Introduction on Research and Application of Nickel Base Superalloy GH4169

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Abstract. In this paper, the research and application of nickel base superalloy GH4169 in recent years was introduced. GH4169 alloy is a precipitation strengthened nickel base superalloy, which has been widely used in aeroengine, petroleum, nuclear industry and other fields. The phase composition, three common heat treatments as well as the application prospect were elaborated. At last, the service temperature range and application area of GH4169 alloy was believed to be further expanded with the adjusted alloy composition and the corresponding hot working process.

Keywords: GH4169 alloy; Phase; Heat treatment; Application.

1. Introduction
Nickel base superalloys are usually worked under certain stress above 600 °C, which not only possess good high temperature oxidation resistance and corrosion resistance, but also have high temperature strength, creep strength, rupture strength and good fatigue resistance [1]. At present, nickel base superalloys are mainly used for the structural components working under high temperature in aerospace field, such as the working blade, turbine disk and combustion chamber of aero-engine, etc. (Fig.1) [2]. However, inclusions mixed in the preparation process will seriously affect the fatigue performance of nickel based alloy, which makes the service life of structural material components not guaranteed, also limiting the wider applications [3]. According to the manufacturing process, nickel base superalloys can be divided into wrought superalloys, casting superalloys and powder metallurgy superalloys. On the basis of the strengthening methods, it can be divided into solution strengthening superalloys, aging strengthening superalloys and oxide dispersion strengthening superalloys.

Among all the superalloys, GH4169 alloy is widely used in many domains to this day. The American brand of GH4169 alloy is Incone1718, and the French brand is NC19FeNb. GH4169 alloy is a nickel based wrought superalloy, which is mainly composed of γ matrix phase, δ phase, carbides and strengthening phases γ′(Ni3Nb) and γ(Ni3(Al, Ti, Nb)) [4]. According to the detailed use requirements of different parts, the chemical composition of GH4169 alloy is slightly different. Adding Nb is the main feature of this alloying, which causes the high strength and good weldability characteristics of GH4169 alloy due to the effect of Nb, leading the alloy widely used than general superalloys [5, 6]. In addition, GH4169 alloy has the advantages of high strength, oxidation resistance, good hot working performance and welding performance. GH4169 alloy possesses high yield strength and good plasticity below 650 °C. Compared with general precipitation strengthened superalloys, the coherent distortion between the precipitate phase and the matrix is more larger, which makes GH4169 alloy can be widely used in the
temperature range of −253–650 °C and the aviation and spaceflight areas. According to the statistical data of America in 1986, Inconel718 alloy is one of the largest production of superalloys, the annual output of which accounts for 45% of the whole deformed superalloy.

Figure 1. The application of Nickel base superalloys
(a) Generator rotor (b) turbine blade of aircraft

2. Phase composition of GH4169 alloy

GH4169 alloy is belong to a highly complex alloy system, which contains more than ten elements and 6–8 phases, except for the 4 phases mentioned above, laves phase can also be precipitated when the alloy composition is not controlled properly. The characteristics of each phase in the alloy are described as follows: (1) γ phase. The γ phase with face centered cubic structure is the matrix phase of GH4169 alloy, which has higher solubility than Co, Cr, Mo and other elements. Therefore, the matrix phase of GH4169 alloy is a solid solution composed of many elements, and with the increase of element content adding in the γ matrix phase, the solid solution strengthening effect will also be enhanced. (2) γ′ phase. γ′-Ni3Al is an intermetallic compound with L12 structure, in which Co can replace nickel, titanium, tantalum, Nb can replace aluminum, while Cr can replace both Ni and Al [7]. γ′ phase and γ matrix phase have the same face centered cubic structure, and the lattice constants of the two phases have little difference, so the γ′ phase and the matrix keep a good coherent relationship. However, the amount of γ′ phase is less than that of γ″ phase, which only plays an auxiliary strengthening role [8]. (3) γ″ phase. γ″-Ni3Nb is a kind of intermetallic compound with DO22 structure, which is the main strengthening phase of GH4169 alloy [9]. It has a body centered tetragonal structure and precipitates uniformly in the matrix in the form of disk. During long-term aging or long-term service, the γ″ phases will be transformed into δ phases, resulting in the decrease of strength. (4) δ phase. δ-Ni3Nb phase is a stable phase with DOa ordered orthorhombic structure, which is not coherent with the γ matrix [10]. δ phases are mainly precipitated along the grain boundary during long-term aging or long-term service, which play the role of pinning grain boundaries and hindering grains coarsening. δ phase with appropriate size, quantity and morphology will improve the impact toughness and plasticity of GH4169 alloy. (4) Carbide phase. There is no carbon in the early nickel base alloys, so there is no carbide phase formed. With the continuous development of nickel base alloy, a small amount of carbon is gradually added into the matrix, resulting in a small amount of carbides. The possible carbides formed in the nickel base alloys are mainly MC, M6C and M23C6. According to the different precipitation conditions, it can also be divided into primary carbides and secondary carbides, which precipitate in solidification and solid phase transformation respectively. Carbides formed in GH4169 alloy have different types, such as TiC, NbC, etc, which are face centered cubic structure with lattice constant between 0.418 to 0.468 nm. The composition range of MC type carbides is wide, and a certain amount of W, Mo, Cr and other elements can be dissolved in it. M6C type carbides have complex face centered cubic structure, and there are 96 metal atoms and 16 carbon atoms in a unit cell. In which, M is mainly represents W, Mo, etc. The precipitation temperature range of M6C type carbides is about 850–1210 °C, and the precipitation peak temperature is in the range
of 50~1100 °C. M23C6 type carbides also possess a complex face centered cubic structure with 92 metal atoms and 24 carbon atoms in per unit cell. (5) TCP phase. When the composition is not controlled properly, the brittle topologically dense packing phase (TCP) will be precipitated during heat treatment and service in GH4169 alloy. The crystal structure of TCP phase is relatively complex, all the atoms are arranged closely and the coordination number is as high as 14~16 with very short atomic spacing and no octahedral gap. In GH4169 alloy, there are a lot of refractory elements such as Mo, W and Ta, which can promote the formation of TCP phase. When TCP phases are precipitated, the short-term properties of GH4169 alloy are not be affected, but the long-term creep properties will be seriously reduced. This is mainly because that the formation of TCP phase consumes a lot of solid solution strengthening elements, and TCP phase is usually proved to be the source of cracks.

3. Heat treatment process of GH4169 alloy
According to the service conditions, different heat treatments of GH4169 alloy should be carried out to control the grain size, morphology, distribution and quantity of δ phase, so as to obtain different mechanical properties [11]. The normal heat treatment of GH4169 alloy can be divided into three types. (1) High strength heat treatment (HST). Heating at (1010~1065)±10 °C for 1 h, oil cooling, air cooling or water cooling, then heat at 720±5 °C for 8h, furnace cooling with rate of 50 °C/h to 620±5 °C, and holding for 8 h, subsequently air cooling. This heat treatment is beneficial to improve the impact properties and low temperature hydrogen embrittlement resistance of GH4169 alloy. (2) Standard heat treatment (ST). Heating at (950~980)±10 °C for 1 h, oil cooling or water cooling to +720±5 °C and holding 8 h, then furnace cooling with rate of 50 °C/h to 620±5 °C, holding for 8 h, air cooling to room temperature. The results show that the δ phase precipitates along the grain boundary in the alloy treated by this system, which is beneficial to eliminate the notch sensitivity. δ phases will precipitate along the grain boundary of GH4169 alloy treated with this more commonly heat treatment, which is beneficial to eliminate the notch sensitivity. (3) Direct aging heat treatment (DA). Heating at 720±5 °C for 8 h, then furnace cooling with rate of 50 °C/h to 620±5 °C, holding for 8 h, air cooling to room temperature. The amount of δ phase precipitated in GH4169 alloy treated with DA is less, and the strength and impact properties while be enhanced. DA is a kind of heat treatment of nickel base superalloy developed in the early 1980s. It is proved that the alloy can obtain higher tensile strength and low cycle fatigue properties also by using this process. The properties of GH4169 alloy after different heat treatments are listed in Table 1.

Table 1. Properties of GH4169 alloy after heat treated by different techniques

| Heat treatment | Temperature (°C) | Tensile properties (≥) | Persistent performances |
|----------------|------------------|------------------------|------------------------|
|                |                  | σ₀.₂ (MPa)             | σ₀ (MPa)               | δ₀ (%)               | Ψ (%) | σ (MPa) | t (h) | δ₀ (%) |
| HST            | 20               | 1030                   | 1280                   | 12                   | 15     | -       | -     | -      |
|                | 500              | 930                    | 1130                   | 12                   | 16     | -       | -     | -      |
|                | 650              | 860                    | 1000                   | 12                   | 18     | 686     | ≥25   | ≥5     |
| ST             | 20               | 1100                   | 1340                   | 12                   | 15     | -       | -     | -      |
|                | 650              | 930                    | 1080                   | 12                   | 15     | 725     | ≥25   | ≥5     |
| DA             | 20               | 1240                   | 1450                   | 10                   | 15     | -       | -     | -      |
|                | 650              | 1000                   | 1170                   | 12                   | 15     | 700     | ≥25   | ≥5     |

4. The application of GH4169 alloy
GH4169 alloy has been widely used in aeroengine in China, its material level and processing technology level have been significantly improved in recent years. The metallurgical products of GH4169 alloy include forged bar, hot rolled bar, cold drawn bar, plate, strip, wire, tube and forging. The common parts manufactured include various types of disc, rotor, ring, casing, shaft, fastener, elastic element, damping element, etc. The amount of this material in the engine has increased from several part numbers to more than 200. For example, the part numbers of GH4169 alloy used in Taihang engine (i.e. turbofan 10 series engine) are up to 261, and the total part mass accounts for 30% of the total engine mass. Besides, GH4169 alloy has also been widely used in large aircraft engines and helicopter turboshaft engines.
5. Concluding
In conclusion, GH4169 alloy has become an indispensable important material in national defense construction and economic construction. Due to the sensitivity of the main strengthening phase $\gamma''$ and stable phase $\delta$ to the heat treatment temperature and time, the complex hot deformation and heat treatment are necessary. Therefore, according to the requirements and characteristics of different mechanical properties, the stability of strengthening phase can be improved by adjusting the alloy composition and the corresponding hot working process, so as to achieve the purpose of intragranular and grain boundary strengthen. At the same time, the service temperature range and application area of GH4169 alloy should also be further expanded.

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