4.4.1

Buckets and Nozzles

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4.4.1-1 Introduction

Gas turbine engines, both aircraft and industrial power generation, represent one of the most aggressive applications for structural materials. With ever growing demands for increasing performance and efficiencies, all classes of materials are being pushed to higher temperature capabilities. These materials must also satisfy stringent durability and reliability criteria. As materials are developed to meet these demanding requirements, the processing of these materials often becomes very complicated and expensive. As a result, the cost of materials and processes has become a much larger consideration in the design and application of high performance materials. Both the aircraft engine and power generation industries are highly cost competitive, and market advantage today relies on reducing cost as well as increasing performance and efficiency.

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. The application of nickel-base superalloys in industrial gas turbines has required particular emphasis on technology development for the production of buckets and nozzles 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. There has been much synergy in the development of these materials for both aircraft engines and industrial power generation turbines, and this synergy is likely to continue to grow as we strive to push materials capability to the limit while providing robust designs for reliable, long-life service.

4.4.1-2 Background

Higher operating temperatures are historically the primary means of improving aircraft engine thrust or industrial power generation gas turbine output. Higher operating temperatures require higher temperature capability materials and associated technologies such as improved oxidation and environmental coatings. For industrial power generation gas turbines, the firing temperature (as defined by the gas temperature that enters the first rotating stage of buckets or blades) has a profound effect on the performance of the turbine.

Since the early 1970's there has been a continuous increase in the output and efficiency of large 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 to investment cast 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.

In order to reduce the amount of cooling air required to keep materials within their high temperature capability, several options have been pursued. The obvious is the use of higher temperature capability materials. The second is the use of thermal barrier coatings (TBCs). The third is the incorporation of more efficient cooling schemes. These approaches are complementary, and system approaches have been developed that take advantage of all three. Advanced industrial gas turbines firing at temperatures of 1425ºC (2600ºF) and above require advanced cooling schemes to keep the metal temperatures within design limits. While aircraft engines have used advanced air cooling techniques including extensive use of convection and film cooling to maintain part temperatures at required levels, they are limited to these techniques because these are the only approaches that are available for turbines that must be flown on aircraft. However, industrial gas turbines do not have these weight limitations and therefore can use other cooling techniques such as steam cooling for buckets and nozzles. The first benefit of steam cooling is that it allows higher firing temperatures for a given set of parts lives or reliability goals. The higher thermal transport properties of steam enable designers to maintain metal temperatures within acceptable limits in higher gas temperature environments. Secondly, film cooling requires that relatively cool air be mixed with the high temperature gas as it passes through the first stage nozzles. This film lowers the temperature of the gas thus increasing the difference between combustor discharge temperature and the firing temperature for a set combustor discharge temperature. Therefore for a given NOx production rate, steam cooling permits higher firing temperatures and hence maximizes output and efficiency. Thus the use of steam cooling allows NOx emissions and efficiency goals to be met simultaneously.

4.4.1-3 Process Development – Investment Casting of 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 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[1]. Figure 1 shows a General Electric F-class gas turbine first stage bucket in relation to a typical aircraft engine turbine blade[2]. This first stage bucket is a directionally solidified (DS) Ni-base superalloy made from GTD-111™, 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.

The earliest industrial gas turbines used forged turbine buckets with cast nozzles. This changed in the late 60's when castings began to be used in bucket applications. Many nozzle and bucket castings used in industrial gas turbines are made by using the conventional equiaxed investment casting process. Vacuum is used in most cases, except for some of the cobalt alloys, to prevent the highly reactive elements in the superalloys from reacting with the oxygen and nitrogen in the air. With proper control of metal and mold thermal conditions, the molten metal solidifies from the surface toward the center of the mold, creating an equiaxed structure. To prevent shrinkage porosity, care is taken to allow proper feeding of molten metal to the casting while it solidifies.

Directional solidification (DS) was first introduced into industrial gas turbines in the late 1980's. Although it has been in aircraft engines for more than 25 years, considerable process development was necessary to scale it up to the sizes of buckets used in industrial gas turbines. By exercising careful control over temperature gradients, a planar solidification front can be developed in these large buckets. The result is a bucket with an oriented grain structure that runs parallel to the major axis of the part and contains no transverse grain boundaries. The elimination of these transverse grain boundaries confers additional creep and rupture strength on the alloy, and the orientation of the grain structure provides a favorable modulus of elasticity in the longitudinal direction to enhance fatigue life. By directionally solidifying the alloy GTD-111™, an increase of approximately 23ºC (40ºF) in creep strength and an increase of approximately 10X in fatigue life can be realized[3].

Fig. 1. Size comparison of an IGT first stage bucket with a typical aircraft engine turbine blade. (Courtesy of General Electric Company).

Source: See Note 2.

Figure 2 shows General Electric's H System^{TM} gas turbine third stage and fourth stage buckets made of DS GTD-444^{TM} Ni-base superalloy[4]. The alloy development of DS GTD-444^{TM} serves as a good example of the alloy modification conducted to adapt an aircraft engine alloy for IGT application. DS GTD-444^{TM} 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^{TM}, 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^{TM}. DS GTD-444^{TM} was first introduced in production in 1999.

More recently, industrial gas turbine OEM's have worked with suppliers and universities to develop large, single-crystal (SX) castings that offer additional creep and fatigue benefits through the elimination of grain boundaries. While directionally solidifying GTD-111^{TM} as a single crystal offers some improvements in creep and fatigue, much more significant improvements can be achieved by adopting alloys developed as single-crystal compositions for aircraft engine applications. The use of one such alloy, Rene' N5, can produce an increase of more than 35ºC (~60ºF) in creep strength and 2X to 3X increase in fatigue life compared to DS GTD-111^{TM}. However, to successfully produce large single crystals weighing more than 11 kg. (~25 lbs) and measuring more than 450mm (~18 inches) in length, modifications had to be made to the alloy. These modifications were necessary to reduce the reaction between the metal and mold materials to enable reasonable yields to be obtained when these buckets and nozzles are solidified for long times at high temperatures[5].

Figure 3 shows General Electric's H System^{TM} gas turbine first stage bucket made of SX Rene' N5[6]. 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 System^{TM} and FB-class gas turbine product lines. These applications are among the first use of SX Ni-base superalloys in IGT's. 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.

Critical processing technology developments were required to scale up the investment casting of Ni-base superalloys for IGT applications. DS and 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, 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 are often conducted in joint partnership between the gas turbine OEM and the investment casting suppliers.

Fig. 2. Third and fourth stage IGT buckets made from DS GTD-444TM. (Courtesy of General Electric Company).

Source: See Note 2.

Fig. 3. First stage IGT bucket made from SX Rene'N5. (Courtesy of General Electric Company).

Source: See Note 2.

The main drivers for yield in large DS and SX airfoil castings are dimensional and grain defects. Dimensions and associated tolerances result from the aerodynamic, mechanical, and heat transfer design of the part that must meet the gas turbine cycle requirements. Grain defects are metallurgical in nature and are controlled by local solidification, chemistry, heat treatment, and geometry. Typical grain defects encountered by developers of DS and SX IGT airfoils are shown in figure 4[7]. Grain defects are typically dealt with by adjusting processing conditions, mold configurations, local geometry, and alloy chemistry[8].

4.4.1-4 Process Development – High Gradient Casting

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, 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[9].

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[10]. 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.

4.4.1-5 Alloy Development – Buckets

Over the past several decades, advanced airfoil alloy development for industrial gas turbines has progressed from poly-crystalline Ni-base superalloys such as U500, U700, and Alloy 738, to poly-crystalline and then directionally solidified superalloys such as (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 5 shows a schematic of IGT airfoil alloy development, plotting application temperature as a function of first introduction. Note that figure 5 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 some important IGT investment cast Ni-base superalloys.

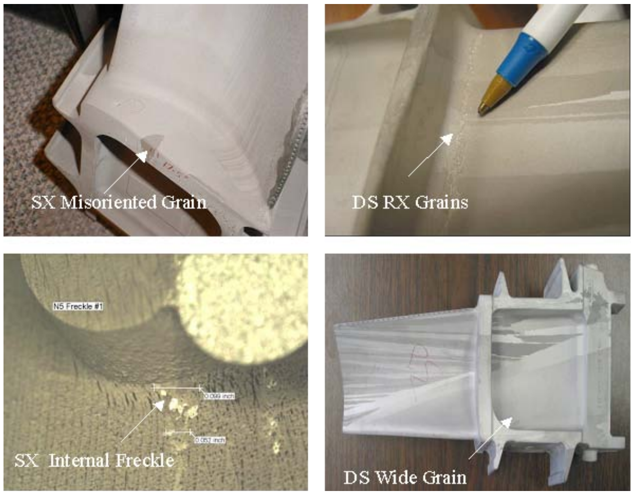

Fig. 4. Typical grain defects in SX and DS airfoil alloys that negatively impact casting yields. (Courtesy of General Electric Company).

Source: See Note 7.

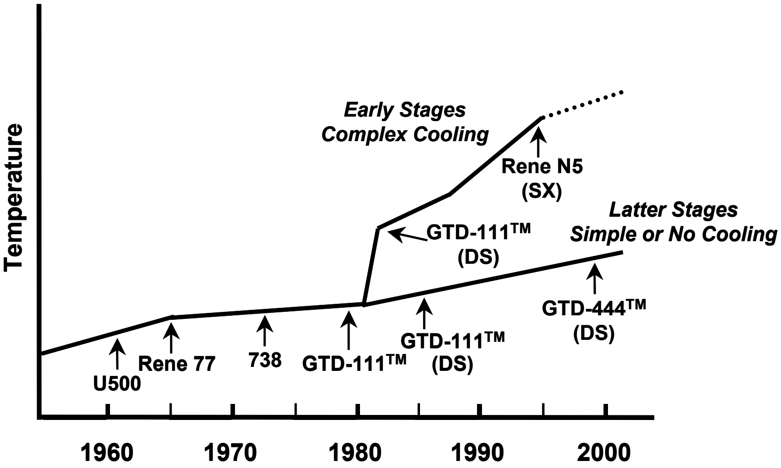

Fig. 5. IGT bucket alloy evolution showing increase in temperature capability.

Source: See Note 2.

The higher firing temperatures of advanced industrial gas turbines place increased demands on protective coatings for hot gas path components. Coatings are required to protect the components from corrosion, oxidation, and mechanical property degradation. As nickel-base superalloys have become more complex, it has been increasingly difficult to obtain both the higher strength levels that are required and a satisfactory level of corrosion and oxidation resistance without the use of coatings. The function of all coatings is to provide a surface reservoir of elements that will form very protective and adherent oxide layers, thus protecting the underlying base material from oxidation and corrosion attack and degradation. Since the mid-1980s, an increase in the oxidation resistance of IGT airfoil alloys has been required to meet the higher firing temperatures of advanced industrial gas turbines. This demand was met with a series of M-CrAlY overlay coatings with increasing oxidation resistance. In addition to these simple overlay coatings, duplex coatings that consisted of an overlay M-CrAlY with a diffusion aluminide were also developed. The enhanced oxidation protection was achieved by an increased aluminum content in the outer region of the coating. As the internal temperatures of these hot section parts increased, it also became necessary to coat the internal surfaces and cooling holes to provide protection against oxidation and embrittlement that would otherwise occur.

Air plasma sprayed yttria-stabilized zirconia thermal barrier coatings (TBCs) have been successfully used to extend life of superalloy components in aircraft engines and industrial gas turbines. A TBC is a multilayer thermal and environmental protection system consisting of an insulating layer of ceramic over a metallic bond coat for substrate oxidation protection and improved metal-ceramic interfacial properties. A typical air plasma sprayed (APS) TBC consists of a low thermal conductivity yttria stabilized zirconia (YSZ) ceramic top coat layer over a metallic bond coat layer. The top ceramic layer may be from 250 to 1250 microns (0.010 to 0.050 inch) thick while the metallic bond coat is typically from 200 to 300 microns (0.008 to 0.012 inch) thick. The bond coat is usually an M-CrAlY chosen to provide oxidation protection to the substrate metal and a rough surface for mechanical adhesion of the ceramic top coat. In conventional APS TBCs, the internal microcracks are “random” or non-directional. Advanced APS TBCs have been developed that mimic the oriented microstructure of vapor phase deposited TBCs. This advanced APS TBC can accommodate the mismatch in thermal strains between the ceramic top layer and the metallic bond coat and substrate. This allows the superior properties of this coating to be achieved by a coating process that can be used to apply TBCs to large industrial gas turbine parts.

4.4.1-6 Alloy Development – Nozzles

Nozzles, also called vanes, are the stationary airfoils that direct the hot gas path flow for proper impingement on the rotating buckets. They must be able to withstand high temperatures. For example, the stage 1 nozzles are subjected to the highest gas path temperatures in the turbine but to lower mechanical stresses than rotating buckets. Much of the stress experience by the nozzles is a result of high thermal stresses and to a lesser degree, mechanical stresses such as the aerodynamic loading. As a result, the nozzles must have excellent resistance to thermal fatigue, as well as high temperature oxidation and corrosion resistance. Good creep resistance is also an important design consideration, especially for large, multi-airfoil latter stage nozzles whose size and weight will lead to creep deformation at temperature as the nozzles support their own weight (and the attached diaphragm structure) from the turbine case.

Since the 1960’s, the cobalt-base alloy, FSX-414, has been the stage 1 nozzle alloy in General Electric’s E-class and F-class gas turbines[11]. FSX-414 has been the alloy of choice for nozzle applications for many years because of the superior highest temperature strength of cobalt alloys as compared with nickel-base alloys. In addition, cobalt-base alloys exhibit excellent corrosion resistance due to the level of Cr in the alloys. The oxidation resistance of FSX-414 is such that it is currently used without a protective oxidation coating. For the larger latter stage nozzles, GTD-222, a nickel-base superalloy, was developed to satisfy the requirement for higher creep resistance at relatively lower temperatures[12]. GTD-222 offered a creep strength improvement of approximately 60ºC (~150ºF) over FSX-414 at the typical operating temperatures for stage 2 and stage 3 nozzle applications. GTD-222 is often coated by an aluminiding process to enhance the oxidation resistance of the alloy. Both FSX-414 and GTD-222 possess good weldability, an important alloy characteristic for new-make nozzle salvage to remove casting defects, nozzle hardware fabrication, and nozzle repair after field service.

As the firing temperature of advanced industrial gas turbines increases, nickel-base superalloys with improved high temperature strength and high temperature oxidation resistance are being introduced for nozzle applications. For example, the bucket alloy GTD-111™ has been used for the stage 1 nozzle on General Electric’s FB-class gas turbines. Also, SX Rene N5 has been used for the stage 1 nozzle on General Electric’s H System™ gas turbine. In these applications, both GTD-111™ and SX Rene N5 are coated with a TBC to allow for higher hot gas path temperatures. As hot gas path temperatures increase for more turbine output and cooling flows decrease to improve turbine efficiencies, alloy development will continue for nozzle applications. Development of new alloy compositions that possess high temperature creep strength, i.e. high gamma prime content and excellent microstructural stability, along with good weldability (difficult with high gamma prime alloys) will be critical for long-life nozzle applications. Excellent oxidation and corrosion resistance are always important, especially for fuel flexibility and future syn-gas or other alternative fuel usage.

4.4.1-7 Materials Performance

As has been mentioned previously, nickel-base superalloys are the highest temperature class of metallic materials currently used in aircraft engines and industrial gas turbines. Among these, the highest temperature subset are the turbine airfoil alloys. The drive to increase output and efficiency in industrial gas turbines results in the need for increased capability materials for both creep and fatigue. It also puts increased demand on thermal and environmental coatings to provide protection for long times in higher temperature environments. Hot section buckets and nozzles must not only have sufficient strength to withstand the mechanical and thermal loading, but must also have coatings that protect the substrate material from damaging effects of exposure to the hot gases. These effects include oxidation, hot corrosion, and embrittlement. Thus these components must be treated as a substrate / coating materials system.

Industrial gas turbine materials must withstand much longer time at operating temperatures but many fewer loading and unloading cycles than aircraft engine materials. Also, industrial gas turbine materials are not subject to the rapid start-up requirements that aircraft engines must tolerate. However, industrial gas turbines must operate for most of their life at maximum power output at a constant 3,600 or 3,000 RPM (depending on whether the power frequency is 60 or 50 Hz) as opposed to aircraft engines that see short times at maximum "take-off" power levels, drop back to cruise conditions, and have varying RPM shaft speeds. Industrial gas turbines must be capable of burning both clean fuels (e.g. natural gas) and distillate fuels with higher alkali metal levels. They are also exposed to much more air borne contaminates.

Industrial gas turbine customers have come to expect long-term durability for airfoils and 30 year lifetimes for major structures (casings, rotors, etc.). Typically, this translates into hot section turbine overhaul intervals of no less/no earlier than 24,000 hours and expected parts lives of greater than 48,000 hours with repair. Reliability of modern combined-cycle power plants is expected to be >98% with an availability of about 90%. These values can easily be achieved with the proper maintenance plan and operation practices. New, more efficient industrial gas turbines will be expected to meet similar standards, despite higher operating temperatures. Improved materials and coatings have allowed significant gains in the durability of critical gas turbine components, even under today's conditions of higher operating temperatures. The current direction in the industrial gas turbine industry is to provide still greater customer value through the availability of improved component repair techniques that permit refurbishment rather than replacement of expensive components such as turbine buckets and nozzles. Given the drive to reduce life-cycle costs of gas turbine operation, increased use of component repair and refurbishment will become a key for future activity in the industry.

Creep

Turbine airfoil alloys are limited in service temperature primarily by creep strength. The improvements in creep strength originate from changes both in alloy composition and in processing history[13]. Increasing the concentration of refractory metals such as W, Nb, Ta, and Mo (all of which diffuse slowly because of their high atomic weight) increases the creep strength of nickel-base alloys. The limits to which these additions can be successfully added are determined largely by their solubility and by the tendency of more concentrated alloys to form detrimental second phases. At the service temperatures of turbine airfoils (> two-thirds of the melting temperature), the principal creep deformation mode is grain boundary sliding. Advanced solidification processing techniques have been developed to alter the grain structure of these alloys during casting. These processes either create columnar grains with long axes parallel to the turbine blade axis (directional solidification or DS) or result in castings that have no grain boundaries at all (single crystals or SX). These structures lead to considerable increases in creep strength. Both of these solidification processing technologies have taken a long time to reduce to practice. Today, however, DS and SX buckets and nozzles are being used in advanced industrial gas turbines[14].

The service life requirements for industrial gas turbines are significantly longer than for aircraft engines. This places more emphasis on time dependent phenomenon such as creep and creep-fatigue interactions. Creep-fatigue interactions become more pronounced when materials are thermally cycled while operating at higher temperatures for long times. The effect of creep-fatigue interactions can significantly reduce the fatigue strength of the material. This phenomenon places an additional demand for fatigue data with hold times to simulate the effect of this interaction.

Fatigue

A consequence of the increased firing temperatures of industrial gas turbines is the increased severity in the thermal cyclic loading of the hot gas path buckets and nozzles[15]. Increased cooling effectiveness achieved with advanced air cooling and steam cooling schemes produces higher thermal gradients in these parts. While the designer can achieve the same or even lower bulk metal temperatures compared to lower firing temperature machines, the thermal gradient increases in more advanced gas turbines. This increases the thermal strain associated with these parts. The increased severity of these thermal cycles is being addressed by moving toward more thermal strain-tolerant materials such as DS and SX hot gas path components. Additionally, thermal barrier coatings are effective in reducing the thermal load into the cooled component and thus reducing the thermal gradient and thermal strains.

Environmental

Environmental degradation involves oxidation or corrosion of the alloy in the hot gas path. Oxidation involves the reaction between oxygen and the metal alloy to form various oxides. These chemical reactions remove material or deplete the material of strength. At high temperatures, these reactions can occur rapidly and create the potential for failure if an excessive amount of the alloy is consumed. The oxidation behavior of an alloy depends on its chemistry, casting segregation, and exposure conditions. At high temperatures, rapid oxidation attack can occur unless there is a barrier to oxygen diffusion and reaction on the exposed alloy surfaces. Ni-base superalloys containing a sufficient amount of Al will form a protective, adherent, and slow growing alumina (Al_2O_3) scale to prevent extensive oxidation damage[16]. Alloy chemistries can be furthered modified to improve oxidation behavior by adding Y or reducing S.

Hot corrosion is another environmental damage mode. It is a rapid form of attack that is generally associated with alkali metal contaminants, such as sodium and potassium, which react with sulfur in the fuel to form molten sulfates. Sodium at levels of only 2ppm (parts per million) or less in the fuel or in the air can lead to hot corrosion damage[17]. In general, uncoated, cooler areas of a hot gas path component are susceptible when fuel is contaminated, synthetic fuel is used, or there is a lot of debris taken into the turbine from the environment. Basically, molten deposits on the component break down the protective oxide scale, and rapid, unpredictable degradation proceeds. The temperature range where this phenomenon occurs is between 650-925°C (~1200-1700°F). At these temperatures, substrate alloys that form faster growing chromia scales show better resistance in corrosion tests. Generally these systems have over 10% Cr.

As Ni-base superalloy development has evolved, the ability to obtain high temperature strength and creep resistance along with satisfactory oxidation and corrosion resistance has become increasingly difficult without the introduction of protective coatings. Many high strength Ni-base superalloys are not capable of forming a sufficiently protective oxide scale because the chemistry of the alloy is dictated by other requirements such as high strength, creep resistance, and microstructural stability. Thus, the alloy chemistry can not be optimized for oxidation or corrosion resistance. In today's advanced industrial gas turbines, coatings are required to provide protection from oxidation, corrosion, and mechanical property degradation with service. The function of these coatings is to provide a surface reservoir of elements such as Al and Cr that will form stable, adherent oxide layers that will protect the substrate alloy from environmental attack.

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
Buckets															
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	
MAR M247	bal	8.25	10.00		0.80	10.00	5.50	1.00		2.80				0.015	Hf 0.15
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
PWA 1483	bal	12.80	9.00		1.90	3.80	3.60	4.00		4.00					
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
CMSX-4®	bal	6.50	9.00		0.60	6.00	5.60	1.00		6.50					Re 3.0, Hf 0.10
PWA 1484	bal	5.00	10.00		2.00	6.00	5.60			9.00					Re 3.0, Hf 0.10
Nozzles															
FSX414	10.00	28.00	bal	1.00		7.00							0.25	0.010	
GTD-222TM	bal	22.50	19.00		2.30	2.00	0.80	1.20		1.00			0.10	0.008	
GTD-111TM	bal	14.00	9.50		1.50	3.80	3.00	4.90		2.80			0.10	0.010	
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

4.4.1-8 Conclusions

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. 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.

4.4.1-9 Notes

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4.4.1 Buckets and Nozzles

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