ALLOY 706 METALLURGY AND TURBINE WHEEL APPLICATION

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Abstract

The basic chemistry of Alloy 706 was developed from Alloy 718 more than 20 years ago but until recently has not been applied to gas turbines. Its excellent chemistry balance has allowed very large ingots to be produced and successfully forged into high quality turbine wheel forgings. This paper describes the metallurgy of Alloy 706, improvements recently made to enhance its producibility and improve its properties, and its application to turbine wheels. A brief review of ultrasonic inspectability is also presented.

Introduction

Alloy 706 has lived in the shadow of its predecessor, Alloy 718, since it was developed more than 20 years ago. Recently, Alloy 706 has begun to be used in heavy duty industrial gas turbine wheel applications, (see Figure 1). New developments have resulted in the production of Alloy 706 ingots weighing more than 33,000 pounds and forgings weighing more than 22,000 pounds, with thicknesses of more than 16 inches and diameters of up to 87 inches. This paper briefly describes the history of the alloy, its current application to high temperature gas turbines, and the recent work done at General Electric Power Generation to optimize alloy processing and scale-up the size of the forgings made from this alloy. This paper also describes new non-destructive inspection techniques used to inspect these turbine forgings to greater levels of sensitivity than previously possible.
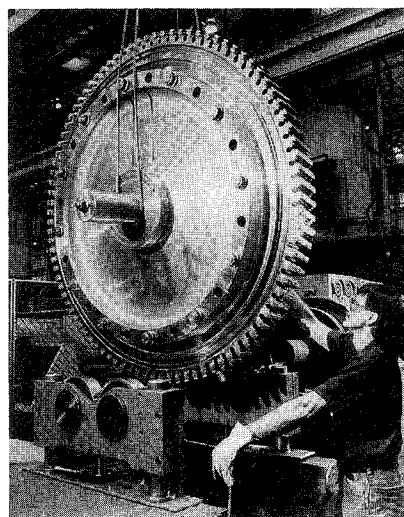

Figure 1. Heavy Duty Industrial Gas Turbine Wheel

Alloy 706 Derivation and Metallurgy

Alloy 706, a nickel-iron superalloy, evolved from studies performed at the International Nickel Company (INCO) in the 1950's. These studies involved investigation of the strengthening effects of various common alloy elements (Cr, Mo, Nb, Al and Ti) in an Alloy 600 alloy base metal[1]. The alloy was originally developed as a higher strength main steam piping material for super critical steam power plants which were being planned by U.S. utilities at that time. During the development process, the potent combined strengthening effects of molybdenum and niobium alloyed with varying amounts of nickel were discovered. This led to the eventual development of Alloy 718, then Alloy 625 and finally Alloy 706, which was patented in 1972. The nominal chemistries of these alloys are shown in Table 1.

Table 1 Chemistries of Several Related Alloys

Alloy	C	Mn	Si	Cr	Ni	Fe	Ti	Al	Mo	Nb+Ta
600	0.08	0.50	0.20	15.5	76.0	8.0	—	—	—	—
718	0.04	0.20	0.20	19.0	52.5	18.5	0.9	0.5	3.0	5.1
625	0.05	0.20	0.20	21.5	61.0	2.5	0.2	0.2	9.0	3.6
706	0.03	0.20	0.20	16.0	41.5	40.0	1.8	0.2	—	2.9

The Alloy 706 development program at INCO had some very specific metallurgical objectives[2]. Among these were (1) an alloy which could be melted freckle free to larger sizes than Alloy 718, (2) an alloy which could be hot worked within the capabilities of existing forging capacity in these large ingot sizes, (3) an alloy which was more economical than Alloy 718 and finally, (4) an alloy which had better machinability than Alloy 718.

The Alloy 706 chemistry was derived from Alloy 718 and was developed from a large statistically designed melting program by H.L. Eiselstein. Molybdenum, which is present in Alloy 718 as a solid solution strengthener, was eliminated in Alloy 706 to improve forgability. Niobium was reduced to decrease the tendency for segregation and freckle formation. But since the primary hardening elements are Nb and Ti, the percentage of titanium was increased to compensate for the lowered niobium content. A low level of aluminum was chosen to provide some strengthening while avoiding rapid age hardening, which would make welding difficult. The chromium content was selected to achieve good oxidation resistance and low magnetic permeability; the nickel level was chosen to be as low as possible to decrease cost, yet maintain phase stability and avoid formation of sigma phase. Finally, carbon was decreased to ensure good machinability.

The most important precipitating phases that occur in Alloy 706 and their typical morphologies are shown in Table 2.

Table 2 Major Precipitates in Alloy 706

Precipitate	Structure	Morphology	Composition
Gamma Prime (γ')	Ordered Face Centered Cubic	Spheres	$Ni_3(Al,Ti)$
Gamma Double Prime (γ'')	Ordered Body Centered Tetragonal	Disks	Ni_3Nb
Laves	Hexagonal Close Packed	Globular	$(Fe,Ni)_2Nb$
Eta (η)	Hexagonal Close Packed	Platelets or Cellular	Ni_3Ti
Delta (δ)	Orthorhombic	Needles	Ni_3Nb

Both gamma prime (γ') and gamma double prime (γ") are present in Alloy 706 as strengthening precipitates with γ" the more prevalent phase[3]. In addition to these phases, other precipitates seen in this alloy are MC carbides, Laves and eta (η). Other investigators have reported the presence of delta phase (δ) but we have not observed this phase in our work. Eiselstein's[4] original time-temperature-transformation diagram is shown in Figure 2. This diagram does not show the γ" transformation. An updated version by Heck[5], which shows the γ" transformation, will be presented as part of this conference. Both γ' and γ" can be put back into solution by holding at 1625° F (885° C). Eta and Delta are resolutioned at about 1750° F (954° C),[6] but as we will show later, segregated areas with slightly higher levels of Nb and Ti may require slightly higher

Figure 2. Time–Temperature–Transformation Diagram According to Eiselstein

temperatures. Small grain boundary particles of Laves can be resolutioned at 1950° F (1066° C) but large Laves particles which may result from poor melt practices can survive temperatures in excess of 2000° F (1093° C). An excellent discussion of the effect of heat treatment and resulting precipitating phases can be found in an article by Moll, et al.[7].
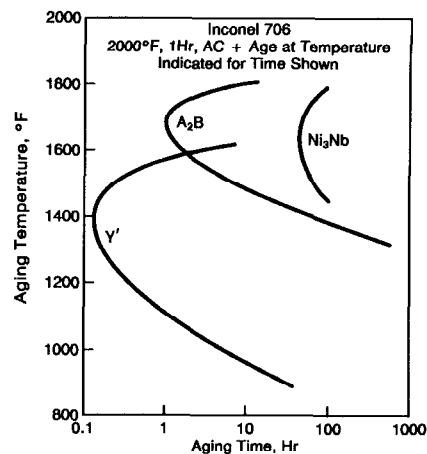
Gas Turbine Application

The turbine rotor design of all General Electric heavy-duty land-based gas turbines is a bolted construction of forged turbine wheels, spacers, and stub shafts. The most highly stressed components in the turbine rotor are the turbine wheels. Historically, CrMoV low alloy steel wheels have been used extensively in heavy-duty gas turbine designs because the high stresses at relatively low temperatures could be accommodated by this low-cost, easily fabricated material.

In the mid 80's, a new class of "advanced" gas turbines, now known as the "F" class turbines, firing at 2300° F (1260° C), was introduced by GE. These machines, operating at temperatures more than 300° F (166° C) higher than the previous generation of industrial gas turbines, required a wheel material with higher yield strength at elevated temperature.

Alloy 706 was selected for this application because of its good mechanical properties, ease of fabrication, and good machinability. A review of commercial alloys showed that only Alloy 706 and Alloy 718 possessed the required strength at temperature for the "F" class machines. The ability to produce large ingot diameters was also a necessity. Ingot diameters exceeding 30 inches were required to avoid exceeding the ingot's length-to-diameter ratio where buckling of the ingot may occur during upsetting. The maximum reported Alloy 718 ingot diameter that had been made without freckling was approximately 24 inches in diameter. Above this size freckling could not be prevented. However, previous good experience (summarized below) had been documented with Alloy 706 in sizes up to almost 12,000 pounds[8], and Suarez, et al.[9] reported that 30 inch electro slag remelted (ESR) ingots might be attainable. In addition, Alloy 706 was reported to have substantially better machinability than Alloy 718 [10].

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Early Alloy 706 Experience

A development program was conducted in the mid 70's by GE to assess the feasibility of making large industrial gas turbine Alloy 706 wheels and to determine the resultant properties[8]. The ingot, produced by the ESR process, measured approximately 24 inches in diameter by approximately 90 inches long and weighed 11,700 pounds. The forge practice consisted of an initial upset, a draw, a second upset and a final forge operation. The final forge operation was carried out at 2,000° F (1093° C) and the earlier steps at slightly higher temperature.

The wheel was machined and sectioned. Portions of the wheel were given either a two or a three step aging heat treatment. The wheel sections were ultrasonically tested using a 2.25 MHz crystal calibrated on a 5/16 in. flat bottom hole. Up to 5 inches of thickness could be penetrated with this technique and no indications were found. In order to penetrate the thicker sections, a 1 MHz crystal was used, and no indications were found at this frequency.

This program showed that a large Alloy 706 ingot could be successfully made, forged into a large wheel shape and heat treated to achieve good property levels. It also demonstrated that this material had significantly less sonic penetrability than low alloy steel.

Current Alloy 706 Experience

Chemistry

The chemistry of Alloy 706 today is much the same as it was when it was introduced in the early 1970's. Standard specifications for Alloy 706 have wide limits for the various chemical elements. Melters of Alloy 706 generally control each element of the chemistry within their own narrower range; but nonetheless, the chemistry variation between melters can lead to variations in the results obtained by forgers. The characteristics which may be affected are toughness, ductility, grain size, and yield strength. Several changes have been made to the chemistry specification for turbine wheels to improve the producibility of these large forgings.

Silicon. To reduce the tendency for formation of Laves phase, the maximum allowable silicon level has been decreased to below 0.10%. Standard heats of Alloy 706 are made with silicon contents of 0.10 to 0.30%. At the high end of this range, Laves begins to precipitate at grain boundaries within one hour at a temperature of 1700° F. Large disc forgings which are air cooled through this temperature range can precipitate extensive grain boundary networks of Laves even at the lower end of this silicon range, and Charpy impact values can dip to as low as 5 ft-lbs. Water quenching eliminates most of the Laves but interdendritic segregation can still lead to some Laves formation. Below 0.10% Si, Laves phase precipitation is minimized so that even air cooling of large forgings is possible.

Niobium/Tantalum/Titanium. Changes in the levels of Nb and Ti affect the solvus temperature for eta phase. Eta phase at grain boundaries can reduce tensile ductility and CVN (Charpy V notch) toughness but not to the same extent as Laves. Eta at grain boundaries can also affect the grain size, as discussed below. Increasing levels of Nb and Ta promote the tendency for the alloy to form freckle defects during solidification. By optimizing levels of Nb and Ti within a narrow range, a good balance of strength and toughness can be achieved while reducing scatter in mechanical properties.

Carbon. Toughness, which is a critical property for turbine wheels, is affected by carbon content. Laboratory studies of heats with varying levels of hardening elements showed
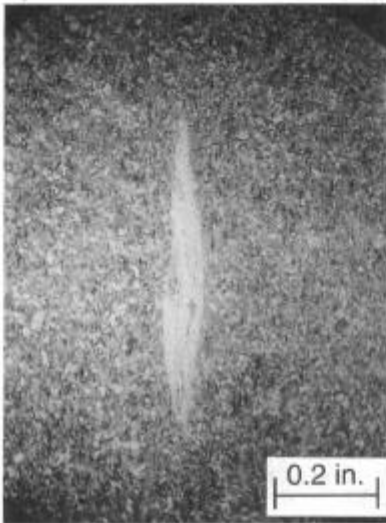
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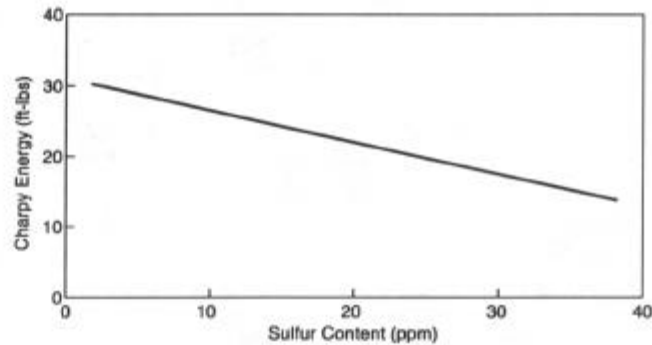
Figure 3. Dirty White Spot in Alloy 706

Figure 4. Effect of Sulfur on Charpy Energy

improvement of approximately 20 ft-lbs in Charpy tests when the carbon level was reduced from a nominal level of 0.03% to a nominal level of 0.01%. Reduced carbon can also be expected to improve machinability through reduction of the number of carbides formed.

Oxygen and Nitrogen. Oxygen and nitrogen levels are not always called out in commercial specifications. There is, however, a benefit in controlling these elements that comes from avoidance of potential problems with "dirty white spots." White spots are areas of negative segregation, that is, areas of lower Nb and Ti content. Nitrides and oxides found in dirty white spots (see Figure 3) are likely initiation sites for early low cycle fatigue failures. Minimizing the oxygen and nitrogen limits the number and size of oxide and nitride inclusion clusters that may occur. To achieve this beneficial effect, the level of oxygen and nitrogen must each be held substantially below 50 ppm.

Sulfur. Low axial Charpy energy, tensile strength, and tensile ductility were observed in some early trial forgings. The cause was $(Ti,Nb)_2CS$, a deformable phase that can cause reduced properties in the short transverse direction of heavily forged parts. This phase smears out into planes of weakness perpendicular to the forging direction. Tests performed on two laboratory heats which were rolled into small bars and heat treated together showed significant improvements in longitudinal CVN (see Figure 4) as a result of lowering the sulfur level. Reducing sulfur to below commercial specification levels has led to an improvement in axial Charpy values of production parts and has truncated the lower end of the Charpy value distribution.

Melting

The development of large, high-quality Alloy 706 ingots mandated significant enhancements to the historical melting technology used for this alloy to prevent the formation of melt-related defects. A triple melt process consisting of vacuum induction melting (VIM), electroslag remelting (ESR), and vacuum arc remelting (VAR) was adopted based upon previous work done on Alloy 718 for aircraft industry applications. The VIM process provides a clean starting material with a well-controlled chemistry. ESR provides some refining of the metal and a sound electrode which remelts in the VAR furnace with little potential for melting anomalies. VAR was chosen as the final melting operation because the shallow melt pools created by this process make it the least likely to cause segregation-related defects.

Freckle segregation can occur in Alloy 706, as it does in Alloy 718 but, because there is less Nb and Ta than in Alloy 718, there is less tendency to form freckles. Freckles are regions of high Nb and Ta content. They typically contain some low-ductility Laves phase which can decrease fatigue properties. In addition, the freckles may develop micro cracks after forging, as shown in Figure 5. Since Alloy 706 is less prone to freckle formation than Alloy 718, it has been possible to produce larger VAR ingots. VAR molds as large as 40 inches in diameter have been successfully cast. Melt rate controls and drip-short controls are used in conjunction with low melt rates to control the tendency for freckling. Melt rate excursion limits have been established through cut-up of many trial ingots to verify that the melt conditions are sufficiently controlled, and macroetching is done to ensure freckle free ingots.
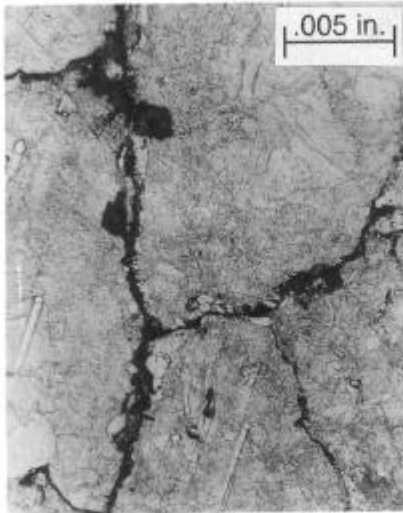

Figure 5. Cracks in Freckle
Region of Alloy 706.

Figure 6. Large Cast Grain Structure (top) in Alloy 706.

White spots, or areas of low alloy (Nb and Ti) content, can occur in Alloy 706. The types of white spots found in Alloy 706 are the same as the types found in Alloy 718, as described by Jackman et al.[11]. "Discrete" white spots have been found in material melted by the VIM/VAR process but have not been found in triple melted material. "Non-discrete" or "solidification" white spots can occur in the normally cropped regions at the bottom and top end of the ingot. However, testing has shown that these white spots have little or no impact on the mechanical properties. Further discussion of our evaluations of white spots and freckles can be found in reference [12].

Forging

Forging of turbine disks is accomplished in several steps. Multiple upset and draw operations of the ingot are performed to break up the initial large as-cast grain size. Special handling and lubrication is used to avoid die lock and assure working of all areas of the forging. This is important because remnants of large as-cast structure (see Figure 6) may not get refined during the final forge operations. Tests have shown that fatigue crack growth rates in large grains can be up to three times higher relative to the surrounding fine grained matrix.

The minimum forge work required for recrystallization in Alloy 706 billet is only about 15%, but in practice significantly more work is applied during each operation to ensure that full recrystallization is attained in all areas of a component. In press forging operations, most of the recrystallization occurs after the forging operation (static recrystallization). Complete dynamic recrystallization (during forging) cannot be

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achieved at the strain rates used for a forge press at strains up to 0.7 inch per inch even at temperatures as high as 2000° F (1093° C). Static recrystallization does not occur below 1700° F (927° C), but full recrystallization can be achieved as low as 1750° F (954° C).

Final forging of the biggest Alloy 706 land based turbine wheels can only be accomplished on the largest forge presses available in the world, rated at 72,000 tons (65,000 tons metric). It is necessary to use a large press in order to minimize the forge temperature while achieving uniform working of the full part. The temperature used during actual forging has very little effect on the grain size obtained after heat treatment. However, higher forge temperatures lead to larger grain size due to grain growth, which occurs during cooling after the forging operation. Large grain size severely hampers ultrasonic inspection of the forging and reduces fatigue life. Therefore, avoidance of high temperatures both during heat treatment and while the part cools from the forge press is important to achieve optimum microstructure and mechanical properties.

Grain size control of Alloy 718 is often achieved by forging the material after small particles of delta phase have been precipitated on the grain boundaries. The particles pin the grain boundaries and prevent grain growth. An analogous process can be employed for Alloy 706 using eta phase[6,13,14]. However, the flow stress of Alloy 706 increases dramatically, thus increasing forge press requirements. Figure 7 shows a comparison of the flow stress of Alloy 706 at 1600° F (871° C), which is below the eta solvus and at 2000° F, (1093° C), which is well above the solvus.
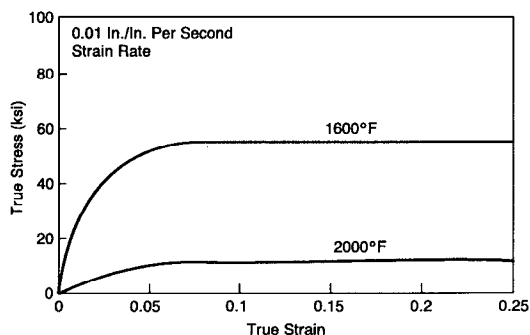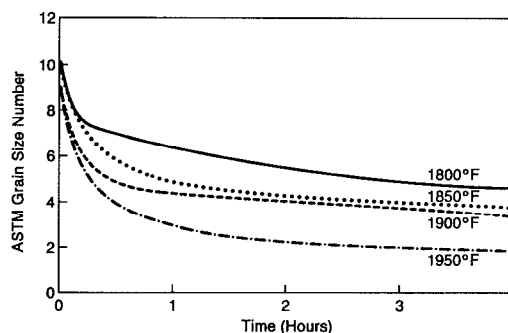

Figure 7. IN-706 Flow Stress

Figure 8. Grain Growth of IN-706

Heat Treatment

Alloy 706 is typically used in a solution treated and aged condition. The strengthening phases, gamma prime and gamma double prime, are completely dissolved above about 1625° F (885° C). However, the solution temperature is usually chosen to be in the range of 1800° F (982° C) to 1850° F (1010° C) to avoid eta and Laves phase precipitation. Higher solution temperatures are generally avoided because grain growth is very rapid and large grains may harm fatigue properties and hinder ultrasonic inspection. Figure 8 shows the time for material with an initial grain size of ASTM 10 to reach various grain sizes at different temperatures.

Turbine wheels are given a combination recrystallization/solution treatment following forging. The optimum treatment temperature is around 1800° F (982° C). At this temperature all of the grains recrystallize, but excessive grain growth is avoided. Below 1750° F (954° C), recrystallization may not be complete and eta phase may exist at grain boundaries or within grains. Eta is effective in controlling grain size by pinning the boundaries. If material with eta in the grain boundaries is heated to a temperature around the eta solvus, bands of large and small grains may form. This is caused by residual interdendritic

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segregation, causing variations in the local eta solvus. The temperature range over which the banding appears is dependent on the nominal Nb and Ti contents, as shown in Figure 9.

Water or oil quenching after solution treatment can prevent precipitation of eta or Laves phase in the deep-seated regions of large forgings. Quenching also limits the time at solution temperature, thereby minimizing grain growth. Cracking is avoided as long as the surface is free from defects and large stress concentrations.

Figure 9. Effect of Nb + Ti on Banding in Alloy 706.

One of two aging treatments originally developed by INCO is generally applied to Alloy 706 when it is aged today. A three-step aging process is used for applications where high temperature stress rupture ductility is required, and a two-step aging process is employed when tensile properties at low to moderate temperature are to be optimized. The three-step aging typically consists of 3 hours at 1550° F (843° C) followed by an air cool to low temperatures. This is then followed by eight hours at 1325° F (718° C), furnace cooling to 1150° F (621° C), eight hours at 1150° F (621° C), and air cooling. In the two-step aging cycle, the classic aging temperature sequence has been 1350° F (732° C) followed by 1150° F (621° C). Improvement in the Charpy energy can be obtained by optimizing the aging temperatures for specific levels of alloy hardener. The precipitation reaction of gamma prime and gamma double prime is sluggish in Alloy 706 compared to Alloy 718. Aging times are typically eight hours at each temperature, but there is little change in properties if times are extended to 16 hours. A slight increase in strength can be achieved if a third aging treatment at 1050° F (566° C) is added to the 1350/1150° F sequence.
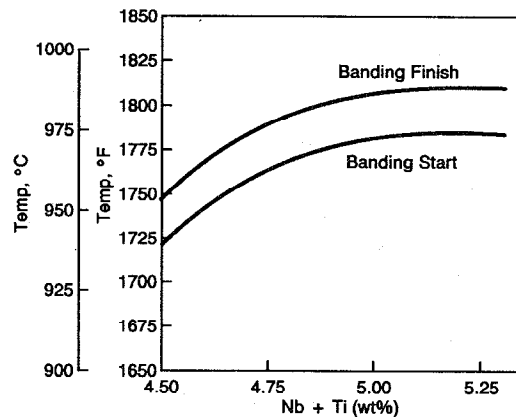
Typical Property Levels and Microstructure of Large Forged Disks

Extensive testing has been performed at GE Power Generation to verify the level and uniformity of critical turbine design properties. Tensile and Charpy properties are measured in the tangential and axial directions at both the rim and the bore (centerline) of each Alloy 706 forging used in "F" class gas turbines. Average properties for triple melted wheel and spacer forgings are shown in Figure 10. The property levels are generally uniform from the center to the rim. Axial ductilities and Charpy energies tend to be slightly lower than the tangential values, but are still relatively high. Figure 11 shows typical hot tensile properties for the rim and the bore in the tangential direction up to 1000° F. Strength levels remain generally high over the entire temperature range and no reduction of ductility is observed. Figure 12 shows a representative microstructure for solution treated and aged Alloy 706. The grains are predominantly equiaxed with some twins. The gamma prime and gamma double prime hardening phases can be observed only by TEM.

Several hundred low cycle fatigue tests have been run on samples taken from large wheel and spacer forgings. Figure 13 shows the average low cycle fatigue life with A=1, 20 CPM at room temperature. Results at temperatures up to 900° F (482° C) show a slight increase of fatigue life as temperature increases. The fatigue crack growth rate was found to exhibit a small increase over the temperature range from 70° F (21° C) to 900° F(482° C). Figure 14 shows the average fatigue crack growth rate at room temperature. Fracture toughness, which characterizes a material's tolerance for defects, is high, averaging about 180 ksi √in. despite the large size of the forgings.
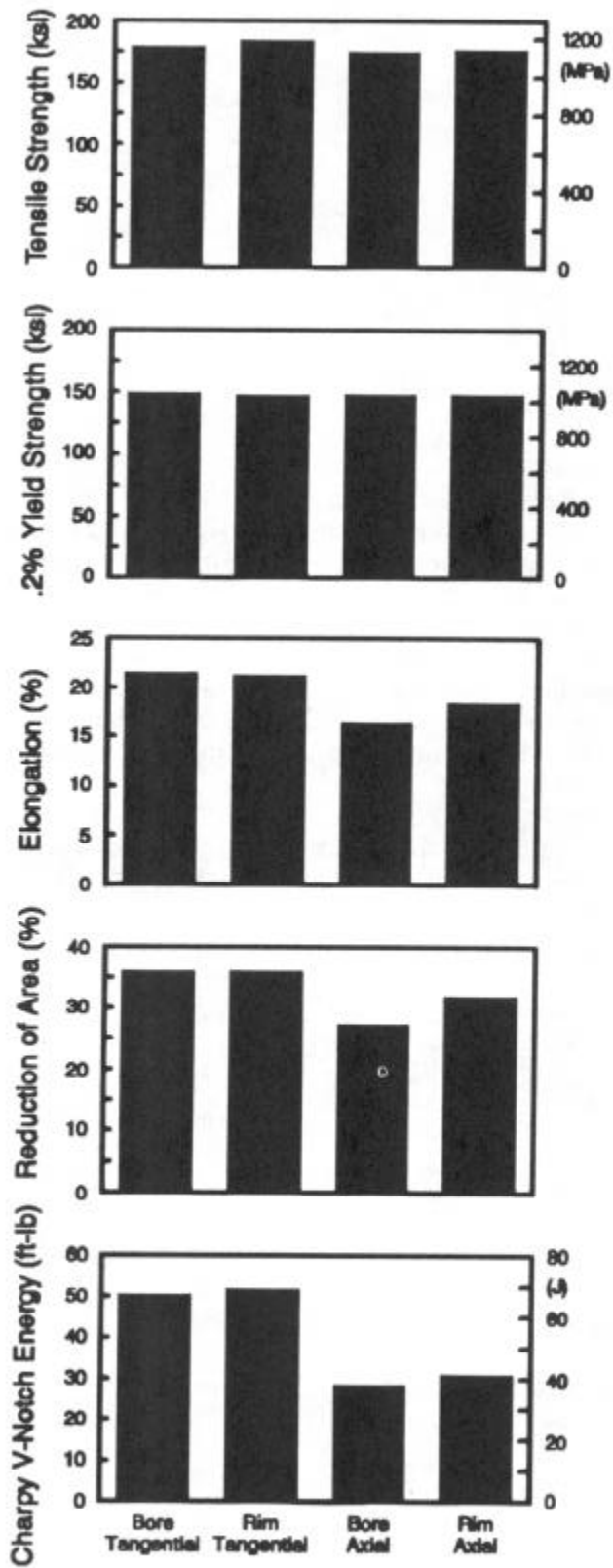
Figure 10. Average Properties in Turbine Disk

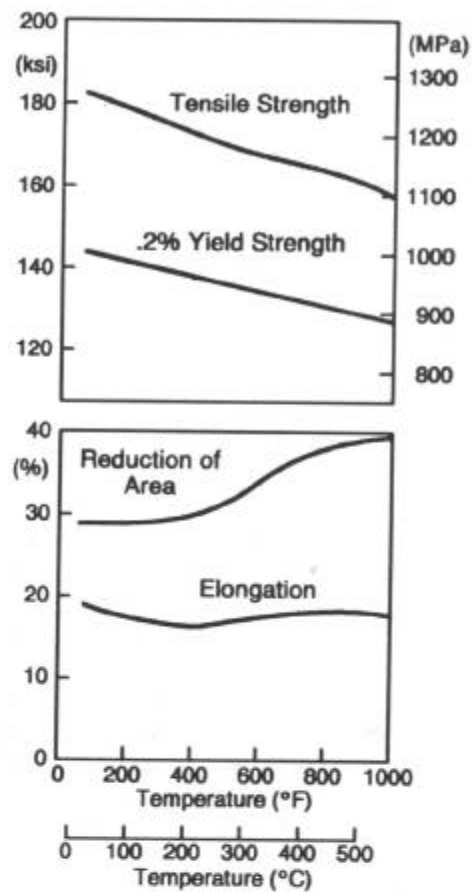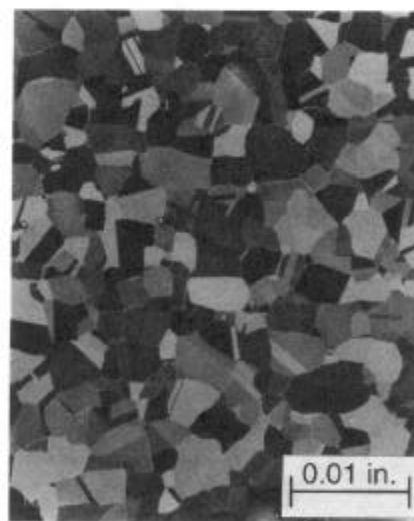Figure 11. Typical Tangential
Properties

Figure 12. Typical Alloy 706
Microstructure

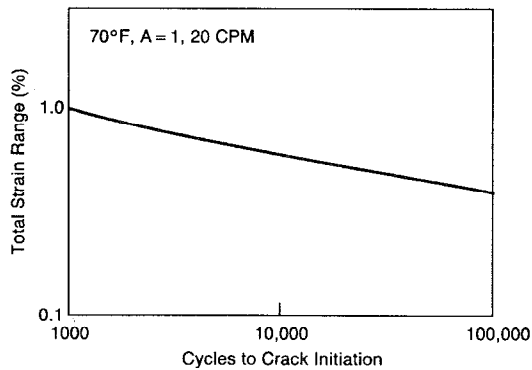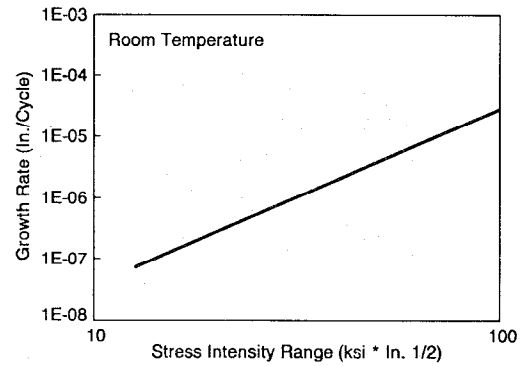Figure 13. Low Cycle Fatigue

Figure 14. Fatigue Crack Growth Rate

Non-Destructive Testing

Special ultrasonic examination methods and equipment were developed to optimize the inspection of large Alloy 706 turbine wheels and spacers[15]. The Alloy 706 forgings are examined by ultrasonic inspection from every available surface. The top and bottom surfaces of the disk-shaped forgings are examined using a $2^{1}/4$ MHz long wave beam. The bore surface of all wheels is examined using a specially designed portable quasi-immersion test. During this inspection, a longitudinal beam searches for axial-circumferential indications while an angle beam, moving first in a clockwise direction and then in a counterclockwise direction, is used to look for axial-radial indications. The dovetail region of each wheel is interrogated with a 60° angle beam in both clockwise and counterclockwise directions.

To guarantee the highest structural integrity of these components, a special ultrasonic test was developed to inspect each forging in the plane perpendicular to the highest operating stress, (i.e., the axial-radial plane). This test, called the "Pitch-Catch" test, is performed on Alloy 706 turbine rotor components near the highly stressed bore region. The Pitch-Catch test uses two search units operated in the transmit-receive mode. A schematic diagram of the test setup is shown in Figure 15. The search units are directed toward an axial-radial plane of the forging. As the forging rotates, its axial-radial planes pass through the beam path intersection, creating the inspection volume. After one rotation, a toroid of material has been inspected. The search units are then swept radially in unison to complete the inspection of one axial slice, or plane of material. To complete the process, the search units are moved relative to each other so that the beam path intersection moves axially across the forging.
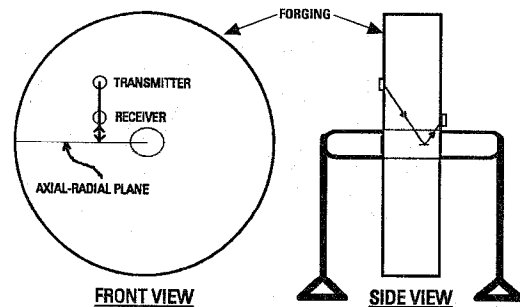

Figure 15. Pitch-Catch Test Setup

Conclusion

Alloy 706 is now being successfully used in large land-based heavy-duty gas turbine components. Its excellent chemistry balance has allowed very large ingots to be produced and forged into high-quality turbine wheel and spacer forgings. Hundreds of these forgings have been applied to the new GE series of "F" class gas turbines produced over the past five years; some wheels have accumulated more than 25,000 hours of successful operation.

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Acknowledgments