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NICKEL-BASE SUPERALLOY MATERIALS TECHNOLOGY FOR ADVANCED IGT APPLICATIONS

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Abstract

The firing temperatures of all gas turbines, both industrial power generation and aircraft engines, have increased over the past ~30 years. More recently, the rate of temperature increase has slowed for aircraft engines but not for industrial gas turbines (IGT). As a result, the materials temperature capability requirements for these two classes of gas turbines are converging. For many years, the high performance requirements of military and commercial aircraft engines fueled the development of advanced materials and processes. Many of these high temperature materials are now being used in industrial gas turbines as output, efficiency, and reliability requirements continue to grow. Directionally solidified and single-crystal nickel-base superalloys have been developed for investment casting of hot gas path components and have been scaled up to the part sizes required for IGT components but not without significant challenges in producibility, defect allowances, and repair. Wrought nickel-base superalloys such as Alloy 706 and Alloy 718 are being used in IGT rotor structures after significant advances in ingot melting/casting, forging, and inspection. This paper will discuss the application of nickel-base superalloys in industrial gas turbines with particular emphasis on the technology development required to produce hot gas path and rotor components in large IGT sizes. Processing scale-up from aircraft engine-sized parts to large IGT-sized parts has presented unique materials development and processing challenges.

Introduction

Since the early 1970's there has been a continuous increase in the output and efficiency of large, land-based industrial gas turbines (IGT) for electrical power generation. This increase is due in large part to the introduction of high temperature structural materials. The use of these advanced materials has resulted in an increase in gas turbine firing temperature from 982ºC (1800ºF) to greater than 1427ºC (2600ºF) over the past 30 years. For every 10ºC (50ºF) increase in the firing temperature, the gas turbine combined-cycle efficiency improves by approximately 1%. A 1% improvement in efficiency means millions of dollars in savings to an electrical power producer looking to deliver electricity at the lowest cost to its customers.

Nickel-base (Ni-base) superalloys are the alloys of choice for high temperature, high strength structural applications, and they have become the standard for IGT hot gas path components such as buckets, nozzles, and shrouds. Many of these investment cast Ni-base superalloys were derived from aircraft engine alloys developed for use in both commercial and military aircraft gas turbines. In addition, high strength wrought Ni-base superalloys such as Alloys 706 and 718 have replaced steel alloys in General Electric IGT rotor applications. Alloy 706 became the first production application of Ni-base superalloy forgings in an IGT in the late 1980's. The first Alloy 718 IGT forgings were introduced in 1995.

In addition to both investment cast and wrought Ni-base superalloys, other high temperature materials are in production or being developed for IGT applications. High temperature coatings such as metallic coatings for oxidation and corrosion resistance and ceramic coatings for thermal protection are becoming standard for hot gas path and combustion hardware. Ceramic-matrix composites are also being developed for high temperature applications such as turbine shrouds, combustion liners, and turbine nozzles. This paper will focus on the development and introduction of Ni-base superalloy technology for advanced IGT applications

Recent Advances in Ni-Base Superalloy Materials and Processes

Airfoil Applications

Over the past several decades, advanced airfoil alloy development at General Electric has progressed from poly-crystalline Ni-base superalloys such as U500, U700, and Alloy 738, to poly-crystalline and then directionally solidified (DS) GTD-111™. GE's most advanced DS Ni-base superalloy in production use is GTD-444™, a DS version of the single-crystal (SX) Rene' N4 alloy used in aircraft engine applications. Figure 1 shows the schematic IGT airfoil alloy development, plotting application temperature as a function of first introduction. Note that Figure 1 shows two paths for advanced IGT airfoil alloy development. One path has been followed for the evolution of cast Ni-base superalloys for latter stage bucket applications that require simple or no internal cooling. The second path shows the introduction of SX Rene' N5, a second generation (containing rhenium) single-crystal Ni-base superalloy developed for aircraft engine applications. SX Rene' N5 has been adopted for IGT use in first stage buckets having complex internal cooling schemes as well as first stage nozzle and shroud applications in General Electric's most advanced IGT's. Table I lists the alloy compositions of these important IGT investment cast Ni-base superalloys.

DS and SX Alloys. The investment cast Ni-base superalloys currently in IGT use have been principally derived from aircraft engine alloys developed to meet stringent high performance

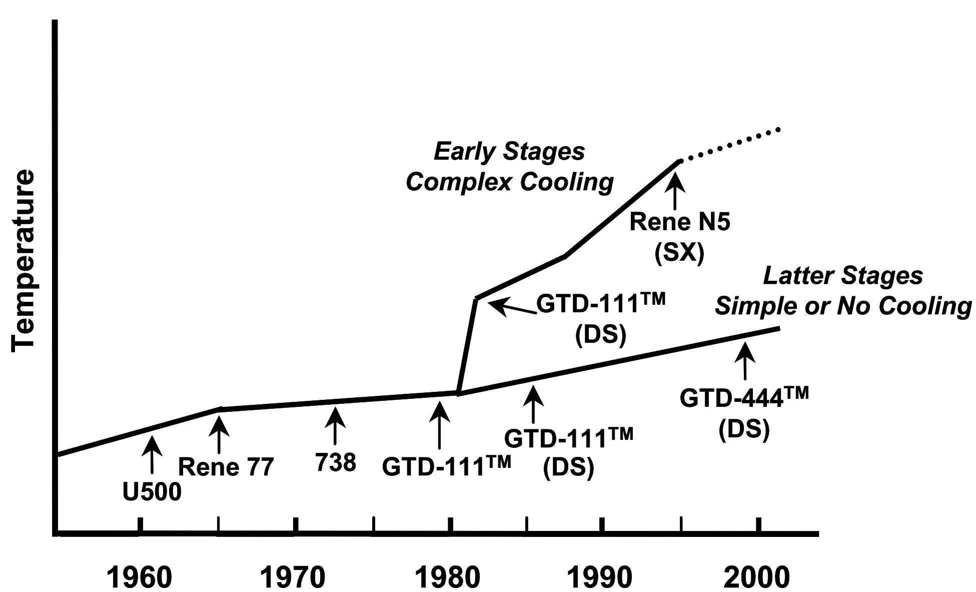

Figure 1. IGT bucket alloy evolution showing increase in temperature capability.

Table I. Nominal Composition of IGT Cast Ni-Base Superalloys

wt %	Ni	Cr	Co	Fe	Mo	W	Al	Ti	Nb	Ta	Mn	V	C	B	other
U500	bal	18.50	18.50		4.00		3.00	3.00					0.07	0.006	
U700 (Rene 77)	bal	15.00	17.00		5.30		4.25	3.35					0.07	0.020	
Alloy 738	bal	16.00	8.30	0.20	1.75	2.60	3.40	3.40	0.90	1.75			0.10	0.001	
GTD-111TM	bal	14.00	9.50		1.50	3.80	3.00	4.90		2.80			0.10	0.010	
GTD-444TM	bal	9.80	7.50		1.50	6.00	4.20	3.50	0.50	4.80			0.08	0.009	Hf 0.15
Rene N5	bal	7.00	7.50		1.50	5.00	6.20			6.50			0.05	0.004	Re 3.0, Hf 0.15, Y 0.01

requirements of both commercial and military aircraft gas turbines. However, the introduction of these aircraft engine alloys in IGT hot gas path components has posed significant development challenges. Figure 2 shows a General Electric F-class gas turbine first stage bucket in relation to a typical aircraft engine turbine blade. This first stage bucket is a directionally solidified (DS) Ni-base superalloy made from GTD-111^{TM}, an alloy derived from Rene' 80 and developed specifically to meet property requirements for long-life operation in IGT's. This first stage bucket demonstrates a greater than 10X increase in part size and a greater than 20X increase in part weight as compared with the aircraft engine blade. These DS Ni-base superalloy buckets are up to 76 cm (30 in) in length and weigh up to 18 kg (40 lbs). In the most advanced IGT's, they are designed and manufactured with complex internal serpentine cooling passages. They are manufactured to very tight dimensional tolerances, and inspection and acceptance standards are today approaching aircraft engine requirements.

Critical processing technology developments were required to scale up the investment casting of Ni-base superalloys for IGT applications. DS and single-crystal (SX) investment casting furnaces were scaled up to handle the size and weight of IGT buckets. Advances in mold materials and construction were required to hold the large volumes of molten metal during the DS and SX casting withdrawal process. Ceramic cores were improved to increase high temperature strength in order to minimize core deformation and hold critical dimensional tolerances. Processing considerations were also important to alloy selection and chemistry modifications, as Ni-base superalloys were adapted from aircraft engines to IGT applications. Alloy chemistries were modified to prevent formation of melt-related defects such as freckles,

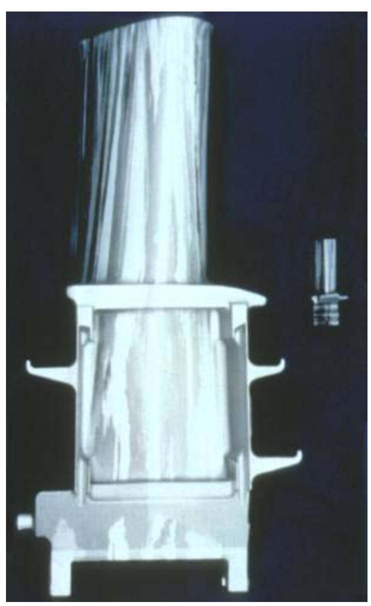

Figure 2. Size comparison of an IGT first stage bucket with a typical aircraft engine turbine blade.

porosity, and hot tearing in the large IGT parts. In addition, minor alloying elements were adjusted to control grain boundary strength. These alloy chemistry changes to improve the castability of alloys in large sizes and to increase casting yields had to be balanced with the alloy mechanical property and environmental resistance requirements for IGT hardware for robust, long-life service. These materials and processes technology developments were conducted in joint partnership with General Electric's strategic investment casting suppliers.

Figure 3 shows General Electric's H-class gas turbine third stage and fourth stage buckets made of DS GTD-444™ Ni-base superalloy. The alloy development of DS GTD-444™ serves as a good example of the alloy modification conducted to adapt an aircraft engine alloy for IGT application. DS GTD-444™ is a directionally solidified version of the first generation SX Ni-base superalloy Rene' N4. When design requirements exceeded the material capability of DS GTD-111™, the SX Rene' N4 alloy was selected because of the alloy's very good high temperature strength. Grain boundary element modifications were made to the alloy to produce a SX Rene' N4 derivative as a DS alloy with improved large-part castability for IGT application. The result was a castable, high temperature DS Ni-base superalloy with improved creep and fatigue properties as compared with DS GTD-111™. DS GTD-444™ was first introduced in production in 1999.

Figure 4 shows General Electric's H-class gas turbine first stage bucket made of SX Rene' N5. This Ni-base superalloy was adopted directly from aircraft engine application and is currently used in production for first stage buckets, as well as first stage nozzles and shrouds, in General Electric's H-class and FB-class gas turbine product lines. These applications are the first use of SX Ni-base superalloys in IGT's manufactured by General Electric. Significant material and processes development was required for the introduction of SX Ni-base superalloys in IGT applications, including SX investment casting equipment and technology, ceramic mold and core development, and post-cast joining, machining, coating, and inspection technology to fabricate these very complex, high performance airfoils.

High Gradient Casting Technology. High gradient is a term used to describe any one of a number of investment casting techniques used to solidify castings under well-controlled, large thermal gradients. This results in cast material have a much-refined microstructure with improved chemical homogeneity. In the conventional DS or SX investment casting process,

Figure 3. Third and fourth stage IGT buckets made from DS GTD-444™.

Figure 4. First stage IGT bucket made from SX Rene'N5.

heat from the mold is removed by conduction to a chill plate and by radiation to the surroundings, including heat loss from the open baffle in the bottom of the furnace during the mold withdrawal process. In a high gradient casting process, heat from the mold is removed by immersing the mold into a cooling media directly from the mold withdrawal from the furnace. The high gradient cooling media is often a bath of liquid metal such as aluminum or tin.

High gradient casting technology promises to increase casting yields and throughput by eliminating melt-related defects such as freckle formation in complex airfoil geometries. In addition, high gradient casting produces a significant refinement of the cast alloy microstructure, as often measured by the primary dendrite arm spacing. This microstructural refinement is also accompanied by a reduction in casting microporosity, a reduction in the volume fraction of eutectic phase, and an improvement in the morphology and distribution of carbides. The chemical homogeneity of the cast alloy is improved, and this allows Ni-base superalloys to be more fully solutioned during heat treatment, resulting in a significant increase in high temperature creep and fatigue properties. This microstructural refinement and improved chemical homogeneity achievable by a high gradient casting process can provide both incremental gains and big leaps in investment casting technology. The improved materials capability provided by high gradient casting provides important design benefits such as component upgrades without redesign, the flexibility to balance higher component performance with extended component life, and the ability to cast more exotic, high performance, hard-to-cast Ni-base superalloys. In addition, a direct material substitution may provide cost reduction by replacing a more costly DS or SX Ni-base superalloy with a less expensive alloy at equivalent performance by improving the capability of the less costly alloy via a high gradient casting process.

Rotor Applications

Wrought Alloy 706 and 718. Table II shows the alloy compositions of several important IGT rotor alloys. As IGT performance has increased, rotor designs have required the strength and temperature capability of wrought Ni-base superalloys. Alloys 706 and 718 possess significantly higher strength and creep resistance than the steel alloys A286, M-152, and CrMoV steel. However, IGT turbine rotor size and construction has presented significant technical challenges in the melting/casting of large Ni-base superalloy ingots and the billetizing/forging into IGT rotor wheels and spacers. Figure 5 shows a General Electric FB-class gas turbine first stage wheel forging (partially machined to sonic shape for NDT inspection) in comparison to a typical aircraft engine turbine disk forging. Large IGT's require large ingots to make large forgings. Typical Ni-base superalloy ingot input weight for the largest wheels and spacers is greater than 14,515 kg (32,000 lbs). Unlike the aircraft engine industry, one ingot makes one IGT wheel or spacer. Because of the large size of the ingot and subsequent billets required for an IGT forging, internal melt-related defects cannot be detected by NDT at the billet stage in the coarse-grain alloy microstructure. A single melt-related defect, such as a dirty white spot or large freckle region, can scrap the part at final NDT

Table II. Nominal Composition of Ni-Base Superalloy (706 and 718) Rotor Alloys

wt %	Ni	Cr	Co	Fe	Mo	W	Al	Ti	Nb	Ta	Mn	V	C	B	other
Alloy 718	bal	19.00	0.40	18.50	3.00		0.50	0.90	5.10				0.03		
Alloy 706	bal	16.00		37.00				1.80	2.90				0.03		
Cr-Mo-V	0.50	1.00		bal	1.25							0.25	0.30		
A286	25.00	15.00		bal	1.20		0.30	2.00				0.25	0.08	0.006	
M152	2.50	12.00		bal	1.70							0.30	0.12		

inspection after machining a final forging to sonic shape as shown in Figure 5. Working jointly in partnership with strategic Ni-base superalloy melting and forging suppliers, General Electric has successfully developed the melting/casting technology for large Ni-base superalloy ingots, the billetizing/forging processes, and the NDT inspection technology required to produce large Alloy 718 wheels and spacers for the FB-class and H-class gas turbines.

The first Alloy 706 Ni-base superalloy IGT forgings were made by General Electric in the mid 1970's. These forgings were made from double melted ingots approximately 61 cm (24 in) in diameter and approximately 5,443 kg (12,000 lbs). In the mid 1980's the melting/casting and billetizing/forging processes were scaled up for F-class gas turbine application to replace CrMoV steel rotors. The Ni-base superalloy ingots grew to 76 to 102 cm (30 to 40 in) in diameter and to 9,072 to 14,968 kg (20,000 to 33,000 lbs) in weight. The triple-melt process (VIM-ESR-VAR) was qualified for Alloy 706, and first production application of Ni-base superalloy forgings in an IGT began in the late 1980's. The first Alloy 718 Ni-base superalloy IGT forgings were made by General Electric in 1995 for the H-class gas turbine. The ingots were 69 cm (27 in) in diameter, larger than any Alloy 718 ingots made to date. Alloy 718 is a proven structural alloy used since the 1960's in aircraft engine disk applications. To produce Alloy 718 ingots of the required IGT size, triple-melt processing similar to aircraft engine Alloy 718 disks and IGT Alloy 706 wheels was successfully applied. Billetizing and forging processes were scaled up through extensive use of process modeling to optimize microstructure throughout the volume of the final forging.

In order to meet FB-class gas turbine rotor size requirements, the Ni-base superalloy melting/casting process had to once again be scaled up. Ingots were produced having 91 cm (36 in) diameters and weighing 12,701 to 14,968 kg (28,000 to 33,000 lbs) in order to get the proper forging input weight. This was achieved through critical improvements in process control of the triple-melt (VIM-ESR-VAR) process. Tight control of the VAR melting step was crucial to prevent melt-related defects. Process modeling was employed extensively to optimize the VAR process. Critical process parameters were optimized to eliminate chemical segregation and freckle formation by closely controlling a stable solidification withdrawal rate and maintaining a shallow molten pool depth in the solidifying ingot during withdrawal from the VAR furnace. Improved process control and equipment modifications helped to eliminate

Figure 5. Size comparison of an IGT first stage wheel forging (machined to sonic inspection shape) with a typical aircraft engine turbine disk forging.

the formation of dirty white spots by stabilizing the shelf and crown of the solidifying ingot at the upper crucible walls of the VAR furnace. As with the H-class gas turbine, billetizing and forging processes were scaled up through the extensive use of forging process modeling to optimize microstructure throughout the volume of the final forging. Forging of wheels and spacers of this size requires very large forge presses. Control of the forging parameters such as preheat temperature, deformation rate, total strain, and post-forge heat treatment is very critical.

Melting/Casting Technology. New wrought Ni-base superalloys are being considered for advanced IGT rotor applications where design requirements will exceed the materials capability of Alloy 718. Key to the identification and development of promising alloy candidates with improved high temperature properties will be the cost/benefit trade-offs between wrought Ni-base superalloys and powder metallurgy Ni-base superalloys like those used for many years in aircraft engine applications. A shift to a powder metallurgy Ni-base superalloy for IGT applications will require a large investment in production infrastructure and the development of powder alloy processing technology in large IGT sizes. However, a promising new Ni-base superalloy melting/casting process called Clean Melt Nucleated Casting (CMNC) is under development by Allegheny-Teledyne Allvac, Monroe NC, and General Electric under government contract that may delay the need to move to powder metallurgy processing. CMNC is being developed as a robust, melting/casting process to produce large diameter Ni-base superalloy ingots without melt-related defects. CMNC promises to provide the required process flexibility and growth potential to melt/cast highly alloyed (high strength), segregation-prone Ni-base superalloy compositions that would otherwise require powder metallurgy processing. CMNC uses a cold induction guide (a water cooled copper nozzle) to pour molten metal from the bottom of an ESR furnace. Since the nozzle contains no ceramic, CMNC enables the casting of clean, inclusion-free ESR alloy. The molten alloy stream is then atomized, and the semi-solid (high liquid-to-gas ratio) spray is directed to fill an ingot mold. Since nucleation of solidified particles is taking place in the spray, the semi-solid liquid results in a uniform, fine-grain ingot in the mold. CMNC also promises to reduce the cost of Ni-base superalloy melting/casting since the melt rate is 3X to 10X faster than the current VAR process, it eliminates the VAR step in the triple-melt process, and it may be possible to forge the resulting fine-grain ingot in fewer steps than is currently required.

Summary

To increase the output and efficiency of IGT's, the firing temperature continues to increase, placing higher demands on the temperature capability of gas turbine materials. Over the past ten years, firing temperature has increased by approximately 93ºC (200ºF), and combined-cycle efficiency has increased by approximately 4%. Materials and processes improvements have enabled these performance increases along with improving the durability and reliability of advanced IGT's. Continued growth in IGT firing temperature and efficiency will require continued materials and processes technology development. Ni-base superalloys have been key to past progress and are key to future IGT growth. Cast Ni-base superalloys for hot gas path applications will require higher temperature strength with improved oxidation/corrosion resistance. Larger component sizes and complex geometries with sophisticated internal cooling schemes will require new investment casting technology to produce defect-free, high performance DS and SX Ni-base superalloys. For IGT rotor applications, future design requirements will demand a new Ni-base superalloy stronger than Alloy 718 that can be produced in a cast + wrought product form, producible in large sizes without melt-related defects. Materials and processes technology development for Ni-base superalloys continues today and into the future to assure that when new design requirements demand the world's best materials, Ni-base superalloys will be ready to meet the most challenging high temperature applications.