Microstructure Control and Mechanical Properties of New Developed C&W Superalloy GH4175 at 800°C

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Abstract. As the thrust-weight ratio continues to increase, the aero-engine turbine disk material required both high strength and high temperature resistant properties which were often not compatible; Besides the working temperature of the turbine disk rim had reached 800 °C, the existing superalloys can not to meet the requirements, which was the reason that GH4175 alloy was produced. GH4175 was derived from Russian BK175 alloy, and the volume content of $\gamma'$ was over 58%. For the new GH4175, the low-segregation melting ingot with diameter of as large as 508mm could be prepared by the Double vacuum melting or Triple metlting process, in which the macro segregation and various metallurgical defects could be effectively controlled, then the conversion of as-cast microstructure and fine-grained billets were achieved on open-die hydraulic press by multi-times upsetting and drawing process and the novel temperature control technology with high efficiency, next, with the multi-cycle thermos-mechanical processing technology, the full-size turbine disks with a diameter of 600mm or more could be produced on hot die forging or isothermal forging. After standard heat treatment, the alloy combines high strength and high temperature characteristics, and balances the relationship between fatigue and creep. The long-term working temperature of the alloy reaches 800 °C.

1. Introduction
As the thrust-weight ratio of aero-engines continues to increase, the operating temperature of the turbine rim has reached 800 °C, and the existing cast and wrought(C&W) superalloy cannot meet the requirements [1]. In this study, the high-pressure turbine disk for the next generation aero engine was used as the research object. The new high-alloyed GH4175 alloy ($\gamma'$ content exceeds 58%) was developed and the 800°C-grade superalloy turbine disk was firstly made in China by the traditional casting-forging process.

In recent years, the superalloy by the traditional casting and forging process come into an explosive development, such as Rene65, AD730 and ВЖ175 [2-5]. Rene 65 was developed by GE and ATI for low-cost, high-performance, and widely used in latest Leap series engines. ВЖ175 was developed by Russia around 2010, it was updated from the Russia series alloys, and could serve at up to 800°C. The design and processing of ВЖ175 was different from previous Russia alloys, it take an America-like process: Fine-gained forging + Sub-solution heat treatment, which made the alloys with high strength and high temperature resistance. ВЖ175 was widely used in PD-14 engines [6].
At present, high-performance engines urgently need an 800°C stage high-performance, high-reliability, low-cost alloy turbine disk. The successful development of GH4175 alloy cannot only fill the gap of 800°C turbine disk material, but also meet the development requirements of advanced engine models.

2. Experimental
Of the experimental GH4175 alloy, the nominal composition was shown in Table 1. GH4175 alloy was developed on the basis of the Russian series alloy system and was an upgraded alloy of GH4151 alloy. For GH4175 alloy, W+Mo content exceeded 7%, Al+Ti+Nb content exceeded 10.5%, which was one of the hardest forging superalloys with the highest \(\gamma'\) content. The content of \(\gamma'\) exceeded 58%, exceeding the partially cast superalloy.

Large-size ingots of \(\phi 508\) was prepared by Double melting process (VIM+VAR), and high-temperature homogenization improve the forging plasticity of the alloy. Ingots were converted into billets by forging at temperature of the full dissolution of \(\gamma'\), the as-cast microstructure was broken and the low-magnification coarse grains were eliminated; then the fine-grained billets were prepared by multi-cycle thermo mechanical process technology, and the billets could enter into next process only if it went through the high-precision Ultrasonic examination; in the die forging stage, isothermal forging technique[7] was developed in order to save the materials, the net-sized forgings with a machining capacity of less than 3 mm was prepared at a strain rate of \(10^{-3}-10^{-2}\); finally, in order to obtain uniform properties, it took a partition cooling of the disk by the special instruments.

Phase analysis was performed using JMatPro, and the precipitation phase of the alloy was measured by STA-449C Differential Scanning Calorimeter (DSC-TG). The rate of heating and cooling was 20 °C/min, and the Olympus GX71 metallographic microscope and JSM-7800F scanning electron microscope were used to measure the microstructure. The tensile properties referred to GB/T 228.1-2010, GB/T4338-2006, the high temperature endurance referred to GB/T2039-1997, and the creep properties referred to GB/T2039-2012.

| Alloy    | Ni    | C   | Co  | Cr  | W   | Mo  | Al  | Ti  | Nb  | Fe  |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| GH4065   | Bal   | 0.01| 13  | 16  | 4   | 4   | 2   | 3.8 | 0.7 | 1   |
| GH4742   | Bal   | 0.06| 10  | 14  | -   | 5   | 2.6 | 2.6 | 2.6 | -   |
| GH4151   | Bal   | 0.06| 15  | 9   | 2.5 | 4.5 | 3.7 | 2.8 | 3.4 | -   |
| GH4175   | Bal   | 0.06| 15.5| 10  | 3   | 4.5 | 4   | 2.5 | 4.5 | 0.10|
| GH4975   | Bal   | 0.1 | 16  | 8   | 10  | 1   | 2.5 | 1.5 | 0.10|

3. Results and Discussion

3.1. Phase diagram and Thermodynamic analysis of GH4175 alloy
Phase diagram and DSC heating and cooling curves were usually used to analyse the precipitation of \(\gamma'\) phase, which was foundation for subsequent forging processing and heat treatment process. Fig 1 shows the thermodynamic equilibrium phase diagram of GH4175 alloy, which contained a mass fraction of 58% and the solvus of 1185.5°C. DSC analysis of the forged sample of GH4175 alloy showed that there were two obvious endothermic peaks during the heating process, which were 1026.9°C and 1171.2°C, respectively. There was a significant exothermic peak during the cooling process, which was 1116.7°C. During the heating process, the tertiary \(\gamma'\) was dissolved at a lower temperature, but the DSC precision was not enough to record the differential thermal reaction of the process, and then the secondary \(\gamma'\) phase was re-dissolved at 913.6-1060.4°C, reaching a peak at 1026.9°C. The larger primary \(\gamma'\) was subsequently remelted, the process started at 1119.9°C, reached a maximum peak at 1171.2 °C, and was finally completely dissolved at 1195.0°C. The DSC test results were basically consistent with the thermodynamic calculations. The error was mainly related to the
rate of the temperature heating and cooling and the slow dissolution of the large size primary $\gamma'$. During the cooling process, when the sample was cooled at 20°C / min, the solid solution accumulated sufficient supersaturating at 1129.3°C. When the temperature decreased further, the $\gamma'$ started to precipitate, reached a peak at 1116.7°C, and the precipitation process was relatively rapid. At 1103.5°C, the precipitation was complete, and the subsequent precipitation of the tertiary smaller $\gamma'$ could not be identified because the thermal difference of process was too small to detected.

![Figure 1. Calculated equilibrium phase diagram and DSC curve of GH4175](image)

3.2. Grain size and Microstructure
After the fine-grain forging + sub-solution heat treatment process of GH4175 alloy turbine disk, the average grain size of as-forged disk was up to ASTM No.10. The microstructure was a typical $\gamma+\gamma'$ duplex structure after the standard heat treatment [8-10]. The average grain size glowed to ASTM No.8, the primary $\gamma'$ had a size of 2-5um, was distributed on the grain boundary, which was the most prominent feature of the duplex structure; the secondary $\gamma'$ phase was mainly square and distributed in the grain with the size between 80-300 nm, which was precipitated during the solution cooling of the alloy; the tertiary $\gamma'$ phase size was between 20-40 nm, and was dispersed between the secondary $\gamma'$.

![Figure 2. Microstructure of GH4175 disk after standard heat treatment](image)

GH4175 alloy contained high carbon content, multiple cycles of thermo-mechanical process technology fully broke the carbides [9, 11-12], which was dispersed in the grains. Carbide could control the grain boundary during heat treatment. During the solution process, as the solution temperature increased, the $\gamma'$ phase dissolved gradually, the pinning effect on the grain boundary decreased, and the grains started to grow. As the temperature further increased, the $\gamma'$ phase dissolved...
completely. At this time, carbide was the main factor controlling the grain. Fig 3 showed that the grain size was controlled by the solution temperature. At 1120°C, the first $\gamma'$ started to dissolve and the grains grew. At 1150°C, a large amount of $\gamma'$ dissolved, and the speed of the grain growth suddenly increased. At 1170°C, carbides were the main controlling factor, and the grains grew from the original ASTM No. 11 to ASTM No. 2. Since the primary $\gamma'$ phase and the carbide distribution were uniform, there was no mixed grain, and the crystal grains grew uniformly. The results obtained by the solution test were highly consistent with the data measured by DSC. The grain growth of GH4175 could achieve stable control with the solution temperature, and the ideal state could be obtained at a specific solution temperature, which provided a possibility of the dual structure [13].

3.3. Hot working and Microstructure Evolution
The volume content of $\gamma'$ was more than 35%, which was called hard-to-deform superalloy. In the extremely narrow temperature window, forging process was performed in limited deformation as $\gamma'$ dispersion structure. It was hard to deform and easily to crack [14]. For the GH4175 alloy with the content of $\gamma'$ up to 58%, it was impossible to deform using traditional thermal process, otherwise a new developed process were created for high alloyed superalloy. As show in Fig.4, the $\gamma'$ dispersion grain was efficiently converted into the $\gamma+\gamma'$ duplex structure by a special thermo mechanical process, then the plasticity of superalloy was largely promoted, which was the foundation of hot working for high alloyed superalloy.

When as-cast ingot was converted into billet, a reasonable annealing process was used to form a large-scale primary $\gamma'$ phase, thereby reducing the concentration of alloying elements in the solid solution. During the hot working process, the primary $\gamma'$ phase had a larger size and a lower strength, it promoted the conversion of as-cast microstructure to the $\gamma+\gamma'$ duplex structure grains[11], while the lower alloying element content in the solid solution reduced the tendency of cracks[11].

In the process of the $\gamma'$ dispersion structure to the $\gamma+\gamma'$ duplex structure, by forging below the solvus of the $\gamma'$, according to the research [12], the lower-temperature and higher strain rate could improve the conversion efficiency and increase the amount of the $\gamma+\gamma'$ duplex structure to over 95%, the plasticity of the alloy would increase significantly and the forging window would expand up to 150 °C. The rest of the $\gamma'$ dispersion structure grains were completely converted to the $\gamma+\gamma'$ duplex structure under the solvus of $\gamma'$.

3.4. Mechanical Properties
According to the characteristics of GH4175 alloy, the sub-solution heat treatment was researched, and the sup-solution heat treatment was explored. In order to balance the properties, the grain size of the alloy was adjusted to the ASTM No. 8.0 by the solution temperature; the size of grain was too fine and the creep property was poor; the grain was too coarse, the structure was transformed into the $\gamma'$
dispersion structure grain, and the advantage of the $\gamma + \gamma'$ duplex structure was vanished, which was the high strength, high fatigue characteristics [9, 11]. As shown in Table 2, the alloy maintained a high strength before 800 °C, the relevant properties met the requirement of Russia BkK175 alloy, the alloy had excellent low cycle fatigue properties. When the cycles were more than $10^4$, the low-cycle fatigue stress reached up to 1200 MPa at 650°C, and 1100 MPa at 750°C. It was the alloy with the best low-cycle fatigue so far, but the alloy creep properties margin was low, which needed to be improved by optimizing the heat treatment process.

In addition, the sup-solution heat treatment was explored. After sup-solution heat treatment, as shown in Fig. 5, the grain size of the disk reached ASTM NO.3.0, the grains grew uniformly, and the grain boundary showed serrated. According to Table 2, the grain enlarged, had a certain loss of strength, the room temperature yield properties reached 1191 MPa and the tensile strength was more than 1500 MPa, but the strength at 800 °C was about 50 MPa higher than the properties of the sub-solution heat treatment; the creep properties were greatly improved, the rupture time was 90.4h at 750°C under 700MPa, while 114h at 800 °C under 530MPa; For the creep properties, the creep plastic strain was only 0.112% at 800°C/350MPa at 300h. Sup-solution heat treatment, GH4175 showed the higher temperature performance, the alloy strength was slightly reduced, but still at a high level.

The properties of GH4175 alloy in terms of sub-solid solution and sup-solid solution could be improved through a certain optimized heat treatment process with both high strength, and high temperature resistance. The performance level of GH4175 at 800°C reached the level of three generations of powder. In the later, the dual-structure disk technology could also be researched to
further increase the alloy’s operating temperature [13, 15].

**Table 2.** Typical mechanical properties of GH4175 alloy after different heat treatments from Dissection turbine disk

| Heat treatment     | T (℃) | $\sigma_b$ (MPa) | $\sigma_{0.2}$ (MPa) | $\delta$ (%) | $\psi$ (%) | $\sigma$ (MPa) | $\tau$ (MPa) | $\delta$ (%) |
|-------------------|-------|------------------|----------------------|-------------|-------------|---------------|---------------|-------------|
| Sub- Solution     | 23    | 1624             | 1196                 | 17          | 16          | -             | -             | -           |
|                   | 650   | 1536             | 1123                 | 13          | 15          | 1050          | 148           | 4           |
|                   | 750   | 1230             | 1070                 | 10          | 10          | 650           | 81.7          | 12          |
|                   | 800   | 1110             | 965                  | 8           | 10          | 500           | 36.2          | 25          |
| Sup- Solution     | 23    | 1513             | 1191                 | 15          | 16          | -             | -             | -           |
|                   | 750   | -                | 1120                 | 14          | 14          | -             | -             | -           |
|                   | 800   | 1150             | 1020                 | 6           | 8           | 530           | 114           | 7.0         |

Fig 6, the tensile and high temperature rupture properties of the GH4175 alloy were compared with the typical deformed superalloy turbine disk materials, such as GH4169, GH4065A, GH4720Li, and GH4975 [8, 9]. It showed that the tensile strength of GH4715 alloy in the temperature range from room temperature to 850 ℃ was 50-100 MPa higher than that of 750 ℃ alloy GH4065A and GH4720Li. For 700MPa/100h rupture properties, GH4175 was about 50 ℃ higher than GH4065A and GH4720Li. It showed the excellent mechanical properties by the reasonable sub-solution treatment process. The tensile strength and rupture properties were greatly improved compared with the existing alloys, especially at 800 ℃.

![Mechanical properties of GH4175 in comparison with typical disc alloys](image)
4. Conclusion
The full-size turbine disk of the high alloyed GH4175 is successfully prepared by double smelting +
thermal mechanical process + sub-solution heat treatment process. The triple melting process will be
explored later.

According to the characteristics of GH4175 alloy, research on sub-solution and sup-solution heat
treatment was carried out. The research shows that the sub-solution heat treatment performance can
meet the requirement of Russia ВЖ175; Sup-solution heat treatment can significantly improve
the high-temperature creep properties, reaching or exceeding the properties of the third generation powder
[15], and more properties could be carried out later.

GH4175 alloy is currently the only 800°C grade superalloy. It can reach the level of third
generations of powder. Later, it can be optimized by improving heat treatment process to further
balance the relationship between fatigue and creep, and obtain a better overall performance.

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