High-Performance Turbine Disk Material GH4065 and Its Advanced Manufacturing Technology: Postprint

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Abstract

Based on systematic comparative selection studies of a series of highly alloyed model alloys, a novel GH4065 wrought superalloy has been developed. The chemical composition of this alloy is similar to that of René 88 DT alloy, with further optimization implemented to meet the requirements of the casting-forging manufacturing process. Development results indicate that GH4065 alloy produced via novel technologies such as triple low-segregation melting and casting and multiple cyclic thermomechanical processing is suitable for fabricating critical hot-section rotating components for advanced aeroengines. Its comprehensive performance fully satisfies the service condition requirements for high-pressure compressor disks and low-pressure turbine disks, and can serve as a high-reliability, low-cost solution for high-pressure turbine disks when necessary. With the advancement of wrought superalloy materials and manufacturing processes, high-performance turbine disk materials prepared by casting-forging processes can meet the technical requirements of advanced aeroengines.

Full Text

Preamble

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Investigation of High Performance Disc Alloy GH4065 and Associated Advanced Processing Techniques

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Abstract

Much attention has been paid to the development of more advanced materials for high-pressure compressor and turbine discs of gas turbine engines. A high performance wrought superalloy GH4065 for disc applications has been recently developed based on the comprehensive evaluation of a series of model alloys with characteristic chemical composition, lattice parameter, particularly γ volume fraction. The concentration of major alloying elements of GH4065 is closely similar with René 88 DT and specifically optimized considering the demands of ingot metallurgy technologies. Therefore, GH4065 can be considered as an ingot metallurgy version of powder metallurgy René 88 DT. Large scale vacuum arc remelting (VAR) ingots of GH4065 alloy with diameter up to 508 mm have been produced via standard triple melting techniques. Micro-scale segregation of alloying elements on large VAR ingot has been effectively suppressed due both to optimized alloying elements concentration and to improved melting techniques. Ultra-low carbon content (less than 0.02% in mass fraction) significantly decreases the dendritic segregation tendency of certain alloying elements and promotes the uniformity of microstructures. VAR ingot of GH4065 exhibits extraordinary hot plasticity, and ingot conversion can be accomplished using conventional open die forging procedure. Fine and uniform $\gamma+\gamma$ duplex structures can be obtained on billets and disc forgings via a newly developed multi-cycle thermomechanical processing method. The flow stress data show that the formation of $\gamma+\gamma$ microduplex results in a significant decrease of flow stress in comparison with γ dispersion structures under exactly the same deformation conditions. The distribution of strain rate sensitivity m in relationship with temperature and strain rate accurately identifies a specific domain within which $\gamma+\gamma$ microduplex exhibits superplasticity. Full-scale turbine discs of GH4065 alloy with diameter of 630 mm achieve an optimal combination of creep resistance, fatigue lifetime and ductility. GH4065 discs exhibit extraordinary microstructural and property stability during prolonged thermal exposure, which means that dendritic segregation has been successfully restricted to an acceptable level. The results reveal that highly alloyed disc alloys produced via ingot metallurgy techniques exhibit lower costs and higher productivity, and can still meet the ever increasing demand of high performance

gas turbine engines.

KEY WORDS Ni-based superalloy, disc forging, ingot metallurgy, microstructure, mechanical property

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As aero-engines continue to evolve toward higher performance, greater reliability, longer service life, and larger scale, the demands for temperature capability and mechanical properties of critical hot-section rotating components such as superalloy turbine discs and high-pressure compressor discs have continuously increased. In recent years, with rapid progress in research on highly alloyed wrought superalloys and continuous improvement in melting and thermomechanical processing technologies and equipment, the production of high-performance superalloy hot-section rotating components via the ingot metallurgy and forging route has re-emerged as an important development direction, gradually demonstrating outstanding advantages in stable and reliable component quality, low life-cycle cost, and high productivity.

High-performance disc materials such as U720Li, René 65, AD730, EP975, EK79, and EK151 developed abroad can fully meet the operational requirements of new advanced aero-engines in terms of temperature capability and mechanical properties. These alloys can be produced as large ingots up to 508 mm in diameter using the standard triple melting process of vacuum induction melting (VIM) + electroslag remelting (ESR) + vacuum arc remelting (VAR), and can undergo open-die forging on a fast forging machine for breakdown, with final forming of full-scale forgings completed using isothermal/hot-die forging technology. This processing route is generally consistent with that for IN718 and its modified alloys, enabling mass production under conventional metallurgical industrial conditions. Currently, such high-performance forgings produced via the ingot metallurgy route have completed testing on a series of new engines and begun extensive application.

Domestically, important progress has also been made in developing high-performance disc materials based on the ingot metallurgy route, with the development of high-performance wrought superalloy disc materials such as GH4065, GH4079, and GH4975. In particular, the comprehensive properties of the GH4065 series alloy reach the level of powder metallurgy materials, offering a mature and reliable solution for material selection of hot-section rotating components in China's advanced aero-engines. The production of highly alloyed superalloy large-scale forgings via the ingot metallurgy route requires mastering the principles and methods of reducing dendritic segregation tendency through chemical composition optimization, solving the stability issues in large-scale consumable remelting ingot casting, and achieving efficient control of forging microstructure and properties under hot-die forging conditions. For a long time, systematic research has been conducted domestically on these issues, with principle verification completed and relevant technologies developed for key technical aspects such as vacuum triple low-segregation melting and thermomechanical processing for fine-grained forgings, successfully producing full-scale GH4065 alloy turbine disc test components with a service temperature up to 750 °C. The rapid development and successful application of this new high-performance superalloy forging preparation technology based on the ingot metallurgy route will play an important role in controlling technical risks in engine development, improving engine efficiency and reliability, and reducing engine life-cycle costs.

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1 Alloy Design of High-Performance Turbine Disc Material GH4065

To meet the requirements of advanced aero-engines for high-performance hot-section rotating components, and based on the latest trends in wrought superalloy material research both domestically and internationally, the newly developed wrought superalloy material needed to simultaneously satisfy two basic conditions: first, the mechanical property level should approach that of powder metallurgy materials to meet engine operational requirements; and second, full-scale forgings should be capable of mass production under existing domestic metallurgical industrial equipment conditions. To achieve these two goals, the development of the new high-performance wrought superalloy fully summarized the successful experience and existing problems of current disc material design. Based on comparative evaluation and screening of the mechanical and processing properties of a series of model alloys, the chemical composition of the mature powder metallurgy turbine disc material René 88 DT was ultimately adopted as the foundation and comprehensively optimized for the ingot metallurgy route requirements, resulting in the development of the new GH4065 alloy. Its typical composition is shown in Table 1 . For comparison, the chemical compositions of other major highly alloyed wrought superalloys developed domestically are also listed in the table.

In Table 1, the GH4586 alloy has a γ phase volume fraction of 25%, exhibits excellent short-term high-temperature properties, and has been successfully applied in aerospace applications, but its application in aero-engines is constrained by microstructural and property stability issues under long-term service conditions. The GH4742 alloy has a γ phase volume fraction close to 40% and is a mature aero-engine turbine disc material with a service temperature of 750 °C, possessing good long-term microstructural and property stability, but its yield strength can no longer meet the requirements of new aero-engines. The GH4975 alloy can serve at temperatures up to 950 °C and maintains relatively high mechanical property levels below 800 °C. This alloy is characterized by its high degree of alloying, with main elements basically consistent with MarM200, a γ phase volume fraction of 63% in the aged condition, and a γ phase complete dissolution temperature exceeding 1200 °C. This high degree of alloying limits the maximum size of GH4975 alloy consumable remelting ingots, and the narrow hot working temperature window increases the difficulty of breaking down the as-cast structure and makes it difficult to achieve satisfactory yield.

The γ phase volume fraction of GH4065 alloy in the aged condition is 42%, the same as René 88 DT alloy, but lower than the 45% of GH4720 alloy. The equilibrium dissolution temperature of γ phase in GH4065 alloy is 1119 °C, thus providing a larger hot working temperature window than GH4720 and GH4975 alloys. Based on René 88 DT alloy, the chemical composition of GH4065 alloy was optimized in several aspects to meet the special requirements of the ingot metallurgy route.

Regarding major elements, while maintaining the γ/γ lattice misfit unchanged, the ratio between solid solution strengthening elements and γ phase forming elements was optimized. Specifically, the addition of Nb was limited compared to René 88 DT alloy to effectively reduce the dendritic segregation tendency during melting and casting. GH4065 alloy allows the addition of Fe up to 1.0% (mass fraction), which can improve the addition method of alloying elements such as Nb during melting on one hand, and enable sharing of crucibles with GH4169, the highest-volume Fe-Ni based alloy, facilitating recycling of revert materials and thus helping to improve production efficiency and reduce production costs.

Regarding interstitial elements, the most significant difference between GH4065 alloy and René 88 DT is the substantial reduction in C content, with the upper limit controlled at 0.01%, only 1/3 to 1/5 of that in René 88 DT alloy, and lower than GH4720 alloy which also adopts low interstitial element design. Reducing C content can significantly decrease both the size and quantity of primary carbides in the ingot, while effectively alleviating the dendritic segregation tendency of carbide-forming elements Nb and Ti. The reduction in size and quantity of primary carbides can improve the problem of large dispersion in austenite grain size caused by non-uniform carbide distribution, and as primary fatigue crack initiation sites, the reduction in carbide size and quantity can also significantly improve fatigue properties. GH4065 alloy limits the maximum addition of B to solve the macro-segregation problem of B during large-scale ingot melting and casting, and optimizes the addition of trace elements such as Zr to improve high-temperature stress rupture properties.

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2 Key Technical Issues in Producing Highly Alloyed GH4065 Alloy via Ingot Metallurgy Route

2.1 Overview of GH4065 Alloy Processing Route

As a highly alloyed precipitation-strengthened wrought superalloy, the VIM+ESR+VAR triple melting process is used to produce large-scale consumable remelting ingots with low segregation and free of metallurgical defects. After multi-stage homogenization treatment, the ingot undergoes open-die forging on a fast forging machine for breakdown. During breakdown, fine-grained billets are prepared using repeated upsetting and drawing processes based on sufficient breaking of the as-cast structure. Disc forgings are formed under hot-die forging conditions, and microstructure and properties are controlled through heat treatment. As shown in Figure 1 [Figure 1: see original paper], the processing route for GH4065 alloy forgings is basically consistent with the framework for preparing key rotating components of GH4169 and its modified alloys. However, as a highly alloyed nickel-based precipitation-strengthened alloy with γ phase volume fraction exceeding 40%, successful implementation of the ingot metallurgy route requires solving a series of key technical issues in large-scale ingot low-segregation melting, breakdown of as-cast structure, and preparation of fine-grained forgings. Currently, domestic production has achieved melting and open-die forging of 508 mm diameter consumable ingots with satisfactory yield, prepared large-scale fine-grained billets up to 300 mm in maximum diameter using repeated upsetting and drawing processes, and realized die forging of full-scale turbine disc forgings of 630 mm diameter under hot-die forging conditions.

The production of full-scale aero-engine turbine disc forgings of GH4065 alloy via the ingot metallurgy route offers outstanding advantages of low cost (forging price is 1/3 of powder metallurgy process), high productivity (mass production can be achieved using standard equipment in domestic metallurgical industry), and stable and reliable product quality (mature process equipment, easy batch inspection, and absence of inherent issues in powder metallurgy such as foreign inclusions and prior particle boundaries).

2.2 Low-Segregation Melting Technology for Large-Scale GH4065 Alloy Ingots

For precipitation-strengthened superalloys with high Al and Ti contents, the international consensus is that the VIM+ESR+VAR triple melting process is required to ensure the metallurgical quality of ingots for critical rotating components, with the VAR process being the most mature and effective method for ensuring metallurgical quality of large-scale ingots.

Based on optimization of the standard triple melting process, a low-segregation melting technology for large-scale ingots of highly alloyed GH4065 alloy has been developed. Through control of VIM and remelting (ESR+VAR) processes, issues such as chemical composition control and reliable removal of gases and inclusions in highly alloyed superalloys are effectively solved. Particularly during VAR of large-scale ingots, with support from technologies such as precise melting rate control and He gas cooling, the solidification process and solute transport behavior at the solidification front can be regulated. This effectively increases the temperature gradient at the solidification front, shortens local solidification time, reduces the melt pool depth, thereby significantly decreasing secondary dendrite arm spacing and controlling dendritic segregation within acceptable ranges. Using this technology, the secondary dendrite arm spacing in GH4065 alloy 508 mm diameter consumable ingots can be reduced to the level of 100 m, while the dendritic segregation coefficients of major elements are distributed within a narrow range of 0.8–1.2. The macrostructure of GH4065 alloy large-scale consumable ingot is shown in Figure 2 [Figure 2: see original paper]. As can be seen, the metallurgical quality of large-scale consumable ingots is reliably guaranteed. Analysis shows no macro-scale chemical composition variation along the axial and radial directions of the consumable ingot, and no various types of metallurgical defects are observed.

Research has shown that due to mature chemical composition control technologies such as desulfurization in vacuum induction melting, double vacuum melting (VIM+VAR) can effectively control the chemical composition of highly alloyed materials. However, practice indicates that the quality of VIM-cast electrodes (mainly density) cannot be reliably guaranteed, which adversely affects the stability of the melt pool during VAR and increases the probability of forming metallurgical defects such as freckles in the consumable ingot. Therefore, from the perspective of VAR process stability, an intermediate melting process is necessary to obtain high-quality VAR electrodes. When constrained by ESR technology and equipment level, consideration can be given to adding an intermediate VAR process on the basis of double vacuum melting to improve electrode quality and ensure stability of the final VAR remelting process.

Application of the triple melting process can produce large-scale consumable ingots with maximum diameter up to 508 mm, with the number of forgings obtained per heat being basically consistent with GH4169 and its modified alloys. For 300 kg high-pressure turbine disc forgings, 8–12 pieces can be obtained per heat, with even more pieces for other forgings such as smaller compressor discs and low-pressure turbine discs, facilitating batch inspection and quality control of forgings.

2.3 Thermomechanical Processing and Microstructure Control of GH4065 Alloy

For wrought superalloys, to meet industrial production requirements for efficiency and cost, open-die forging on a fast forging machine is the main approach for breakdown of consumable ingot as-cast structure. As a highly alloyed precipitation-strengthened alloy, the open-die forging breakdown of GH4065 alloy requires reasonable ingot homogenization schedules combined with new billet temperature control technology and efficient insulation materials to ensure successful breakdown and achieve satisfactory yield.

Practice has shown that GH4065 alloy large-scale consumable ingots possess good hot plasticity, outperforming GH4720 and GH4742 alloys in terms of ingot surface quality, forgeable time per heat, and total number of forging heats during breakdown.

For producing small-to-medium specification billets with diameter less than 150 mm from 508 mm diameter consumable ingots, continuous drawing using a fast forging machine plus radial forging machine can produce high-quality fine-grained billets with average grain diameter less than 20 m. For large-scale billets with diameter greater than 200 mm, 1-3 upsetting and drawing cycles are needed during breakdown to increase cumulative deformation and thereby effectively control billet microstructure and properties. Overall, except for temperature schedules, the open-die forging breakdown process for GH4065 alloy is basically consistent with the breakdown process for GH4169 alloy used for turbine discs, representing a mature industrial-scale production technology that provides reliable guarantee for high-efficiency, low-cost batch production of GH4065 alloy billets of various specifications.

To expand the hot working temperature window of GH4065 alloy, maximize material hot plasticity, and improve microstructure control capability of billets and forgings, a new multi-cycle thermomechanical processing technology has been applied during hot working. This technology can produce a special duplex fine-grained microstructure in precipitation-strengthened alloys with high γ phase volume fraction through specific thermomechanical processing procedures. Compared with conventional microstructures, the topological relationship between precipitates and austenite matrix grains is fundamentally changed in the duplex fine-grained microstructure. In conventional microstructures, fine precipitates are coherently dispersed within relatively coarse austenite matrix grains, whereas in duplex fine-grained microstructures, the precipitate size is significantly increased and approaches that of fine austenite grains, forming incoherent interfaces with each other and serving as mutual grain boundaries, creating a typical duplex microstructure morphology. Two typical microstructure morphologies in GH4065 alloy are shown in Figure 3 [Figure 3: see original paper]. Figures 3a and 3c show conventional coarse-grained microstructure morphology, where austenite grains become distorted during plastic deformation and intragranular γ phase exhibits a dispersed distribution. During thermoplastic deformation, the dispersed precipitation of γ phase produces a strong strain aging effect, resulting in high flow stress and poor hot plasticity, making recrystallization of the austenite matrix difficult. Figures 3b and 3d show duplex fine-grained microstructure morphology. After forming the duplex fine-grained microstructure, flow stress decreases significantly while hot plasticity increases substantially. Research has shown that precipitation-strengthened alloys exhibit substantially improved hot plasticity after forming duplex fine-grained microstructures, particularly maintaining superplastic deformation capability even at high strain rates of 10^{-2} s^{-1}, which is directly related to the rapid migration capability of incoherent γ-γ phase boundaries.

Figure 4a [Figure 4: see original paper] shows the flow stress corresponding to two different microstructure morphologies in GH4065 alloy under the same deformation conditions. As can be seen, the flow stress of duplex fine-grained microstructure decreases significantly under the same conditions. Figure 4b presents the variation of strain rate sensitivity coefficient m of duplex fine-grained microstructure flow stress. It can be observed that a high m-value region is formed within the two-phase field for duplex fine-grained microstructure, indicating a range of plastic deformation conditions with superplastic deformation capability. After forming the duplex fine-grained microstructure, deformation temperature can be reduced to below 1000 °C in the low strain rate direction, allowing forgings to be formed under hot-die forging conditions without requiring isothermal forging, thereby substantially reducing costs. More importantly, at temperatures approaching the complete dissolution temperature of γ phase, the material can undergo large deformation at high strain rates greater than 10^{-2} s^{-1}, enabling breakdown of as-cast structure and preparation of fine-grained billets on conventional fast forging machines.

Figure 5 [Figure 5: see original paper] shows a full-scale GH4065 alloy turbine disc forging with 630 mm diameter. This forging has exactly the same dimensions as a certain specification of GH4169 alloy high-pressure turbine disc forging. Figure 6 [Figure 6: see original paper] shows the macrostructures of GH4065 alloy billet and full-scale turbine disc forging. As can be seen, the microstructural uniformity of the alloy is effectively guaranteed. These results demonstrate that optimized novel thermomechanical processing technology can be used to mass-produce GH4065 alloy large-scale billets and forgings under conventional forging equipment conditions in the metallurgical industry, thereby effectively controlling production costs.

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3 Mechanical Properties of GH4065 Alloy

Analysis and testing of full-scale forgings show that within the temperature range from room temperature to 750 °C, the mechanical properties of GH4065 alloy are generally consistent with those of René 88 DT alloy, which is determined by the basically identical main compositions of the two alloys. As shown in Figure 7 [Figure 7: see original paper], the room temperature yield strength of GH4065 alloy is comparable to that of GH4169 (DA718) alloy prepared using the direct aging process, while its comprehensive properties above 650 °C show obvious advantages over GH4169 and its modified alloys, with all key performance indicators reaching the level of René 88 DT alloy. Particularly, the alloy simultaneously possesses excellent low-cycle fatigue properties and high-temperature creep properties, thus well meeting the service requirements of rotating components such as turbine discs. Among nickel-based wrought alloys, the properties of GH4065 alloy are close to those of GH4720 (U720Li) alloy, while showing obvious advantages over other conventional turbine disc materials, particularly in yield strength, where GH4065 alloy is significantly higher than highly alloyed turbine disc materials such as GH4586 and GH4742, better meeting the requirements of new high-performance engines.

Experiments have shown that GH4065 alloy possesses good long-term microstructural stability under high-temperature service conditions, with topological phase precipitation beginning at 1$×10^{4}$ h at 750 °C. In terms of mechanical properties, analysis and testing to date indicate that when GH4065 alloy is in service below 700 °C, various mechanical properties do not show significant time dependence and can remain stable within 1$×10^{4}$ h.

Theoretically, as service temperature increases, the effect of alloying element dendritic segregation on material microstructure and properties will gradually strengthen. Evaluation of long-term microstructural and property stability of GH4065 alloy at the relatively high temperature of 750 °C is currently underway. Preliminary studies show that no significant degradation occurs within 5×10^{3} h, indicating that the effect of alloying element dendritic segregation on the properties and long-term microstructural stability of GH4065 alloy is within an acceptable range.

GH4065 alloy maintains significant cost advantages while achieving high performance, making it an ideal material for preparing aero-engine compressor discs and low-pressure turbine discs operating below 750 °C, and can serve as a high-reliability, low-cost alternative solution for powder metallurgy high-pressure turbine discs.

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4 Future Research Work

In terms of alloy design, in-depth systematic research is needed on the role of trace elements and their optimal addition amounts, determination of the upper limit of Fe element addition, and austenite grain boundary strengthening mechanisms under ultra-low C conditions.

In terms of processing technology, further development and improvement of melting methods for ultra-low C content precipitation-strengthened alloys are needed to achieve precise control of C content at the 0.01% level. Since the heat treatment process of GH4065 alloy is similar to the direct aging process of GH4169 alloy, higher requirements are placed on the microstructure control capability of thermomechanical processing. Further work is needed on how to improve microstructural uniformity of large-scale billets and forgings under mass production conditions to minimize dispersion of forging mechanical properties and improve ultrasonic inspection performance. Additionally, research should be conducted on developing heat treatment technologies and equipment adapted for preparing dual-property discs according to new engine requirements for disc forgings, and on studying the alloy’ s welding process performance to further expand the alloy’ s application range.

In terms of service behavior, systematic evaluation of long-term microstructural and property stability of GH4065 alloy in the relatively high temperature range of 730–760 °C is needed, along with investigation of damage mechanisms under service conditions approaching actual operating conditions, to provide a basis for component life prediction.

Conclusions

(1) As a new wrought superalloy developed for the operational requirements of aero-engine hot-section rotating components, GH4065 alloy has a service temperature of 750 °C, with main mechanical property indicators basically consistent with those of René 88 DT alloy produced by powder metallurgy.

(2) Relying on existing high-temperature alloy melting and thermomechanical processing equipment conditions in domestic metallurgical industry, GH4065 alloy billets and forgings can be mass-produced via the ingot metallurgy route. Large-scale consumable ingots of GH4065 alloy produced using the VIM+ESR+VAR triple melting process exhibit excellent metallurgical quality, with reliable elimination of various metallurgical defects and dendritic segregation controlled within acceptable ranges. GH4065 alloy consumable ingots possess good hot plasticity reserves, enabling open-die forging breakdown on fast forging machines. Application of multi-cycle thermomechanical processing technology enables effective control of microstructure and properties of full-scale forgings under hot-die forging conditions.

(3) GH4065 alloy is suitable for preparing critical hot-section rotating components of advanced aero-engines, with properties fully meeting the operational requirements of high-pressure compressor discs and low-pressure turbine discs, and can serve as a high-reliability, low-cost solution for high-pressure turbine discs when necessary. With the development of wrought superalloy materials and processing technologies, high-performance turbine disc materials produced via the ingot metallurgy route can meet the technical requirements of advanced aero-engines.

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Note: Figure translations are in progress. See original paper for figures.