EXTENDING THE SIZE OF ALLOY 718 ROTATING COMPONENTS

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Abstract

Alloy 718 rotors, in previously unheard of sizes, have been introduced into GE heavy-duty gas turbines. The forged area of each disk in a rotor is an order of magnitude larger than those of aircraft engine disks. The production challenges posed by the very large 718 ingots and forgings needed to make the rotors are discussed in this paper. The issues include segregation, abnormal grain growth and processing limitations imposed by the size of production equipment.

Introduction

GE introduced alloy 718 into its FB and H gas turbines in 2002 to achieve higher firing temperatures and accompanying increases in operating efficiency. Alloy 718 is not new. Inco Alloys invented it in 1959 and it has since become the most widely used superalloy of all time. Much is known about the properties of alloy 718 and the processing required to produce it. However, all of the experience with rotating 718 components until now has been with components that are much smaller than large land-based turbine disks. Jet engines have been the primary application for high speed rotating components. Jet engine disks typically weigh less than 2000 pounds as forgings and most commonly come from 17 to 20 inch diameter ingots.

Figure 1 compares the size a jet engine spool forging to a much larger disk used for GE’s 9FB gas turbine. The as-machined gas turbine disk is more than three times the diameter of the spool forging and therefore has ten times the area to forge. The ingot used to make the gas turbine disk weighs seven times the aircraft ingot, and more importantly is twice the diameter, making it much more susceptible to the freckle type segregation known to occur in alloy 718. This paper describes the challenges posed in producing 718 disks in excess of six feet in diameter and the metallurgical characteristics of these large components.

Figure 1. Size Comparison of a 9FB Turbine Wheel and a Jet Engine Rotating Component
The First Step – Melting

The initial steps taken toward manufacturing large 718 components were actually part of the march that started in 1989 to make alloy 706 rotor disks for the first F class turbines. Alloy 718 was considered for this application, but all the experts involved in the production of aircraft components “knew” that 718 ingots larger than 20 inches in diameter could not be produced. Therefore a development effort to make large alloy 706 ingots was launched, because alloy 706 was thought to be less prone to segregation due to its lower niobium content. Alloy 706 also had another advantage. The solidification temperature range for 706 is smaller than the range for 718, only 65°F for 706 verses 137°F [1] for alloy 718, so there is less opportunity for segregation to develop during solidification. One other chemistry characteristic made 706 a better candidate for large component trials. That characteristic is lower levels of hardener in alloy 706, which makes 706 less susceptible to cracking in the ingot, billet, and forging states than alloy 718.

The first large 706 ingots were 30 inches in diameter. Some early ingots made by vacuum induction melting (VIM) followed by electroslag remelting (ESR), had centerline segregation. Measurements indicated that the segregation had little effect on mechanical properties but to be conservative the segregation was eliminated through adoption of a triple melt process which utilized VIM/ESR followed by vacuum arc remelting (VAR). Solidification by VAR yields a shallower molten pool than ESR and also one that has less steeply sloped sides. Both of these characteristics help reduce the formation of macro-segregation. The real breakthrough in large superalloy production occurred when several melters demonstrated that a suitable window in VAR melt rate existed that allowed them to make large diameter ingots without positive segregation, which is normally caused by a rate that is too high, and without negative segregation (white spots) caused by a rate that is too low.

The large ingot melting process was optimized over the next couple of years in parallel with a need for still larger ingots for larger turbines. Melt algorithms were tightened. Arc gap, as measured by drip shorts, was more tightly controlled. Electrode integrity was improved by better cropping rules, better stub welding and rigorous surface cleaning. Annulus requirements for the space between the electrode and crucible were fixed, leading to more precision in making straight electrodes. As a result, VAR ingot sizes quickly jumped to 33-inch diameter, then to 36 inch and finally 40 inch diameter.

Ultimately hundreds of successful 706 ingots were made. In parallel, designs of more efficient, hotter land based turbines were proposed. The question was then posed as to whether the improvements in melting which evolved during optimization of 706 melting, could yield successful production of the more difficult alloy 718. The answer was yes. The first trials were made at a 27-inch diameter and ingot size progressively increased to 30, 33 and 36 inch diameter while ingot weight increased as shown in Figure 2.

Some chemistry adjustments were made in hopes of reducing the
tendency to segregate. Carbon, nitrogen and niobium were all reduced. Carbon was specified at lower levels for two reasons. The first was based on experience with the large diameter 706 ingots where a decrease in carbon content was found to favor improvement in properties [2]. The second reason was to limit the size of carbide particles that could reduce fatigue life. Nitrogen was initially decreased in hopes of limiting the formation of nitrides, which were thought to nucleate harmful carbides. Further study indicated that the slightly higher nitrogen levels commonly prevalent in heats of 718 caused no reduction of properties due to carbides and the maximum nitrogen level was relaxed. Niobium was reduced slightly to reduce the density of the last liquid to solidify and interrupt the mechanism that forms freckles. There was a concern that lower niobium might reduce the strength of the alloy but lab scale trials showed that this would not be an issue. Over the range of cooling rates from the solution temperature experienced by these larger section size parts, there was no impact of lower niobium content on ultimate tensile strength [3]. The rest of the chemistry remained close to nominal as shown in Table I.

<table>
<thead>
<tr>
<th>Table I. Chemistry of Alloy 718 (wt%)</th>
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<tbody>
<tr>
<td>Carbon.</td>
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<tr>
<td>Manganese, max.</td>
</tr>
<tr>
<td>Silicon, max.</td>
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<tr>
<td>Phosphorus, max.</td>
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<tr>
<td>Sulfur, max.</td>
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<tr>
<td>Chromium</td>
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<tr>
<td>Nickel</td>
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<tr>
<td>Cobalt, max.</td>
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<tr>
<td>Molybdenum</td>
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<tr>
<td>Niobium</td>
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<tr>
<td>Titanium</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Boron, max.</td>
</tr>
<tr>
<td>Copper, max.</td>
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<tr>
<td>Tantalum, max.</td>
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<tr>
<td>Magnesium, max.</td>
</tr>
<tr>
<td>Nitrogen, max.</td>
</tr>
<tr>
<td>Oxygen, max.</td>
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<tr>
<td>Iron</td>
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In the end, the melt rate window for 718 proved to be tighter than the window for 706 but statistical analysis showed that the acceptable range of melt rate was within the control capability of the improved melting protocols developed for alloy 706, for ingots up to 36 inches in diameter. Figure 3 shows several 36-inch ingots melted by ATI Allvac. Later work on a small number of ingots suggested that the reduction of carbon and niobium may not be needed but the tighter chemistry controls were preserved because the heats used to validate the melt rate window had been made with low carbon and niobium.

**The Other Half of the Battle - Forging**

The other half of the battle was to forge the large ingots of alloy 718 into useable shapes with an appropriate microstructure. It was suspected that 718 would be more difficult to recrystallize than alloy 706, and hence require more forge work. It was known that achieving higher forge work would be complicated by the higher flow stress of alloy 718, which would challenge the capability of the forge presses used for billetization and final forging. It was also thought that
increased sensitivity to billet surface cracking would lead to poor ingot yields and perhaps even loss of the entire ingot.

There are many steps to forging a turbine disk and each has its challenges. The first problem to be overcome was caused by the shape of the ingot to be forged. All of the weight needed to make the final disk could not be achieved solely through increases in the ingot diameter. Part of the weight had to be achieved by increased ingot length. This created an ingot with a length to diameter ratio that was vulnerable to buckling. The coarse as-cast grain size in these large ingots require multiple upset and draw billetizing operations to refine the microstructure. Buckling could occur during any one of the multiple steps in the process. During all steps of the upset, proper lubrication of the ends to avoid excessive barreling of the ingot is essential. The relatively long upset times also require excellent insulation at the top and bottom to avoid chilling of the ends which promotes higher flow stresses and contributes to unwanted barreling. Heat loss in the radial direction during the upset and draw operations posed another problem because the long times required to forge such long ingots allows the surface to cool significantly, making them more susceptible to surface cracking.

Prior work with alloy 706 helped to define forge process capabilities with respect to heat loss and strain rate verses time during both preliminary and final forging. However, the entire large ingot process needed refinement and closer control to make alloy 718. The preliminary billetization upset required multiple dies to ensure rigid positioning of the ingot ends while reducing the ingot height. Tight control of the diameter was essential to maintaining a nominal cylindrical shape during each step of the upset. Drawing operations and subsequent upsets were performed in a cogging press. Here the emphasis was on quick but accurate forging to avoid excessive heat loss while at the same time maintaining a shape that would resist buckling and skewing.

Forging to the final diameter posed the biggest challenge because of difficulty in handling such large parts in the shop and limitations of the press to deform large billets of a high flow stress alloy. The longer than normal transfer time from the forging furnace to the press during final forging created surface cooling issues similar to the cooling problems encountered during billetization. During final forging there is limited excess surface material so the part is less tolerant of surface cracking. Long transfer times also had the potential to cool the part so much that the average flow stress would increase to the point where the press would stall due to power limitations. The largest forging equipment in the world is sized for making smaller aircraft engine size parts. A gas turbine disk with a plane view area ten times that of an aircraft disk requires similarly more force to deform to a final shape. Unfortunately building a higher tonnage press comes with an expensive price tag, in the range of hundreds of millions of dollars. Since such a large press would have only limited usage, its cost could not be justified and it was necessary to use existing facilities. Increasing the forging temperature was a possible path to lower the required press force, but this has the negative effect of creating a coarse grain size with
reduced sonic penetrability and fatigue properties, so it was not pursued. It was therefore important to keep the work piece well insulated to keep it as close to furnace temperature as possible. It was also necessary to maintain a uniform circumferential temperature distribution in order to be sure that the part would deform evenly and meet required dimensions in all areas.

The forge press tonnage limitation was overcome by creating a final shape using multiple dies that engaged a limited area of the forging, thus reducing the force needed to deform the metal. Ultrasonic inspection, however, detected an unexpected region of abnormal grain growth (AGG), as shown in Figure 4. It was localized to the low strain regions associated with the edges of one die set. This was unexpected because this phenomenon has been found in other alloys but there is limited information about AGG in alloy 718 in the open literature [4].

A systematic study was undertaken to understand the conditions in which AGG takes place. Laboratory compression tests on double cone specimens, as shown in Figure 5, were performed at different temperatures and strain rates to check for undesirable forging conditions.

![Figure 4. Abnormal Grain Growth](image1)

![Figure 5. Double Cone Compression Specimen and Example Strain Profile](image2)
Finite element modeling and microstructural evaluation identified a narrow range of strains at the forging temperature that could potentially cause AGG. This posed a serious problem in the design of the forging process. As mentioned previously, the process requires multiple dies that make partial contact with the part in order to overcome the press tonnage limitation. This meant that the part would develop strains ranging from zero to the maximum strain including all intermediate values of strain. With this approach it would be impossible to avoid the critical strains that permit AGG to occur. To overcome this problem, the forging shape had to be re-designed to limit any potential AGG to a low duty region that had less restrictive ultrasonic and LCF requirements. Sophisticated finite element modeling generated die geometries that placed the region of potential AGG in an appropriate area of the part. The new dies worked better than expected, eliminating AGG as confirmed by ultrasonic inspection of all production parts produced to date. Figure 6 shows a turbine wheel shortly after removal from the press after the final forging step.

Figure 6. As Forged 9FB Turbine Wheel

Heat treatment was the final hurdle. Heat treatment must be accomplished in a way that ensures that all areas receive a similar thermal cycle despite the inherent potential for thermal gradients through the large cross section. A solution treatment below the delta phase solvus temperature was employed to maintain a fine grain size. Thermal modeling of the solution treatment and the aging cycle demonstrated that slow heating and cooling could provide a similar heat treatment for all regions of the forging.

**Ingot Evaluation**

One of the risks of making large 718 ingots is that internal segregation generally cannot be detected by nondestructive means and so detection occurs only after expensive, time consuming forging operations. Hence it is important to have a reliable evaluation of chemical uniformity over a range of possible melt rate variations. To accomplish this, melt rate variations were intentionally introduced during melting of production scale 718 ingots. The ingots were then sectioned in the radial and longitudinal directions. The long lengths of these ingots, which typically have length to diameter ratios of above three, permitted inclusion of three evaluation melt rates in most development ingots. Ingots made for evaluation were commonly made with high, low and mid point melt rates.
After forging to relatively small 10-inch diameter billet, multiple sections representing each melt rate were ground, ultrasonic tested, and macro etched to look for questionable material. The transition regions between the various melt rates were also examined along with the start-up and hot top regions, to see if instabilities would be introduced by transient melting variations. Intentional power interruptions were also introduced to check for signs of potential segregation from these even more exaggerated transients. Figure 7 is a typical evaluation diagram illustrating the locations of ingot etch-plates relative to planned variations in the melt rate. Each etch-plate was examined for freckles, white spots, white center, shelf, and tree rings.

![Diagram showing etch plate locations and melt rate over time.]

**Forging Evaluation**

The goal of using large 718 components in land-based turbines was to achieve the property levels and microstructure found in other 718 products. Figure 8 shows the average tensile properties for 9FB disks. The UTS is comparable to small forgings despite the disparity in size of the parts. However a slight decrease in 0.2% yield strength is observed because of the slower cooling rates in the very large section sizes.

![Graph showing tensile strength and 0.2% yield strength over temperature.]

Low cycle fatigue data from a large 718 forging are shown in Figures 9 shows. The values are comparable to aero engine disks.
As a result of the uniformly fine microstructure, ultrasonic penetrability of the large disks is excellent. All parts receive a 100% examination with tests that can detect a number 2 flat bottom hole. Sonic indications are a rarity. Figure 10 shows a typical microstructure. Grain sizes in the forgings are slightly larger than the finest grain 718 aero engine disks but are still very good, ranging from ASTM 8 to 11. In addition to material property evaluations, every forging is etched on all surfaces as an in process check for macro-segregation. The billet top and bottom crops are also etched to provide added assurance. Figure 11 shows a finished set of 718 wheels in a 9FB turbine.

Figure 9. Fatigue Strength, Tangential Orientation, A=1, 20 cpm

Figure 10. Typical Microstructure

Figure 11. 9FB Turbine

What Next?

Alloy 718 has brought GE turbines to the next efficiency level. A fair question now is, what enabler is on the horizon for still higher turbine efficiencies and still larger size components? One potential candidate is an improved method for making large ingots called Clean Metal Nucleated Casting (CMNC). ATI Allvac and GE are developing this process in an eight-year joint venture development supported by the Department of Energy. Clean Metal Nucleated casting, as shown in Figure 12, is a process whereby partially solidified particles are sprayed into an ingot form after melting in a special type of ESR furnace. The furnace is able to maintain an
appropriate melting rate via use of parallel current paths through the electrode and furnace that keep the pool at the proper temperature even when the electrode is melting at a low rate. The furnace is able to maintain the proper tapping rate though use of a patented cold induction guide at the bottom of the furnace.

![Diagram of CMNC system](image)

Figure 12. Clean Metal Nucleated Casting System

CMNC can operate at a melt rate three times higher than is possible in a VAR operation. This productivity improvement is supplemented by a reduction in the number of melting operations needed from three used by the current VIM/ESR/VAR process to two for CMNC. CMNC also has the potential to eliminate the need for ingot billetization since the as-cast grain sizes could be fine enough for direct forging to the final forging shape. However, the biggest attraction of CMNC is not its potential for improved productivity, but rather its potential to melt large ingots of high temperature Ni-base alloys despite the strong tendency for these alloys to segregate when melted by conventional means. Increased temperature capability will open the door to still higher turbine efficiency.

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**References**