore, the crack may also be blunted or deflected by the ductile phase [15–17]. Once a crack had initiated, the plastic work expended upon stretching these second-phase particles during crack propagation provided a resistance to crack growth and was referred to as crack bridging [18]. The amount of toughening provided by crack bridging depended

upon the toughness of precipitates [12]. However, a large amount of Cr (Mo)-rich precipitates made the matrix brittle [19], which reduces the mechanical properties of GH4720Li alloy. In addition, because the cracks were easy to occur in Cr (Mo) precipitates and the fracture surface of Cr (Mo) precipitates was flat and intact, it showed that the Cr (Mo) precipitates absorbed less energy in the fracture process [19–21]. Therefore, Cr (Mo) precipitates would reduce the compressive strength of GH4720Li alloy. In addition, secondary cracks usually occurred at the edge of Cr (Mo) precipitates [19, 21], which further reduced the mechanical properties of GH4720Li alloy. Figure 6 was an enlarged view of the rectangular area in Figures 7(a) and 7(b). It can be seen

FIGURE 3: The microstructure and XRD pattern and EDS spectra of GH4720Li alloy.

from Figures 6(a) and 6(b) that under the condition of low strain rate (10 s^{-1}), Cr (Mo) precipitation was similar to lamellar when the temperature was 20°C , while the shape of Cr (Mo) precipitation was approximately spherical when the temperature was 800°C . During the dynamic compression test, the lamellar Cr (Mo) precipitates were not completely pinched off [22]; only a part of the layered structure was destroyed [22], which showed high compressive strength. In addition, the density defect of Cr (Mo) lamellar precipitate was smaller [12], so it would improve the mechanical properties of the material. Moreover, due to the different morphology of the two Cr (Mo) precipitates, different lattice defects were caused, which made the dislocation spacing of Cr (Mo) lamellar precipitates smaller than that of spherical precipitates, so the Cr (Mo) lamellar precipitates displayed a slightly greater strength over the low strain rates tested [12]. Besides, the pres-

ence of shear ribs demonstrated that Cr (Mo) lamella phase could absorb more fracture energy in comparison to spherical precipitates. Therefore, compared with spherical precipitates, the dynamic mechanical properties of layered precipitates are better [21].

It would be concluded that under the low strain rate (10 s^{-1}) experimental conditions, the true stress of GH4720Li alloy was smaller than that under high strain rate conditions due to the presence of a large amount of Cr (Mo) precipitates in the test piece; moreover, the strength of lamellar Cr (Mo) precipitates was greater than that of spherical Cr (Mo) precipitates [19, 23], resulting in a stress of 20°C greater than that of 800°C .

Under the condition of high strain rate ($1000/5000 \text{ s}^{-1}$), precipitates appeared in GH4720Li alloy test pieces, as shown in Figures 4(c)–4(f) and Figures 7(c)–7(f). Compared with the low strain rate (10 s^{-1}), the content of Fe in the precipitate

FIGURE 4: XRD patterns of GH4720Li superalloy under different conditions: (a) 10s^{-1} , 20°C; (b) 10s^{-1} , 800°C; (c) 1000s^{-1} , 20°C; (d) 1000s^{-1} , 800°C; (e) 5000s^{-1} , 20°C; (f) 5000s^{-1} , 800°C.

(a)

(b)

FIGURE 5: Continued.

(c)

(d)

FIGURE 5: Continued.

(e)

(f)

FIGURE 5: EDS spectra of GH4720Li alloy under different deformation conditions: (a) 10 s^{-1} , 20°C ; (b) 10 s^{-1} , 800°C ; (c) 1000 s^{-1} , 20°C ; (d) 1000 s^{-1} , 800°C ; (e) 5000 s^{-1} , 20°C ; (f) 5000 s^{-1} , 800°C .

(a)

(b)

FIGURE 6: The magnified microstructures of GH4720Li alloy corresponding to the closed rectangle area in Figure 7(a) [12] and Figure 7(b).

FIGURE 7: Microstructure of the GH4720Li alloy under different test conditions: (a) 10 s⁻¹, 20°C; (b) 10 s⁻¹, 800°C; (c) 1000 s⁻¹, 20°C; (d) 1000 s⁻¹, 800°C; (e) 5000 s⁻¹, 20°C; (f) 5000 s⁻¹, 800°C.

at a high strain rate (1000/5000 s⁻¹) was significantly increased, and the content of Cr was significantly reduced or even disappeared, as shown in Figure 5. In addition, when the strain rate is 1000 s⁻¹ or 5000 s⁻¹, the Fe content in the precipitate at 800°C was higher than that in the precipitate at 20°C. In addition, compared with the initial microstructure

of GH4720Li alloy, the content of Fe in the precipitate at a high strain rate (1000/5000 s⁻¹) increased, but the content of Ni decreased. This indicated that Fe and Ni atoms transferred between the precipitate and the surrounding phase. The precipitates absorbed Fe atoms from the surrounding phase and released their own Ni atoms [24]. In this case, the Fe atoms in

the precipitates occupied the position originally belonging to Ni atoms, which led to the increase of vacancy concentration. Furthermore, with the increase of Fe content, the lattice parameters of GH4720Li alloy decreased slightly, which promoted the increase of vacancy concentration [17]. The compressive strength of GH4720Li alloy was improved with the increase of vacancy concentration. Besides, the increase of Fe content resulted in the increasement of metallic bond and the decrease of covalent bond [19, 25]; the increase of metallic bond would improve the ductility for metal materials [12]. Therefore, the true stress value of GH4720Li alloy at a high strain rate ($1000/5000\text{ s}^{-1}$) was larger than that at low strain rate, and at a high strain rate ($1000/5000\text{ s}^{-1}$), the true stress at 800°C was greater than that at 20°C . This was the reason why the true stress of GH4720Li alloy appeared abnormal characteristics at a high strain rate ($1000/5000\text{ s}^{-1}$).

4. Conclusion

In this paper, the hot compression tests were conducted over a wide range of temperature ($20\sim 1000^{\circ}\text{C}$) and strain rate ($10\sim 5000\text{ s}^{-1}$) to obtain further understandings of the deformation behavior of GH4720Li alloy. It was found that the mechanical properties of GH4720Li alloy showed different trends under high and low strain rates. The reasons for the difference were analyzed from the perspective of microstructure. The following conclusions were drawn:

- (1) Under the condition of a high strain rate ($1000/5000\text{ s}^{-1}$), the mechanical properties of GH4720Li did not decrease with the increase of temperature; on the contrary, the abnormal phenomenon that the stress increased with the increase of temperature appeared. This anomalous phenomenon was different from our common sense, which the flow stress decreased successively with increasing temperature
- (2) In the low strain rate (10 s^{-1}), a large number of precipitates containing Cr (Mo) elements appeared in the GH4720Li alloy specimens. The precipitation containing Cr (Mo) elements reduced the compressive strength of GH4720Li alloy. In addition, compared with the precipitates of spherical Cr (Mo), the precipitates of lamellar Cr (Mo) elements would improve the mechanical properties of GH4720Li alloy better
- (3) Under the condition of a high strain rate ($1000/5000\text{ s}^{-1}$), precipitates containing a large amount of Fe element appeared in the test piece. The mechanical properties of GH4720Li alloy would be improved with the increase of Fe content and the decrease of Cr content

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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