GE Energy

Advanced Gas Turbine Materials and Coatings

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Introduction

Advanced GE materials are paving the way for dramatic improvements in gas turbines — improvements that are setting new records in giving customers the most fuel-efficient power generation systems available. Combined-cycle efficiencies as high as 60% are now achievable because of increased firing temperature coupled with more efficient component and system designs. Ongoing GE developments now promise that the coming decade will witness continued growth of gas turbines with higher firing temperatures, pressures and outputs.

This paper describes the evolution of solutions to what used to be incompatible market demands: high firing temperatures and long life, corrosion protection from contaminated fuels and air, and higher efficiency with fuel flexibility. It concentrates on advances made in the hot gas path components because they are generally the most critical part of the gas turbine. Improvements in superalloys and processing now permit the hot gas path components to operate in advanced gas turbines firing at increased temperatures for many thousands of hours under severe conditions of centrifugal, thermal and vibratory stresses. Recent improvements to compressors and rotors are also discussed.

GE engineers continue to lead the way in understanding and developing materials technology for gas turbines because they can tap knowledge from the laboratories of one of the world's most diversified companies, with products ranging from aircraft engines to high-technology plastics. They have used these resources and data collected from more than 5,000 gas turbines operating in many climates, and on a wide range of fuels, to verify that the materials will perform under demanding conditions.

Materials Philosophy

The primary philosophy is to build a reliable, efficient, cost-effective machine for the intended service. Whenever possible, standard materials with histories of successful application are used. In many cases, proven technology is utilized from aircraft or steam turbine applications. However, many times the unique requirements of heavy-duty gas path components demand special materials and processes. Working with alloy and component suppliers in conjunction with internal GE development programs, alloys and processes have been developed to meet the needs of the gas turbine industry.

The first phase of a materials development program is expensive and time-consuming. First, new ideas and emerging developments are screened to select the one or two with the best potential for satisfying the material design goals.

Extensive testing follows to ensure that the materials will perform satisfactorily in heavy-duty gas turbines for tens of thousands of hours. Long-term creep testing at the expected operating temperatures of the material is conducted to characterize alloy performance.

Additionally, laboratory evaluations typically include items such as tensile, rupture, low- and high-cycle fatigue, thermal mechanical fatigue, toughness, corrosion/oxidation resistance, production/ processing trials and complete physical property determinations. This phase of testing can last several years for a new nozzle or bucket material.

After laboratory testing, actual machine-operating experience, the best and final test of a new material, is gained through cooperation with GE customers. Rainbow field tests that contain the material(s) for evaluation are installed in customers' machines for side-by-side comparison with the current baseline material.

More than 50 Rainbows have been installed since the 1950s, covering compressor blade, compressor coating, combustor, nozzle, nozzle coating, bucket and bucket coating materials. Virtually all of the improved hot gas path materials that we now regard as standard were rain-bow tested in Rainbow rotors prior to introduction. Typically, the Rainbow materials are removed and evaluated periodically, then replaced with standard parts. Current Rainbow tests include bucket and nozzle coatings, combustion components and bucket and nozzle materials.

The Rainbow rotor tests, including the long-term laboratory tests, constitute the cornerstone of the materials development philosophy. They have successfully provided a continuous stream of carefully evolved materials and processes for GE heavy-duty gas turbines.

After a material has been proven in a Rainbow rotor, producibility is verified through extensive first piece qualification tests and pilot lot evaluations. Components must continue to meet rigorous production non-destructive and destructive test requirements. Extensive work with suppliers is completed in order to qualify parts that use a new material. During this time, trial parts are destructively tested and analyzed to determine that the properties meet the requirements defined by the GE specifications. Hundreds of bucket and nozzle castings and many wheel forgings have been cut up for analysis to verify that the processing (starting stock, casting/forging parameters, heat treatment, etc.) is correct.

Once a supplier becomes qualified, the processes used to make that component are "frozen" for production and can not be changed without GE approval. Once in production, specimens produced with certain forgings and select-ed castings are destructively tested to ensure specification compliance. Critical rotating components are subjected to non-destructive inspection techniques such as ultrasonics, liquid penetrant, magnetic particle and X-ray examination, depending upon the component. Proof testing is also performed on the most critical components.

This philosophy of material development and production qualification has existed since GE began building gas turbines in the 1950s, and it will continue in the future to meet the needs for improved materials in new and uprated machines.

Turbine Buckets and Nozzles

Processing

GE has used investment cast nozzles and buckets made by the lost wax technique since the mid-1960s. This casting process allows the use of alloys that are difficult to form or machine and provides great design flexibility for internal cooling schemes. For example, ceramic coring is used extensively in these castings to form air-cooling passages and to provide weight reduction.

Most nozzle and bucket castings used by GE are made by using the conventional equiaxed investment casting process. In this process, the molten metal is poured into a ceramic mold at a pressure below 10^{-2} torr (10^{-2} mm Hg). 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 then 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.A variety of investment cast buckets and nozzles has been produced during the past 30 years. The examples in *Figures 1 and 2* indicate the process flexibility in accommodating design and size variations.

Directional solidification (DS) is also being employed to produce advanced technology buckets. First used in aircraft engines more than 25 years ago, it was adapted for use in large air-foils through the efforts of GEPG and its suppliers several years ago. By exercising careful control over temperature gradients, a planar solidification front is developed in the bucket, and the part is solidified by moving this planar front longitudinally through the entire length of the part. 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. More recently, GEPG has worked with its suppliers to develop large, single-crystal castings that offer additional creep and fatigue benefits through the elimination of grain boundaries.

The MS5002C directionally solidified bucket was the first large land-based gas turbine DS bucket made on a production basis and has been in commercial service since 1989. *Figure 3* shows three recent examples of directionally solidified stage 1 buckets: an MS9001FA, an MS7001FA and an MS6001FA. All are etched to show the directional grain structure.

Secondary operations include electrochemical and electrodischarge machining, hard-coating on some components and conventional and creep feed grinding. These processes and subsequent coatings for corrosion and oxidation protection are fully qualified for each design to ensure that metallurgical quality is maintained, adverse residual stresses are not introduced and overall properties are not degraded. In addition, dovetails are shot-peened to provide residual compressive stresses for improved fatigue strength.

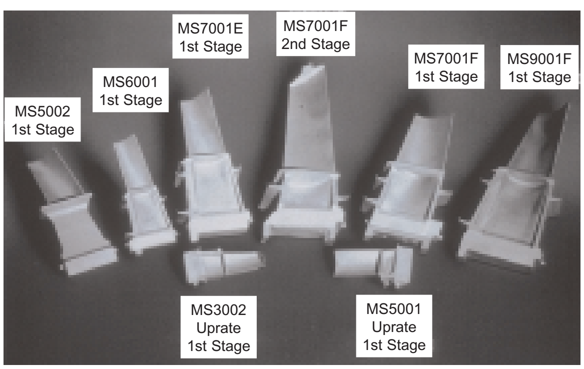


Figure 1. Investment cast buckets

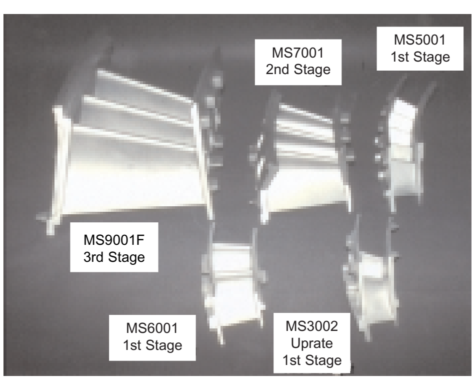


Figure 2. Investment cast nozzles

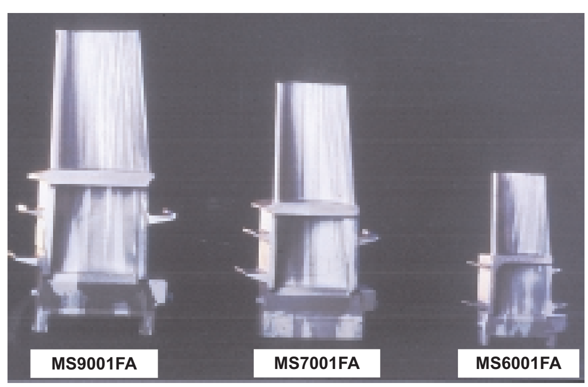


Figure 3. Directionally solidified buckets

Bucket Materials

The stage 1 bucket must withstand the most severe combination of temperature, stress and environment; it is generally the limiting component in the machine.

Since 1950, turbine bucket material temperature capability has advanced approximately 850°F/472°C, approximately 20°F/10°C per year. The importance of this increase can be appreciated by noting that an increase of 100°F/56°C in turbine firing temperature can provide a corresponding increase of 8% to 13% in output and 2% to 4% improvement in simple-cycle efficiency. Advances in alloys and processing, while expensive and time-consuming, provide significant incentives through increased power density and improved efficiency.

Figure 4 shows the trend of firing temperature and bucket alloy capability. The composition of the new and conventional alloys discussed is shown in *Table 1*. The increases in bucket alloy temperature capability accounted for the majority of the firing temperature increase until the 1970s, when air cooling was introduced, which decoupled firing temperature from bucket metal temperature. Also, as the metal temperatures approached the 1600°F/870°C range, hot corrosion of buckets became more life-limiting than strength until the introduction of protective coatings.

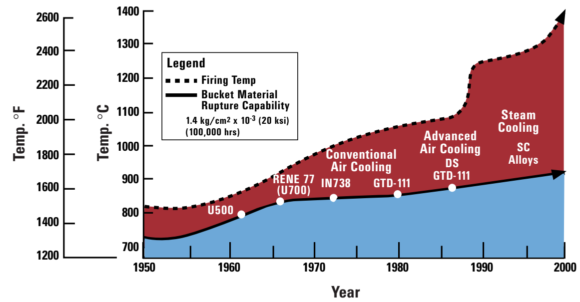


Figure 4. Firing temperature trend and bucket material capability

During the 1980s, emphasis turned toward two major areas: improved processing to achieve greater bucket alloy capability without sacrificing alloy corrosion resistance; and advanced, highly sophisticated air-cooling technology to achieve the firing temperature capability required for the new F generation of gas tur-

COMPONENT	Cr	Ni	Co	Fe	W	Mo	Ti	Al	Cb	V	C	B	Ta
BUCKETS													
U500	18.5	BAL	18.5	—	—	4	3	3	—	—	0.07	0.006	—
RENE 77 (U700)	15	BAL	17	—	—	5.3	3.35	4.25	—	—	0.07	0.02	—
IN738	16	BAL	8.3	0.2	2.6	1.75	3.4	3.4	0.9	—	0.10	0.001	1.75
GTD111	14	BAL	9.5		3.8	1.5	4.9	3.0	—	—	0.10	0.01	2.8
NOZZLES													
X40	25	10	BAL	1	8	—	—	—	—	—	0.50	0.01	—
X45	25	10	BAL	1	8	—	—	—	—	—	0.25	0.01	—
FSX414	28	10	BAL	1	7	—	—	—	—	—	0.25	0.01	—
N155	21	20	20	BAL	2.5	3	—	—	—	—	0.20	—	—
GTD-222	22.5	BAL	19	—	2.0	2.3	1.2	0.8	—	0.10	0.008	1.00	—
COMBUSTORS													
SS309	23	13	—	BAL	—	—	—	—	—	—	0.10	—	—
HAST X	22	BAL	1.5	1.9	0.7	9	—	—	—	—	0.07	0.005	—
N-263	20	BAL	20	0.4		6	2.1	0.4	—	—	0.06	—	—
HA-188	22	22	BAL	1.5	14.0	—	—	—	—	—	0.05	0.01	—
TURBINE WHEELS													
ALLOY 718	19	BAL	—	18.5	—	3.0	0.9	0.5	5.1	—	0.03	—	—
ALLOY 706	16	BAL	—	37.0	—	—	1.8	—	2.9	—	0.03	—	—
Cr-Mo-V	1	0.5	—	BAL	—	1.25	—	—	—	0.25	0.30	—	—
A286	15	25	—	BAL	—	1.2	2	0.3	—	0.25	0.08	0.006	—
M152	12	2.5	—	BAL	—	1.7	—	—	—	0.3	0.12	—	—
COMPRESSOR BLADES													
AISI 403	12	—	—	BAL	—	—	—	—	—	—	0.11	—	—
AISI 403 + Cb	12	—	—	BAL	—	—	—	—	0.2	—	0.15	—	—
GTD-450	15.5	6.3	—	BAL	—	0.8	—	—	—	—	0.03	—	—

Table 1. High-Temperature Alloys

bines. (*See Figure 5.*) The use of steam cooling to further increase combined-cycle efficiencies will be realized in the 1990s.

All GE gas turbine bucket alloys are vacuum-cast, nickel-base superalloys that are strengthened through solution and precipitation-hardening heat treatments. *Figure 6* shows the stress rupture strength of these alloys and the superalloys used for nozzle applications: GTD-222, FSX-414 and N-155. This comparison is presented in the form of the stress required for rupture as a function of a parameter that relates time and temperature (the Larson-Miller Parameter).

This parameter is one of several important design parameters that must be satisfied to ensure proper performance of the alloy in a bucket application, especially for long service life. Creep life, high- and low-cycle fatigue, thermal fatigue, tensile strength and ductility, impact strength, hot corrosion and oxidation resistance, producibility, coatability and physical properties must also be considered.

Directionally Solidified—GTD-111 Buckets

The stage 1 bucket material currently in production is directionally solidified GTD-111. This is the same as GTD-111 equiaxed except for tighter control on the alloy chemistry. This bucket material is currently being used on the 6FA, 7FA and 9FA turbines, and on the 6B, 9EC, 7EA and on the 5/2C and D and 3/2J uprated turbines. DS GTD-111 is also being applied to stage 2 and stage 3 buckets of the 7FA and 9FA gas turbines.

As discussed earlier, the use of directionally solidified GT-111 results in a substantial increase in the creep life, or substantial increase in tolerable stress for a fixed life. *Figure 7* shows the advantage of directionally solidified GTD-111 compared to equiaxed. This advantage is due to the elimination of transverse grain boundaries from the bucket, the traditional weak link in the microstructure.

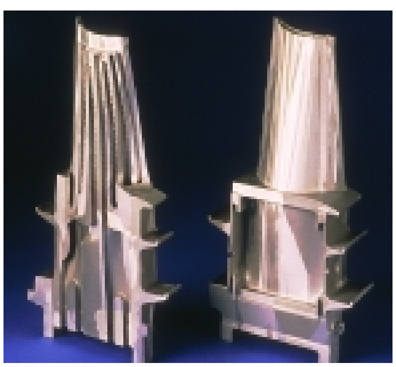


Figure 5. Advanced air-cooling technology

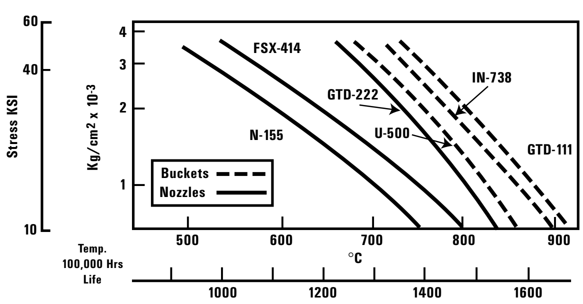
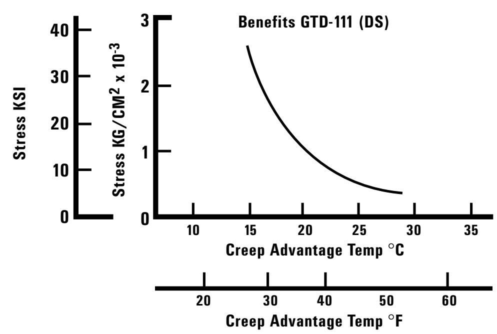


Figure 6. Stress rupture comparison – bucket and nozzle materials



- Increased Tensile Strength: ~ 25%
- Increased Tensile Ductility: ~ 100%
- Increased Fatigue Strength: ~ 900% (Strain Controlled)
- Increased Impact Strength: ~ 33%
- Increased Creep Strength: ~ 22°C (40°F)

Figure 7. Directionally solidified GT-111 vs. equiaxed

In addition to improved creep life, DS GTD-111 possesses more than 10 times the strain control or thermal fatigue compared to equiaxed GTD-111. The impact strength of DS GTD-111 is also superior to that of equiaxed, showing an advantage of more than 33%.

Equiaxed Buckets — GTD-111

GTD-111, the basic alloy used for both DS and equiaxed applications, was developed and patented by GE in the mid-1970s. It possesses about a 35°F/20°C improvement in rupture strength in the equiaxed form, compared to IN-738. GTD-111 is also superior to IN-738 in low-cycle fatigue strength. At the same time, GTD-111 has corrosion resistance comparable to IN-738, the acknowledged corrosion standard for the industry.

The design of this alloy was unique in that it utilized phase stability and other predictive techniques to balance the levels of critical elements (Cr, Mo, Co, Al, W and Ta), thereby maintaining the hot corrosion resistance of IN-738 at higher strength levels without compromising phase stability. The same principles that were used to enhance the castability of IN-738 were also incorporated into GTD-111.

A substantial effort was made to "tune in" GTD-111 so that it could be used to make high quality investment cast buckets. During this phase of the process/alloy development, a large number of trial parts were made, representing the span of bucket sizes envisioned. At first, trials were confined to stage 1 parts, but more recently this has expanded, and GTD-111 is now being used in the larger, latter-stage buckets. During all of these producibility trials, buckets were made, non-destructively tested, and many were cut up to determine properties. These evaluations provided the feedback required for optimizing the processing of these parts.

IN-738 Buckets

IN-738 has been the stage 1 bucket material on all models built between 1971 and 1984, when GTD-111 was introduced. In addition, IN-738 has been used in more recent years as the stage 2 bucket material in the three-stage MS6001, MS7001 and MS9001 models. IN-738 is notable as being one of a very small class of modern superalloys that has an outstanding combination of elevated temperature strength and hot corrosion resistance. The balance of these two properties was optimal for heavy-duty gas turbine applications. It was specifically designed for application in a land-based gas turbine, as opposed to aircraft use. IN-738 was the first cast bucket material used by GE in the heavy-duty gas turbines that had not seen prior service in aircraft gas turbine applications.

IN-738 was first developed by the International Nickel Company, but its chemistry was subsequently modified by GE to improve its castability. This, together with considerable work on modifying the casting techniques, them-selves, enabled the commercial adoption of an alloy that otherwise would have been classed as nearly impossible to cast in large sizes. This work enabled the successful application of IN-738 over the past 20 years in GE gas turbines. Indeed, this alloy is now used throughout the entire heavy-duty gas turbine industry.

U-500 Buckets

Many of GE's stage 3 gas turbine buckets are currently made of U-500, an alloy that was used for stage 1 buckets in the mid-1960s. Like IN-738 and GTD-111, this alloy is a precipitation-hardened (gamma prime), nickel-base alloy. It is currently being applied to the latter stages of buckets in selected gas turbine models.

Future Buckets

With the introduction of DS GTD-111, a commercial reality, development efforts are now focusing on single-crystal processing and advanced DS alloy development. Single-crystal airfoils offer the potential to further improve component high-temperature material strength and, by control of crystal orientation, can provide an optimum balance of properties.

In single-crystal material, all grain boundaries are eliminated from the material structure and a single crystal with controlled orientation is produced in an airfoil shape. By eliminating all grain boundaries and the associated grain boundary strengthening additives, a substantial increase in the melting point of the alloy can be achieved, thus providing a corresponding increase in high-temperature strength. The transverse creep and fatigue strength is increased, compared to equiaxed or DS structures. GE Aircraft Engines has been applying single-crystal bucket technology for more than 10 years in flight engines. The advantage of single-crystal alloys compared to equiaxed and DS alloys in low-cycle fatigue (LCF) is shown in *Figure 8*. GE is currently evaluating and Rainbow rotor testing some of these single-crystal alloys for application in our next generation gas turbines.

The continuing and projected temperature capability improvements in bucket material capabilities are illustrated in *Figure 9*. Together with improved coatings, these new bucket materials will provide continued growth capability for GE gas turbines in the years to come.

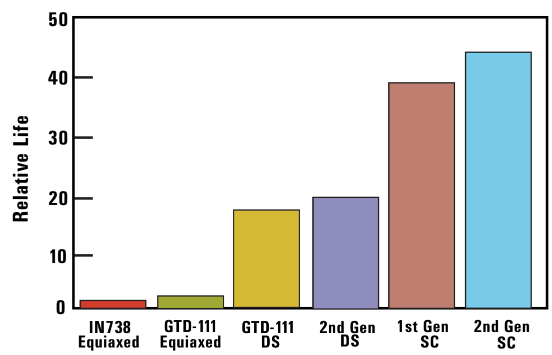


Figure 8. Bucket alloys — LCF life

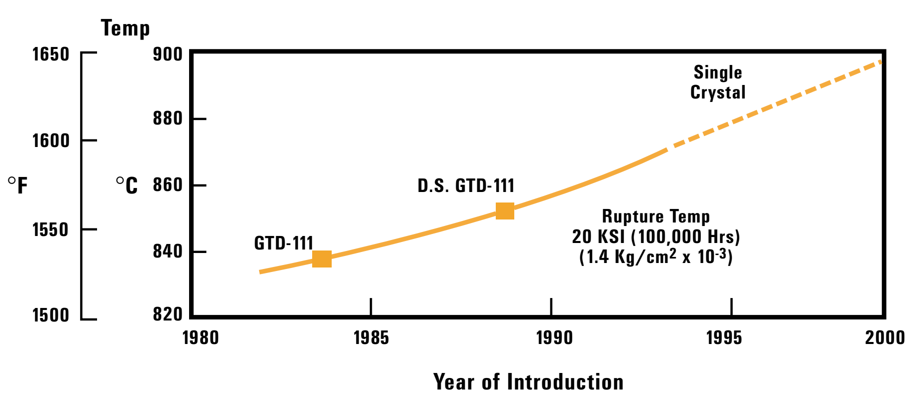


Figure 9. Continuing improvements in bucket materials capability

Nozzle Materials

Stage 1 nozzles (GE terminology for the stationary vanes in the turbine) are subjected to the hottest gas temperatures in the turbine, but to lower mechanical stresses than the buckets. Their function is to direct the hot gases toward the buckets and they must, therefore, be able to withstand high temperatures and provide minimal gas turning losses. The nozzles are required to have excellent high-temperature oxidation and corrosion resistance, high resistance to thermal fatigue, relatively good weldability for ease of manufacture and repair, and good castability. Latter-stage nozzles must also possess adequate creep strength to support themselves and the attached diaphragms from the external casing.

FSX-414 Nozzles

The current alloy used for all production stage 1 nozzles and some latter-stage nozzles is FSX-414, a GE-patented cobalt base alloy. Cobalt-base alloys generally possess superior strength at very high temperatures, compared to nickel-based alloys. This alloy is a derivative of X-40 and X-45, both of which were also developed by GE and first used in the 1960s. FSX-414 contains less carbon than X-40 to enhance weldability, and more chromium to improve oxidation/corrosion resistance. Long-life tests in a simulated gas turbine combustion chamber have demonstrated a two- to three-fold increase in oxidation resistance compared to X-40 and X-45. This improvement permitted an increase in the firing temperatures of approximately 100°F/56°C for equivalent nozzle oxidation life.

GTD-222 Nozzles

The latter-stage, nickel-based nozzle alloy, GTD-222, was developed in response to the need for improved creep strength in some stage 2 and stage 3 nozzles. It offers an improvement of more than 150°F/66°C in creep strength compared to FSX-414, and is weld-repairable.

An important additional benefit derived from this alloy is enhanced low-temperature hot corrosion resistance. By tailoring the alloy to provide an optimum combination of creep strength and weldability, a unique GE-patented nickel-base alloy was created to satisfy the demands of advanced and uprated GE gas turbines. This alloy is vacuum investment cast and has exhibited good producibility. Rainbow nozzle segments were fabricated from GTD-222 and have shown excellent performance after more than 40,000 hours of service. This nozzle alloy is now being used in the 6FA, 7FA, 9FA 9E, 9EC and 6B machines.

N-155 Nozzles

N-155, also referred to as Multimet, is an iron-based alloy chemically similar to the S-590 used in early bucket applications. It is more readily available, possesses better weldability than S-590 and is used in the latter-stage nozzles of the MS3000 and MS5000 series of turbines.

Future Nozzle Materials and Coatings

FSX-414 nozzle material has been extremely successful since the 1960s. However, because of the continuous increase in turbine operating temperatures, developmental programs have been initiated to bring advanced nozzle alloys into commercial production. The first of these programs resulted in the introduction of GTD-222 for latter-stage nozzles. In the stage 2 nozzle application, GTD-222 is coated with an aluminide coating to provide added oxidation resistance to this component. Another program is directed toward the evaluation and modification of currently used Aircraft Engine alloys with improved high-temperature strength and high temperature oxidation resistance.

Bucket Coatings

Bucket coatings are required to protect the bucket from corrosion, oxidation and mechanical property degradation. As 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. Thus, the trend toward higher firing temperatures increases the need for 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.

Experience has shown that the lives of both uncoated and coated buckets depend to a large degree on the amount of fuel and air contamination, as well as the operating temperature of the bucket. This effect is shown in *Figure 10*, which illustrates the effect of sodium, a common contaminant, on bucket life at 1600°F/871°C. The presence of increased levels of contaminants give rise to an accelerated form of attack called hot corrosion.

In addition to hot corrosion, high-temperature oxidation and thermal fatigue resistance have become important criteria in the higher firing gas turbines, as shown in *Figure 11*. In today's advanced machines, oxidation is of concern not only for external buckets surfaces, but also for internal passages such as cooling holes.

Hot Corrosion

Hot corrosion is a rapid form of attack that is generally associated with alkali metal contaminants, such as sodium and potassium, reacting with sulfur in the fuel to form molten sulfates. The presence of only a few parts per million (ppm) of such contaminants in the fuel, or equivalent in the air, is sufficient to cause this corrosion. Sodium can be introduced in a number of ways, such as salt water in liquid fuel, through the turbine air inlet at sites near salt water or other contaminated areas, or as contaminants in water/steam injections. Besides the alkali metals such as sodium and potassium, other chemical elements can influence or cause corrosion on bucketing. Notable in this connection are vanadium, primarily found in crude and residual oils, and lead, most frequently resulting automobile exhaust emissions or as a transportation contaminate from leaded gasolines.

There are now two distinct forms of hot corrosion recognized by the industry, although the end result is the same. These two types are high-temperature (Type 1) and low-temperature (Type 2) hot corrosion.

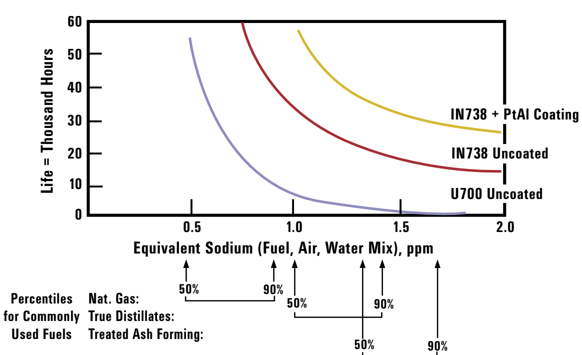


Figure 10. Effect of sodium on bucket corrosion life

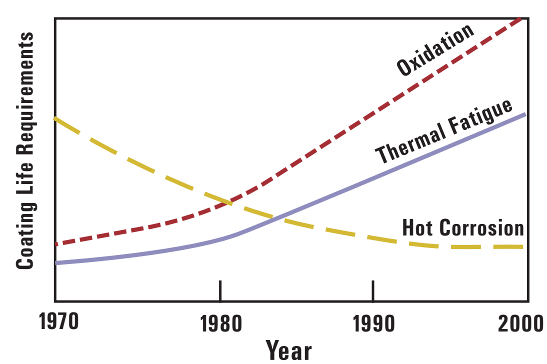


Figure 11. Bucket coating requirements and coating evolution

High-temperature hot corrosion has been known since the 1950s. It is an extremely rapid form of oxidation that takes place at temperatures between 1500°F/816°C and 1700°F/927°C in the presence of sodium sulfate (Na_2SO_4). Sodium sulfate is generated in the combustion process as a result of the reaction between sodium, sulfur and oxygen. Sulfur is present as a natural contaminant in the fuel.

Low-temperature hot corrosion was recognized as a separate mechanism of corrosion attack in the mid-1970s. This attack can be very aggressive if the conditions are right. It takes place at temperatures in the 1100°F/593°C to 1400°F/760°C range and requires a significant partial pressure of SO_2. It is caused by low melting eutectic compounds resulting from the combination of sodium sulfate and some of the alloy constituents such as nickel and cobalt. It is, in fact, somewhat analogous to the type of corrosion called Fireside Corrosion in coal-fired boilers.

The two types of hot corrosion cause different types of attack, as shown in *Figures 12 and 13.* These are metallographic cross sections of corroded material. High-temperature corrosion features intergranular attack, sulfide particles and a denuded zone of base metal. Low-temperature corrosion characteristically shows no denuded zone, no intergranular attack, and a layered type of corrosion scale.

The lines of defense against both types of corrosion are similar. First, reduce the contaminants. Second, use materials that are as corrosion-resistant as possible. Third, apply coatings to improve the corrosion resistance of the bucket alloy.

High-Temperature Oxidation

Metal oxidation occurs when oxygen atoms combine with metal atoms to form oxide scales. The higher the temperature, the more rapidly this process takes place, creating the potential for failure of the component if too much of the substrate material is consumed in the formation of these oxides. *Figure 14a* shows the microstructure of a coated bucket that has seen about 30,000 hours of service. At the temperatures seen in this region of the airfoil, no significant oxidation attack of the coating can be seen.

By contrast, *Figure 14b* shows the microstructure of the same type of coating, which has been severely attacked after about the same length of service. At the higher temperatures,

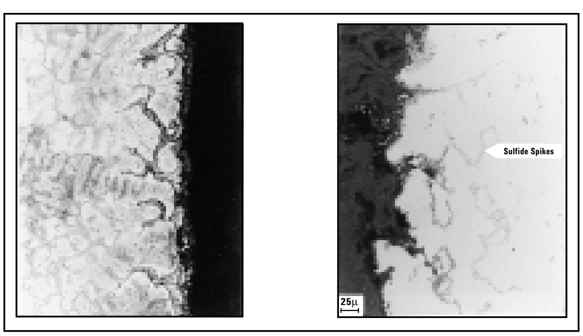


Figure 12. Hot corrosion (high-temperature type)

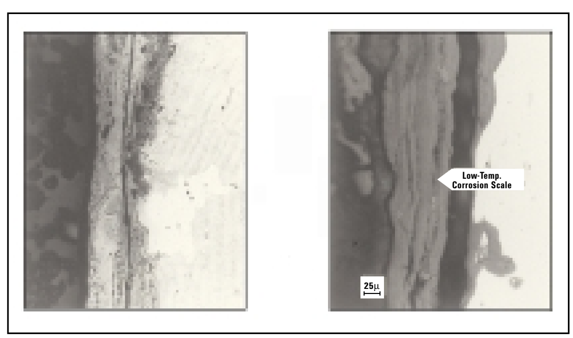


Figure 13. Hot corrosion (low-temperature type)

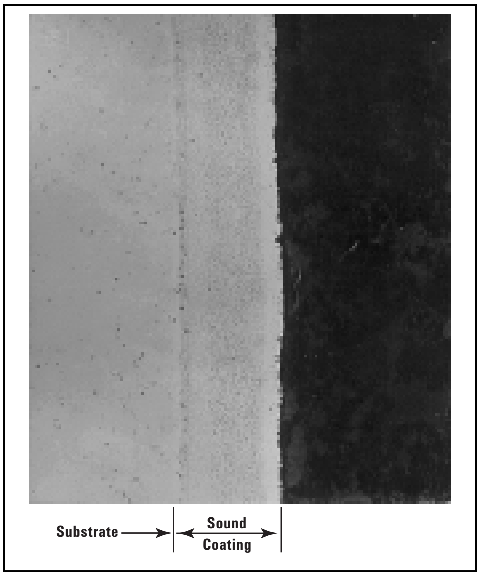


Figure 14a. Photomicrograph showing sound microstructure of a coated bucket that has been in service

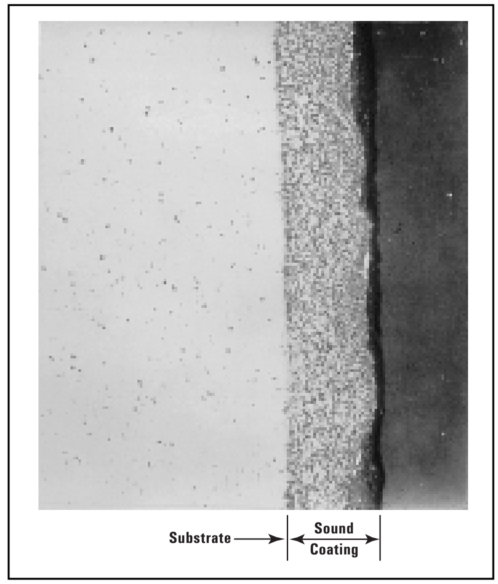


Figure 14b. Photomicrograph of a coating on a bucket material showing internal oxidation of coating (dark particles)

which must have been present in the *Figure 14b* case, insufficient aluminum was available in the coating to maintain a protective oxide at the surface, and oxygen was able to diffuse into the interior of the coating structure where it formed discrete, discontinuous, aluminum oxide particles. This phenomenon is known as internal oxidation. Such a situation quickly depletes the coating of its available aluminum, rendering it non-protective.

At the higher temperatures, >1650°F/>899°C, relatively rapid oxidation attack of some materials can occur unless there is a barrier to oxygen diffusion on the metal surface. Aluminum oxide (Al_2O_3) provides such a barrier. Aluminum oxide will form on the surface of a superalloy at high temperatures if the superalloy's aluminum content is sufficiently high. Thus, the alloy forms its own protective barrier in the early stages of oxidation by the creation of a dense, adherent aluminum-oxide scale.

However, many high-strength superalloys in use today cannot form sufficient protective scales because the compositional requirements for achieving other properties, such as high strength and metallurgical stability, do not allow for the optimization of oxidation/corrosion resistance in the superalloy itself. Therefore, most of today's superalloys must receive their oxidation protection from specially engineered coatings.

High-Temperature Coatings

High-temperature coatings are used where the temperatures of the components exceed the inherent oxidation resistance of the material. Considerable development has occurred during the past 20 years in the field of high temperature coatings. The result has been a marked increase in the capability of these coatings to resist not only hot corrosion attack over long periods of time, but high-temperature oxidation as well. GE heavy-duty coatings available today have lives that are 10 to 20 times longer than the first-generation coatings under a wider diversity of corrosion and oxidizing conditions.

GE has used two basic classes of coatings during the past 25 years. The first class used was a diffusion-style coating called platinum aluminide (PtAl). The second class is an overlay-style coating such as PLASMAGUARD™ GT-29 IN-PLUS™.

The development of each of these coating systems was in response to field needs. The platinum aluminide was the original heavy-duty coating and addressed corrosion problems seen by a large segment of the fleet in the 1960s. It doubled the corrosion life of the uncoated IN-738 buckets of that time. The PLASMAGUARD™ GT-29 coating improved that corrosion resistance by a further 50%. That same high level of hot-corrosion resistance is kept in the more recent PLASMAGUARD™ GT-29 PLUS, which also has substantially more oxidation resistance, as required by the more advanced machines. PLASMAGUARD™ GT-29 IN-PLUS™ is a two-layer coating, with the top layer also applied to the internal surface of the bucket. Most recently, GT-33 IN-COAT™ and IN-PLUS™ have been developed and applied to the stage 1 buckets of the higher firing temperature machines, such as the 7FA and 9FA machines. This coating possesses even greater high-temperature oxidation capability than the GT-29 IN-PLUS™.

A comparison of stage 1 bucket coatings is shown in *Figure 15*, while a more detailed description of each is in the following sections.

Platinum-Aluminide Coatings

All stage 1 buckets have been coated since the late 1970s. Up until mid-1983, the coating used by GE on most stage 1 buckets was a platinum-aluminum (PtAl) diffusion coating. This coating was selected over the straight aluminide coatings because it provided superior corrosion resistance both in burner test rigs and in field trials. The platinum-aluminum coating is applied by electroplating a thin (0.00025 inch/0.006 mm) layer of platinum uniformly onto the bucket air-foil surface, followed by a pack diffusion step to deposit aluminum. This results in a nickel-aluminide coating with platinum in solid solution or present as a $PtAl_2$ phase near the surface.

The platinum in the coating increases the activity of the aluminum in the coating,

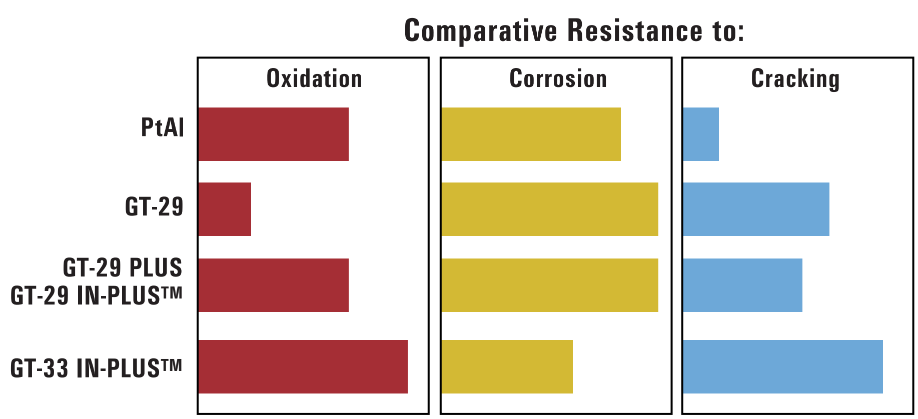


Figure 15. Comparative resistance in types of coatings

enabling a very protective and adherent Al_2O_3 scale to form on the surface.

A Rainbow example of comparative corrosion on PtAl-coated and uncoated IN-738 buckets, run side-by-side in the same machine under corrosive conditions, is shown in *Figure 16*. The two buckets were removed for interim evaluation after 25,000 hours of service. This unit burned sour natural gas containing about 3.5% sulfur and was located in a region where the soil surrounding the site contained up to 3% sodium.

The uncoated IN-738 bucket has penetration extending 0.010 to 0.015 inches (0.25 to 0.4 mm) into the base metal over most of the bucket surface. The coated bucket generally shows no evidence of base metal hot corrosion attack, although some of the bucket areas showed coating thinning. Only at some very small locations on the leading edge of the coated bucket was the coating breached and then to only a depth of 0.001 to 0.002 inches (0.025 to 0.05 mm).

PLASMAGUARD™ Coatings

The latest GE-developed and patented PLASMAGUARD™ coatings are now GE's standard stage 1 bucket coatings — GT-29 PLUS™ and GT-33 PLUS™ for solid buckets; GT-29 IN-PLUS™ and GT-33 IN-PLUS™ for cooled or hollow vaned buckets.

PLASMAGUARD™ coatings are examples of overlay coatings and differ from diffusion coatings, such as the platinum-aluminum coatings, in one major respect. At least one of the major constituents, (generally nickel) in a diffusion coating is supplied by the base metal. An overlay coating, on the other hand, has all the constituents supplied by the coating itself. The advantage of overlay coatings is that more varied corrosion resistant compositions can be applied since the composition is not limited by the base metal composition, nor is thickness limited by process considerations.

PLASMAGUARD™ coatings are applied by the Vacuum Plasma Spray (VPS) process in equipment especially designed to apply this coating in a uniform and controlled manner to GE buckets. In this process, powder particles of the desired composition are accelerated through a plasma jet to velocities higher than those achievable through atmospheric plasma spray methods. (*See Figure 17.*) The solidification of the powder onto the airfoil results in a much stronger coating bond than can be achieved by using conventional atmospheric plasma spray deposition because of the higher particle speeds and the cleaner, hotter sub-

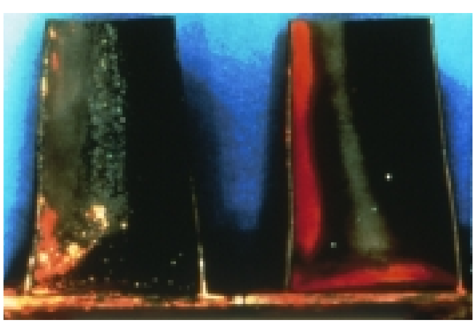


Figure 16. Stage 1 turbine buckets: coated and uncoated IN-738; 25,000 service hours

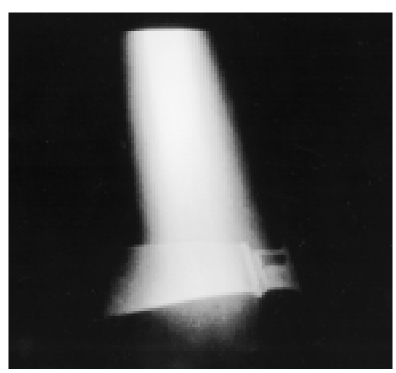


Figure 17. PLASMAGUARD™ GT-20 coated shroud

strate. In addition, higher coating densities and soundness are achievable using the VPS approach.

The first production VPS facility was installed in Schenectady during the early 1980s. This facility has been augmented by a newer, higher capacity and more-automated VPS facility in the gas turbine manufacturing plant in Greenville, South Carolina. (*See Figure 18.*) This facility has the capability to coat the latter stage buckets with PLASMAGUARD™ coatings and to provide refurbishment capability for used buckets.

Extensive laboratory corrosion testing was performed on candidate PLASMAGUARD™ coating compositions in the late 1960s to the early 1970s. This led to the selection of GT-29 as the original PLASMAGUARD™ coating because it satisfied the field need for superior hot corrosion resistance, compared to the original PtAl coating. This laboratory testing was confirmed by field experience in Rainbow rotors that were installed in the mid-1970s. More than 40,000 hours of satisfactory turbine operation have now been accumulated on this coating, as shown in *Figure 19.*

In the mid-1980s, GE found that more oxidation resistance was required for the higher firing temperature gas turbines, generally above 1950°F/1065°C in air cooled machines and above 1750°F/954°C in uncooled machines. (*See Figure 11.*) This led to the introduction of the patented PLASMAGUARD™ GT-29 PLUS coating that combines the demonstrated hot corrosion protection of GT-29 with a substantial increase in oxidation protection. The enhanced oxidation protection offered by GT-29 PLUS is gained from an increased aluminum content in the outer region of the coating matrix. In service, the higher aluminum content of the GT-29 PLUS forms a more oxidation-protective aluminum oxide layer that greatly improves the high temperature oxidation resistance. PLASMAGUARD™ GT-29 IN-PLUS™ was introduced for advanced cooled and hollow vaned buckets. This coating includes a diffused, aluminum-rich layer on those inner passages, cooling holes and surfaces to protect against oxidation that would otherwise occur.

Recently, a new PLASMAGUARD™ coating has been developed and Rainbow tested in several gas turbines and has shown excellent durability after more than 24,000 hours of service. This new coating, GT-33, was designed to provide more oxidation resistance and more

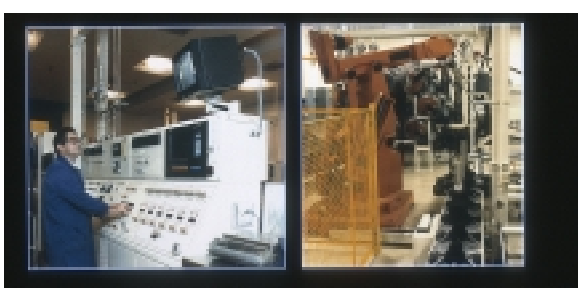


Figure 18. VPS production facility

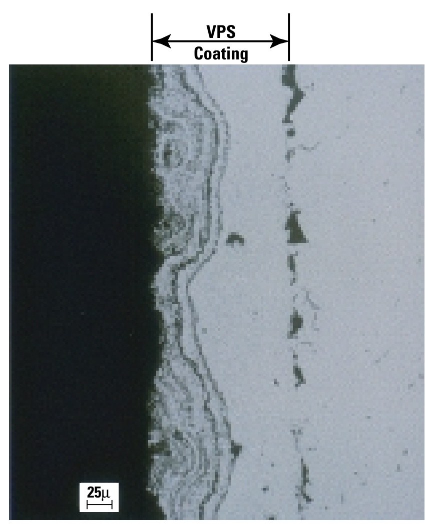


Figure 19. VPS coating after more than 40,000 hours turbine exposure – pressure face

resistance to cracking than the GT-29 composition. This coating may also be used with an outer layer enriched with aluminum to provide maximum long-term life. PLASMAGUARD™ GT-33 is currently being introduced in the F class machines.

Coatings for bucket refurbishment have also been introduced recently. These coatings, known as EXTEND-COAT™, are based upon the GT-29 and GT-33 PLASMAGUARD™ compositions and were developed to be applied to serviced hardware. Several GE Service Centers have been qualified to apply these coatings for the service market.

Low-Temperature Coatings

Low-temperature coatings find their greatest need in latter stage buckets and in stage 1 buckets of machines that run a substantial portion of their duty cycle at part load.

For instance, the stage 3 buckets of the 7FA and 9FA machines are currently coated with a diffused chromide coating which, although not suitable for higher temperature stages, will impart substantial protection against both corrosion and oxidation at the lower temperatures of this part. In addition, a PLASMAGUARD™ GT-43 coating composition has been developed, after an extensive laboratory corrosion rig and mechanical testing program, for use in severe low temperature corrosion applications. This GE-patented coating, also applied by the same VPS process, has shown excellent performance in Rainbow rotors, confirming its laboratory corrosion resistance.

Shroud Coatings

New gas turbine models such as the 6FA, 7FA and 9FA operate at considerably higher temperatures than previous heavy-duty gas turbines. Therefore, to provide a durable stage 1 bucket stationary shroud component, PLASMAGUARD™ GT-20 is being used to coat the surface of this high temperature, inner shroud component. (*See Figure 20.*) This coating was developed and has been used extensively by GE Aircraft Engines on its flight engine shrouds. It provides an extremely oxidation-resistant surface and a rub-tolerant coating in the event that the bucket blade tips rub against the stationary shroud.

Future Coatings

Coating development work is continuing at GE, aiming at further improvements to the oxidation- resistance and thermal fatigue resistance of high-temperature bucket coatings. In addition to these environmentally resistant coating development efforts, work is also underway to develop advanced thermal barrier coatings (TBCs) for application to stationary and rotating gas path components. By careful process control, the structure of these TBCs may be made more resistant to thermal fatigue and their lives greatly extended. Rainbow rotor testing of some of these coatings is currently in progress.

Combustion Hardware

The combustion system is a multiple-chamber assembly composed of three basic parts: the

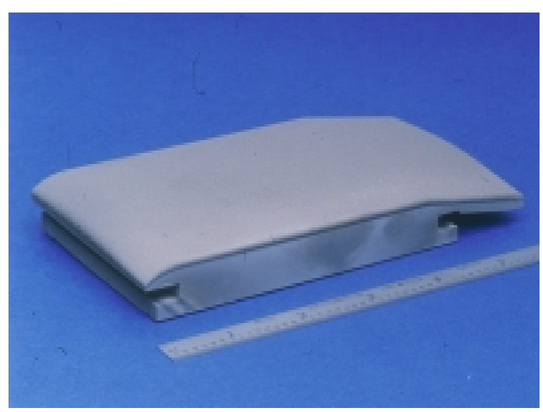


Figure 20. 7FA PLASMAGUARD™ GT-20 coated shroud

fuel injection system, the cylindrical combustion liner and the transition piece. Driven by the ever-increasing firing temperatures of the gas turbines and the need for improved emissions control, significant development efforts are being made to advance the combustion hardware of heavy-duty gas turbines. What were originally simple parts in early gas turbines are now highly complex pieces of hardware with sophisticated materials and processing requirements.

The primary basis for the material changes that have occurred has been increased high temperature creep rupture strength. These material changes had to be done while maintaining satisfactory oxidation/corrosion resistance. An indication of the strength improvement is shown in *Figure 21*, which compares the creep rupture strength of the three material classes now in use. Nimonic 263, the most recently introduced alloy, is some 250°F/140°C stronger than the original AISI 309 stainless steel. Hastelloy-X, which was used in the 1960s through the early 1980s, is intermediate in strength between the two.

Combustion Liners

Two major changes have occurred since the original AISI 309 stainless louver cooled liners: the adoption of Hastelloy X/RA333 in the 1960s, and the adoption of the slot-cooled liner in the early 1970s. This slot-cooled design offers considerably more liner cooling effectiveness, and, from a materials standpoint, presents a new area of processing challenges. Fabrication is primarily by a combination of brazing and welding. Earlier liners, on the other hand, were made using a welded construction with mechanically formed louvers.

As firing temperatures increased in the newer gas turbine models, HS-188 has recently been employed in the latter section of some combustion liners for improved creep rupture strength.

In addition to the base material changes, the use of a thermal barrier coating (TBC) on combustion liners of advanced and uprated machines has been incorporated. TBCs consist of two different materials applied to the hot side of the component: a bond coat applied to the surface of the part, and an insulating oxide

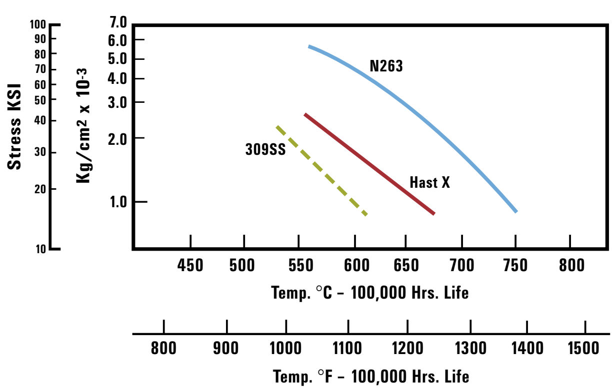


Figure 21. Rupture comparison, N-263 vs. Hallestoy-X vs. 309SS

CHARACTERISTICS

- 15–25 Mil (380–640 Micron) Thickness
- Insulating – Porous
- Plasma Sprayed in Air
- Two Layers
  – Bond Coat – NiCrAlY
  – Top Coat – YTTRIA Stabilized Zirconia

ADVANTAGE

- Reduced Metal Temperature of Cooled Components
- 8–16°F (4–9°C) Reduction Per Mil (25.4 Micron) of Coating

Figure 22. Thermal barrier coatings

applied over the bond coat. The total thickness used is 0.015 to 0.025 inch (0.4 to 0.6 mm). Characteristics and advantages of the TBCs are shown in *Figure 22*, and the microstructure and a coated liner are shown in *Figure 23*. The primary benefit of the TBCs is to provide an insulating layer that reduces the underlying base material temperature and mitigates the effects of hot streaking or uneven gas temperature distributions. These coatings are now standard on a number of GE gas turbines and have demonstrated excellent performance in production machines.

Transition Pieces

Although less complicated than the liners, the transition pieces have probably been more challenging from a materials/processes standpoint. Therefore, new materials have tended to be first introduced on the transition piece.

From a design standpoint, significant improvements have been made on advanced models through the use of heavier walls, single-piece aft ends, ribs, floating seal arrangements, selective cooling, etc. These design changes have been matched by material improvements. Initial 1950s transition pieces were made from AISI 309 stainless steel. In the early 1960s, nickel base alloys Hastelloy-X and RA-333 were used in the more limiting parts. These alloys became standard for transition pieces by 1970.

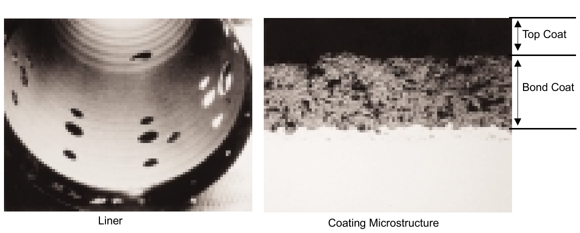


Figure 23 Thermal barrier coated liner, Hallestoy-X vs. 309SS

In the early 1980s, a new material, Nimonic 263, was introduced into service for transition pieces on the MS7001 and MS9001 models. This material is a precipitation-strengthened, nickel-base alloy with higher strength capability than Hastelloy-X. It was extensively tested in the Gas Turbine Combustion Development Laboratory and successfully tested in Rainbow combustion hardware. Nimonic 263 transition pieces have accumulated more than 25,000 hours of successful experience in MS7001 machines. The Nimonic 263 material is being phased into the higher firing temperature gas turbine models and will be used in future uprated machines.

Since the early 1980s, TBCs have been applied to the transition pieces of the higher firing temperature gas turbine models and to uprated machines. Field experience over thousands of hours of service has demonstrated good durability for this coating on transition pieces.

A recent improvement has also been made to increase the wear resistance of some transition pieces in the aft end or picture frame area. Cobalt-base hard coatings applied by thermal spray have been tested in field machines and the best spray has been shown to improve the wear life of sealing components by more than four times. The selected coating, called Extendor™, is available for many of the current gas turbine models to extend the wear life of these components. This improvement in transition piece seal wear is now also being incorporated into many of the new production machines.

Turbine and Compressor Wheels

The rotor design of all GE heavy-duty alloy gas turbines is a bolted construction made up of forged compressor and turbine wheels, distance pieces (junction between compressor and turbine), spacers (between some of the turbine wheels) and stub shafts. The most critical components in the rotor are the turbine wheels because of the combined conditions of elevated temperatures and the requirements for strength and toughness. Further, unlike the aircraft gas turbine, these wheels are of very large diameter and section thickness. For this reason, extensive use of steel wheels has been made in heavy-duty gas turbine designs. This has been made possible by the lower compressor pressure ratios (i.e., lower compressor discharge temperatures) and by using long shank buckets, permitting lower temperature operation of the dovetailed periphery of the wheels. With increasing firing temperatures, the incorporation of air cooling of wheels has also extended the application of steel wheels.

With the advent of the advanced 7FA, 9FA and 6FA type machines with much higher firing temperatures and compressor ratios, it has been necessary to utilize a nickel-base wheel material, Alloy 706, for the turbine wheels and spacers of this machine. The use of this material provides the added temperature capability required to meet the current 7FA and 9FA firing temperature requirements now and in the future.

A full range of testing evaluation is required during wheel material development, as is the case with bucket and nozzle partition materials. For instance, tensile and creep/rupture properties, metallurgical stability, inspectability, fracture mechanics characteristics and producibility on a commercial scale are among the aspects that must be considered and evaluated. A complete test evaluation of forgings is required for process qualification of each material and supplier encompassing the section size involved.

Turbine Wheel Processes

All of the turbine wheels currently manufactured for GE designs are produced either from vacuum arc remelted (VAR) or electroslag remelted (ESR) material, or from ladle refined, vacuum-degassed steel. In the VAR process, an electrode is arc-melted under vacuum into a water-cooled copper crucible. ESR is somewhat similar, with remelting done under a specially formulated slag. Both result in a very low level of inclusions and chemical segregation and quite uniform structure because of the shallow, molten pool present throughout the formation of the ingot.

Control of microstructure and properties in the bore region of low sulfur (less than 0.005%), vacuum degassed steel, is achieved to the same level as required for VAR/ESR steel. This is done by controlling the amount and morphology of sulfide inclusions. In the case of the nickel-base alloy, Alloy 706, control of microstructure and properties in this material starts by using triple-melted ingots VIM/VAR/ESR to achieve a very high quality ingot that is homogeneous and free of harmful phases.

Following melting, wheels are either open-die or closed-die forged, depending on the capability of the forging supplier. Alloy steel wheels are quenched and tempered to provide the correct properties, while austenitic nickel base and iron base wheels are strengthened by an aging heat treatment somewhat analogous to the heat treatment given to buckets.

Following heat treatment, all wheels are fully ultrasonically inspected to stringent standards. Mechanical testing of rings removed from the turbine wheels, including room temperature and hot tensile tests, impact tests, fatigue tests and rupture tests, where required, are performed to verify that all design requirements are met.

Each turbine wheel is spin-tested prior to its installation into a rotor in a facility such as the one shown in *Figure 24.* Alloy steel wheels, because of the brittle-to-ductile transition temperature phenomenon, are first spun cold to verify the absence of critical size defects. All wheels, including the cold spun steel wheels, are hot spun at bore stresses slightly above their yield strength to induce residual compressive stresses in the bore region. These spinning operations, in addition to the stringent, non-destructive testing performed both before and after spin testing, provide maximum assurance against brittle fracture in service.

TURBINE WHEEL ALLOYS

Alloy 706 Nickel-Base Alloy

This nickel-based, precipitation-hardened alloy is the newest to be used in turbine wheel application. It is the 7FA, 9FA, 6FA and 9EC turbine wheel and spacer alloy, and it offers a very significant increase in stress rupture and tensile yield strength compared to the other wheel alloys. (*See Figures 25 and 26.*) This alloy is similar to Alloy 718, an alloy that has been used for wheels in aircraft turbines for more than 20 years. Alloy 706 contains somewhat lower concentrations of alloying elements than Alloy 718, and is there-fore possible to produce in the very large ingot sizes needed for the large 7FA and 9FA wheel and spacer forgings. (*See Figure 27.*)

Figure 24. Spin test facility (Greenville plant)

Cr-Mo-V Alloy

Turbine wheels and spacers of most GE single shaft heavy-duty gas turbines are made of 1% Cr - 1.25% Mo - 0.25% V steel. This alloy is used in the quenched and tempered condition to enhance bore toughness. Stress rupture strength of the dovetail region (periphery) is controlled by providing extra stock at the periphery to produce a slower cooling rate during quenching. The stress rupture proper-

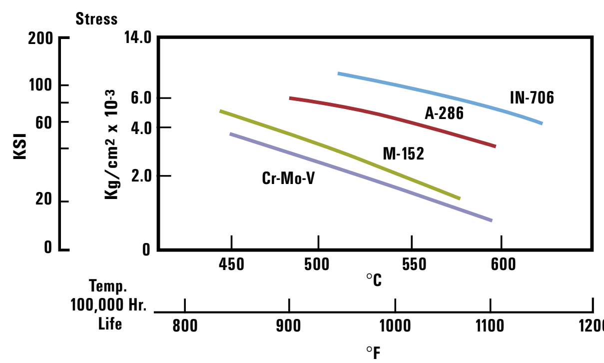


Figure 25. Stress rupture comparison (turbine wheel alloys)

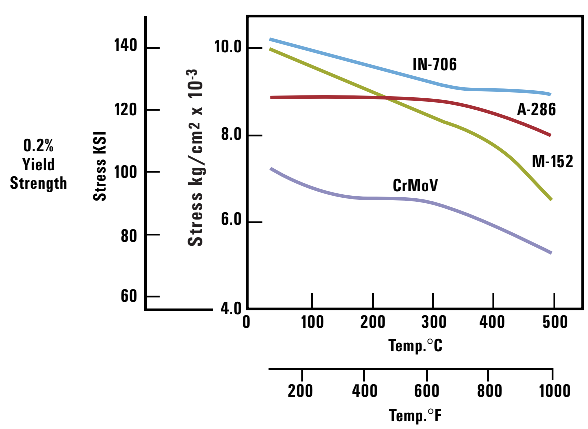


Figure 26. Tensile yield strength comparison (turbine wheel alloys)

Figure 27. 7FA IN-706 turbine forging

ties of this alloy are shown in *Figure 25*.

12 Cr Alloys

This family of alloys has a combination of properties that makes it especially valuable for turbine wheels. These properties include good ductility at high strength levels, uniform properties throughout thick sections and favorable strength at temperatures up to about 900°F/482°C.

M-152 alloy is a 2% to 3% nickel-containing member of the 12 Cr family of alloys. Initially, it was and still is used on the MS5002 machine as a replacement for A286. It features outstanding fracture toughness, in addition to the properties common to other 12 Cr alloys. M-152 alloy is intermediate in rupture strength, between Cr-Mo-V and A286 alloy, and has higher tensile strength than either one. (*See Figure 25*.) These features, together with its favorable coefficient of expansion and good fracture toughness, make the alloy attractive for use in gas turbine applications.

A286 Alloy

A286 is an austenitic iron base alloy that has been used for years in aircraft engine applications. Its use for industrial gas turbines started about 1965, when technological advances made the production of sound ingots sufficient in size to produce these wheels possible. Since that time, some 1,400 MS3002 production wheels have been placed in service.

As knowledge of the capabilities of M-152 increased, production of the MS5002 wheels was switched from A286 to M-152. A286 is currently being introduced into the new 9EC turbines as part of a composite aft shaft.

Other Rotor Components

All of the other rotor parts are individually forged. This includes compressor wheels, spacers, distance pieces and stub shafts. All are made from quenched and tempered low-alloy steels (Cr–Mo–V or Ni–Cr–Mo–V) with the material and heat treatment optimized for the specific part. The intent is to achieve the best balance of strength, toughness/ductility, processing and non-destructive evaluation capability, particularly when it is recognized that some of these parts may be exposed to operating temperatures as low as -60°F/-51°C.

All parts are sonic and magnetic particle tested. Many last-stage compressor wheels are spun in a manner analogous to turbine wheels as a means of proof testing and imparting bore residual stresses. This last-stage compressor steel is probably the next most critical rotor component after the turbine wheels.

Rotor Developments

The most recent major rotor development effort that has been underway at GE is the development of an Alloy 718 turbine rotor for the next generation of gas turbine machines. This effort required close cooperation between GE, and its superalloy melters and large forging suppliers to conduct the solidification and forging flow studies, the necessary sub-scale wheel forging experiments and the extensive mechanical and physical property determinations necessary to bring into production a new wheel material.

This development effort has resulted in the production of the largest ingots ever made and forged into high quality qualification turbine wheel and spacer forgings. Concurrent with the process development effort was an effort to develop new non-destructive techniques to inspect these turbine forgings to greater levels of sensitivity than ever before possible. These new ultrasonic inspection techniques are being applied to all the Alloy 706 and the Alloy 718 turbine forgings to ensure an even greater level of confidence in these high strength forgings.

Additional development efforts continue to improve the current processing of other forgings by working with our suppliers on the further optimization of properties and forging quality. In-process, non-destructive evaluation of all rotor components continues to be emphasized as a critical aspect to produce quality forgings.

Compressor Blades

Compressor blading is variously made by forging, extrusion or machining. All production blades, until recently, have been made from Type 403 or 403 Cb (both 12 Cr) stainless steels. During the 1980s, a new compressor blade material, GTD-450, a precipitation hardened, martensitic stainless steel, was introduced into production for advanced and uprated machines, as shown in *Table 1*. This material provides increased tensile strength without sacrificing stress corrosion resistance. Substantial increases in the high-cycle fatigue and corrosion fatigue strength are also achieved with this material, compared to Type 403. Superior corrosion resistance is also achieved due to its higher concentration of chromium and molybdenum. Compressor corrosion results from moisture containing salts and acids collecting on the blading. During operation, moisture can be present because of rain, use of evaporative coolers or condensation resulting from humid air being accelerated at the compressor inlet. Moisture may be present in the compressor during operation up to between stage 5 and stage 8, where it usually becomes warm enough to prevent condensation. When the turbine is not in operation, the compressor can still become wet if metal temperatures are below the local dew point. (This can happen to units stored in humid environments.) The chemistry of this moisture deposit on the blading determines the severity of the corrosion phenomenon.

In the early 1960s, GE first experienced corrosion pitting on bare 403 in oil platform applications when several machines developed pits and failed compressor blades. Generally, the service time on these machines ranged from 20,000 to 60,000 hours. As a result of this experience, GE adopted NiCd coating for use in selected applications, and later for all compressor blades in the "wet" stages (normally up to stage 8). However, because of recent, more stringent EPA requirements, this coating has now been replaced by a new GE developed and patented coating called GECC-1. This new aluminum slurry coating has a protective ceramic top layer that provides improved erosion resistance. (*See Figure 28.*) This coating has accumulated more than 100,000 hours of field testing and has shown to be equal to or better than conventional aluminum slurry coatings in corrosion protection and substantially better in erosion resistance. This coating has been applied by GE Service Shops as a refurbishment coating for several years and is now

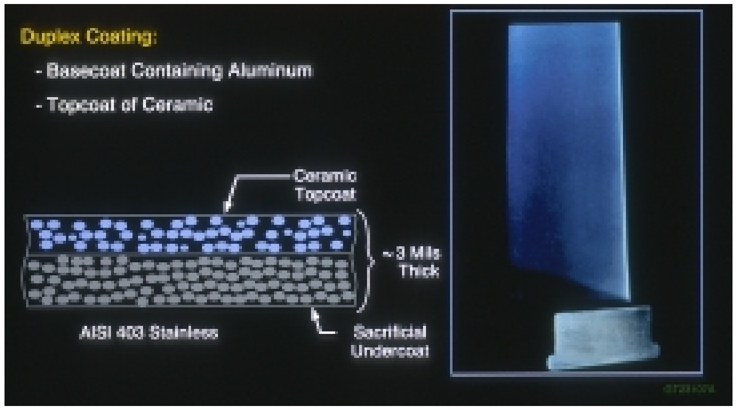


Figure 28. GEEC-1 compressor blade coating

being applied to all new units. All IGVs and the first three stages of rotating and stationary airfoils in the compressor will be made from GTD-450; the next five stages will be made of GTD-450 for the F class machines and GECC-1 coated AISI 403 or 403 Cb for the other machines. The rest of the blading will be AISI 403 or 403 Cb uncoated. This change will provide GE's machines with better corrosion and erosion protection and eliminate cadmium from the environment.

GTD-450 is a precipitation-hardened, martensitic stainless steel with excellent aqueous corrosion resistance. Laboratory tests have shown that GTD-450, in very acidic salt environments (pH~4), possesses excellent resistance to pitting. These test results, shown in *Figure 29*, indicate that uncoated GTD-450 without a coating is equivalent or better than Al or NiCd coatings for acidic corrosion resistance. Field experience of more than 48,000 hours has confirmed the excellent corrosion resistance of uncoated GTD-450. These tests have also shown that conventional aluminum slurry coatings can suffer erosion damage and leave significant areas of the blading unprotected. Therefore, in machines where erosion may be experienced, GECC-1 on 12 chromium blades, or uncoated GTD-450, is recommended. The GTD-450 material should not be used coated, as coating will decrease fatigue life.

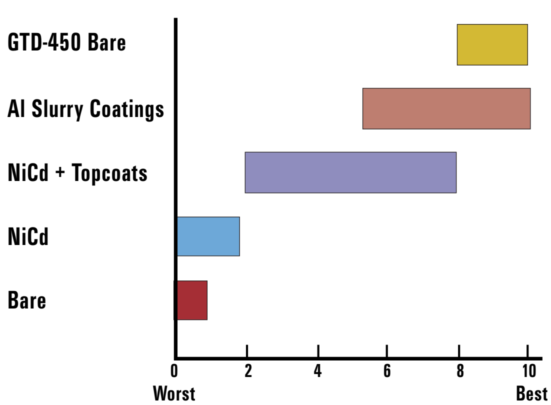


Figure 29. Acidic laboratory tests

Casings

For all models except the F-technology machines, the entire "tube" surrounding the gas turbine rotor is composed of a series of cast iron castings bolted together end-to-end. The castings (inlet and compressor) at the forward end of the machines are made of gray iron, while those at the aft end (discharge and turbine shell) are generally made of ductile iron or, in some, steel castings or fabrications. The excellent castability and machinability offered by cast iron makes it the obvious choice for these somewhat complex parts that have close tolerances. Cast iron is less prone to hot tears and shrinkage problems than cast steel. Experience has also shown it to provide a higher degree of dimensional stability during shop processing.

Although stress is important in determining which of the two types of cast iron (gray or ductile) is used in the castings, operating temperature is of prime importance. Gray iron is generally limited to applications where temperatures do not exceed 450°F/239°C, ductile iron to applications no greater than 650°F/343°C. In the case of gray iron, GE uses a type that has a minimum tensile strength of 30 ksi (2.1 kg/cm^2 x 10^{-3}), similar to ASTM-A48, Class 30. Ductile iron, on the other hand, is a ferritic type [60 ksi (4.2 kg/cm^2 x 10^{-3}) TS, 40 ksi (2.8 kg/cm^2 x 10^{-3}) YS, 18% E1], similar to ASTM-A395. The 7FA and 9F machines utilize ductile iron for the inlet and compressor casing and a fabricated CrMo steel combustion wrapper and turbine shell. More recently, cast 2 1⁄4 Cr - 1Mo steel is being introduced into the F-technology machines for the combustion wrapper and turbine shells.

Future Materials

Advances in ductile iron have been made in laboratory trial castings that will enable this material to be extended to higher temperature applications. These trial heats have shown the capability to extend the useful temperature of this material by 100°F/56°C. This development program is now in the Rainbow field trial phase and will most likely find application in advanced and uprated GE gas turbines.

Additional Sand Castings

In addition to the casings, several other large components, such as bearing housings, inner barrels, support rings and diaphragms in the stator section of the turbine, are produced from sand castings. Cast iron is again used where possible; however, where higher temperature or planned welding is encountered, steel is employed. For example, Cr-Mo-V has been used for support rings where temperatures reach 1000°F/538°C, and carbon steel has been used for bearing housings requiring weld fabrication.

Quality is a key factor in the successful operation of any part, and sand castings are no exception. From the conceptual stage, quality is built into these parts. Foundry personnel are called in early in the design stage to provide the best possible castability consistent with functional requirements. Before any casting is granted production approval, a process must be found that produces three consecutive castings meeting rigid X-ray inspection requirements. Once such a process is found, it is precisely documented and must be followed for all subsequent production. Recently, a sonic screening procedure was developed to supplement X-ray inspection. It was designed to reduce inspection time and increase coverage while maintaining strict standards of casting integrity.

In addition to the X-ray/sonic monitoring of casting visual examinations, magnetic particle inspection and, in the case of bearing housings, leak tests, are always employed. All these combine to provide a very comprehensive quality check on sand cast components.

Inlet and Exhaust Systems

Inlet Systems

The inlet system environment is ambient air with low velocity air flow over interior surfaces. Materials of construction are generally low carbon steel, including the inter baffles used over acoustic material to reduce the noise level. In selected marine environments, a corrosion-resistant steel may be used for these interior baffles. Standard protection practice for the inlet system is an inorganic zinc primer paint and/or galvanizing. External finish coats are applied by the customer.

Exhaust Systems

The stack construction consists of low carbon or low alloy steel structural members and sheets that are protected from the elevated temperature exhaust gases by 409 stainless steel. Further up the stack, silencers that consist of acoustical material encapsulated in perforated 409 stain-less steel are used to reduce the noise level to low values.

On stacks, standard protection is an inorganic zinc primer, a paint with an excellent combination of corrosion resistance and temperature capability. For better weathering resistance and high temperature performance, this primer is being topcoated with an aluminum silicone paint on wing, cowl, plenums and plenum expansion joint surfaces in the factory. All other exhaust system surfaces are primed with an inorganic zinc primer and topcoated in the field with the same high temperature aluminum silicone paint for maximum corrosion protection.

The introduction of the inorganic zinc primer mentioned above for inlet and exhaust systems protection was the result of a high-temperature paint test program. Various types of paint systems were tested at temperatures between 400°F/204°C and 1000°F/538°C for two month-long periods. These tests differed from previous high-temperature paint tests in that humidity exposures were inserted between thermal cycling exposures. Humidity exposures were introduced to provide a better assessment of the effects of weathering and humidity combined with cyclic heating.

The tests yielded useful information. Best overall results were obtained with a system consisting of inorganic zinc primer top coated with the standard aluminum silicone paint. This system satisfactorily survived all exposures including 1000°F/538°C tests. All systems employing inorganic zinc primer were sacrificially protective in salt spray exposures.

While the excellent weathering characteristics of the inorganic zinc primers are well-established, these tests additionally confirmed their high temperature cycling capability.

Summary

The purpose of this paper has been to describe some of the materials currently being used in GE gas turbines and to verify our commitment to continued GE leadership in material and process development. The activities described in this paper are by no means complete. Major materials development work is underway at GE to provide a continuous stream of new and improved materials for gas turbine application to meet our customers' needs for the most efficient gas turbines. GE's intent is to provide the materials necessary for the advancement of turbine firing temperatures while maintaining the high levels of unit reliability, availability and maintainability.

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