DEVELOPMENT OF A CONVENTIONAL FINE GRAIN CASTING PROCESS

Michael Woulds and Howard Benson

AiResearch Casting Company
19800 Van Ness Ave.
Torrance, California 90509
USA

Summary

Integrally cast wheels have been used in small gas turbine engines for many years. As performance requirements have increased, a major design concern has been the improvement of low-cycle fatigue life. Conventional investment castings--which are characterized by coarse, columnar grain structures--have variable, non-predictable fatigue lives. Experimental work has shown that a fine-grain structure can double the service life of castings.

This paper describes an economical casting process--the Fine Grain Process (FGP)--that produces a controlled fine-grain structure in the thick hub section of a wheel while maintaining the cast structure and properties of the thin airfoils. The Fine Grain Process uses controllable investment casting procedures and has been shown to be adaptable for various wheel configurations and alloys.

Introduction

The Fine Grain Process development program was the culmination of a series of experiments which were begun in 1975 to produce a fine, equiaxed grain structure with a vacuum-cast IN713LC radial turbine wheel. The goal was to increase the low-cycle fatigue life in the hub section of the wheel and reduce the data scatter so that design life could be accurately predicted, while at the same time retaining the other positive features of casting and economics.

It has long been realized that a forged disc with its inherent fine grain has tensile and fatigue properties that are superior to those of a cast disc. Conversely, the rupture and creep properties of a cast airfoil are superior to those of a forged airfoil. Presently, there are efforts under way to bond a cast airfoil ring to a forged disc in order to combine the benefits of both. Unfortunately, there are many problems associated with the bond. The current program utilizes an integral casting procedure that produces the desired fine grain hub and cast airfoils and results in optimum properties.

Grain size can be controlled in three basic ways: mechanically, chemically, or thermally. Thermal control was selected as the most adaptable technique and the easiest to implement in a conventional casting process. By maintaining a low pouring temperature, the alloy can freeze rapidly, thus restricting grain growth.

The mechanical approach relies on the continual agitation of the liquid metal as it freezes. The agitation breaks up the dendrites as they begin to form, thus producing more nucleation sites and inhibiting grain growth. However, because solidification is restricted, microporosity occurs between the grains, and pore closure by a hot isostatic processing (HIP) operation is necessary. The chemical approach involves the use of innoculants, which are compounds that have a lower melting point than the alloy itself and produce localized inhomogeneity and preferential nucleation sites. Although a finer grain is obtained with this technique, the innoculants introduce oxides, which as non-metallic inclusions, become nucleation sites for fatigue crack initiation.

The thermal technique study program examined three phases of casting: materials, processing, and casting evaluation. For each of these phases the following were studied.

Materials

- mold systems
- crucible types
- alloys

Processing

- alloy pouring temperature
- alloy superheat temperature
- mold temperature
- control of cooling rate in the mold
- hot isostatic processing

Evaluation

- grain size
- casting quality (x-ray, penetrant inspection)
- mechanical properties

The Fine Grain Process does not necessitate chemical modifications. Essentially, the process modifies parameters that are common to the conventional casting process. These parameters are discussed in the sections on Materials and Processing.

Materials

Mold System

Because low pouring temperatures were used, the castings were prone to misruns; the liquid metal was unable to penetrate into thin sections such as the trailing edges of airfoils, which can be as thin as 0.010 in.

Added to this was the problem of generated gas pressure. Even though the alloys are poured in a vacuum (and thus do not have a back pressure of air as in a traditional airmelt casting) a small gas pressure is generated. The mold material is generally preheated to 2000°F (1100°C) and complete outgassing of the refractory is obtained. However, the molten alloy is typically poured into the mold at a temperature of about 2800°F (1550°C) and the additional heat can generate an instantaneous outgas that becomes trapped in the mold, thus creating non-fill areas. The permeability of the mold material at temperature is therefore critical. With a more permeable wall the evolved gas can be evacuated more rapidly allowing the molten metal to fill the cavity.

The standard investment cast process uses a wax or plastic pattern and a colloidal silica/zircon flour slurry as the face coat. Approximately seven successive layers of zircon sand and slurry are built up on the surface, creating a fairly dense shell. Misruns are common due to the low shell permeability. In order to produce a more porous texture without loss of strength, various additives have been tried. Sawdust has been used for many years in the third or fourth layer in place of the sand. When the mold is heated, the sawdust burns off leaving a porous layer. Unfortunately, the shell strength suffers because the layer is poorly bonded.

A unique solution was obtained using a layer of hollow glass microspheres--each approximately 1 mm in diameter--in place of one of the stucco layers. When the shell was fired, the glass fritted with the adjacent zircon particles leaving a porous layer. The entire shell had good strength and permeability at temperature.

Another solution was to use a proprietary system known as AiRefrac, which had been developed especially for wheel-type castings. The mold cavity is formed by a reusable rubber pattern in a block mold type process using a silica-based refractory. The mold is fabricated in segments and is assembled as a unit with a pouring cup attached. The advantage of this system over a conventional investment mold is that silica has a lower thermal conductivity than zircon, hence the heat is not abstracted so rapidly from the freezing alloy. Also, there is a higher permeability.

Another unique feature is that the mold system is easy to machine so that varying shell thicknesses can be obtained to control cooling rates in particular sections of the mold. It is this feature that enables a fine-grain casting to be produced with directional solidified airfoils.

Depending on casting size, shell thickness can be reduced and alternative materials such as alumina stucco can be used in shell construction. These methods of improving permeability and reducing chill are now used in the production of fine-grain castings.

Crucible Types

The initial development work on the FGP made use of alloys IN713LC and IN100. In order to maintain casting cleanliness, the alloys were melted in a refractory liner in the melt crucible. The liner, which was made of zircon, was discarded after one use to prevent skull material and oxides from being carried into subsequent melts or building up on the crucible wall.

Bars cut from fine-grain castings made with hafnium-modified superalloys, such as Mar-M247 and IN792+Hf, failed prematurely in low-cycle fatigue tests, often after only a few hundred cycles. The failed bars were examined, and it was seen that brittle fracture had occurred and a pale yellow oxide was present on the cleavage planes (Figure 1). This substance was identified as hafnium oxide. It was concluded that the silica present in the zircon had reacted with the hafnium in the molten alloy to form HfO_2.

Figure 1 - Fracture surface of Mar-M247 showing HfO_2 inclusion (20x magnification by SEM)

To prevent this chemical reaction, it was necessary to develop a non-silica-containing crucible liner. Magnesia-, zirconia-, and alumina-base systems were all studied as alternatives. However, most of these refractories required a silica binder to achieve sufficient fired strength, and therefore were unacceptable.

An alumina-base liner was made using a wax mandrel and building up six coats of alumina slurry and stucco. The resulting liners were fired and Mar-M247 was melted in them. There were no obvious reactions, i.e., the melt surfaces were dross free. However, all the liners cracked or spalled due to low thermal strength.

It was then decided to combine the strength of the original zircon liner with the inertness of the alumina, so some liners were coated on their inside surfaces with an alumina slurry wash and fired. Mar-M247 melted in these liners exhibited no reaction; fracture surfaces exhibited no oxide films. The liners did not crack and the alumina face coat did not exfoliate; hence, the system was incorporated as the standard procedure for hafnium-containing alloys.

Alloys

As stated before, alloy cleanliness is critical in fine grain wheels; any inclusions will serve as initiation sites for fatigue cracks.

Experimental fine-grain castings poured from a variety of master heats of IN713LC exhibited a wide data scatter in low-cycle fatigue testing. Failure analysis indicated that nonmetallic inclusions were the source of the premature fatigue cracks. These inclusions were found to be alumina-magnesia type and were generated in the preparation of the master alloy. For the balance of the development program and in current production, filtered master alloy is specified.

With improved master melt refining techniques and liquid metal filtration, the incidence of nonmetallic inclusions has dropped markedly. Also, chemistry modifications--within the specification ranges for the alloys--were made to increase the number of grain nucleation sites, specifically, carbides, borides, and refractory elements.

Processing

Alloy Pouring Temperature

A program was established to determine a pour temperature that achieved optimum grain size without attendant casting defects.

It was first necessary to establish an accurate value of the freezing point of the alloy (P) so that specific values of P+T could be set to vary the pouring temperature. (T is the temperature differential above the freezing point.) This was achieved both by differential thermal analysis measurements and by actual freezing in the crucible and monitoring the cooling curve using an immersion thermocouple. Since most investment castings are poured in the P+150°F to P+350°F temperature range, the initial trials employed pour temperatures of P+100°, P+80°, P+60°, P+40°, and P+20°F, using IN713C in an axial turbine wheel casting. Figure 2 shows cross sections of three castings, revealing the decreasing grain obtained by decreasing pouring temperatures.

At P+20°F, misruns (i.e., non-fill of airfoil areas) occurred, and it was concluded that this temperature was too low. At P+60°F and above, some large equiaxed and columnar grains were still visible. A further trial was made at P+50°, P+30°, and P+25°F. Non-fill still occurred at the lower

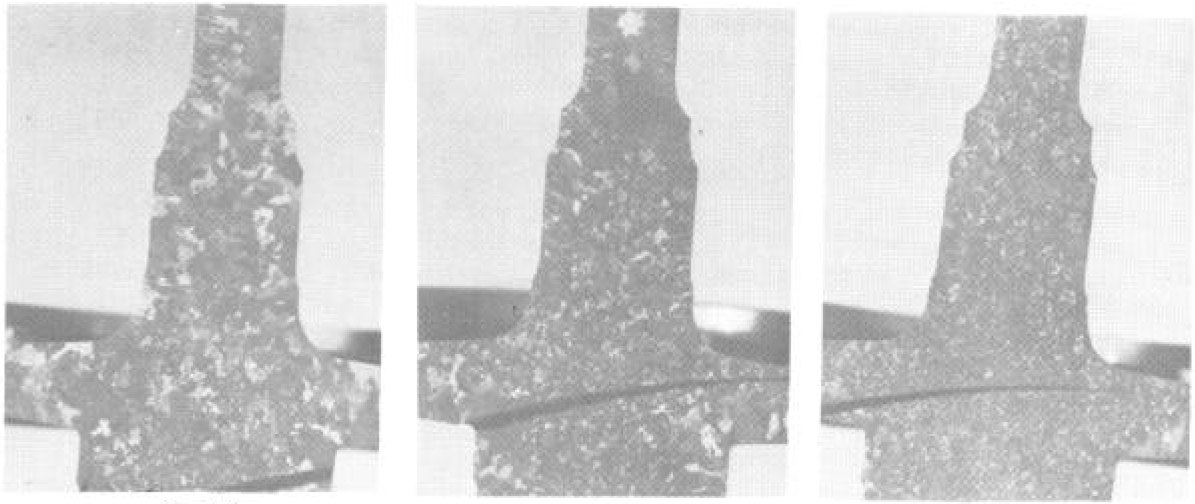

Figure 2 - Axial turbine wheel castings made with IN713LC. Note how grain size decreases with pour temperature. (Magnification, 2/3X)

pouring temperatures, but to a lesser extent. Therefore, the pouring temperature range was narrowed to P+40° to P+50°F for optimum grain. Different casting configurations were poured using various alloys such as Mar-M247, IN792+HF, and IN713C. All produced a satisfactory fine grain when poured at P+40°F, so this was established as the optimum pouring temperature for the FGP. Examples of these castings compared with those made by standard production practices are shown in Figures 3 and 4.

Alloy Superheat Temperature

In many casting processes the molten metal is raised to a temperature significantly above its melting point and held for a specified time to stabilize the alloy. This superheat, often performed at P+500°F, homogenizes and takes into solution all phases including the refractory element carbides, thus removing the previous processing history of the alloy. It was found that if such a superheat process was performed, and the molten metal was allowed to cool to the P+40°F pour temperature, a coarser grain resulted. It was thus assumed that the carbides present in the original master heat contributed to the grain nucleation process. Therefore, superheat time and temperature were reduced to the minimum sufficient for complete melting of the ingot without taking the carbides into solution. Another beneficial effect of lower metal/refractory contact is the reduced potential for chemical reactions.

Mold Temperature

Initially, molds preheated to 1900°F (1050°C) were used, but a certain degree of non-fill occurred. Other molds preheated to 2000°, 2100°, and 2200°F (1100°, 1150°, and 1200°C) were tried, but larger grains were obtained at the higher temperatures. An optimum preheat temperature of 2000°F (1100°C) was selected. This temperature is compatible with conventional production casting methods enabling molds for fine-grain castings to be preheated along with conventional production castings.

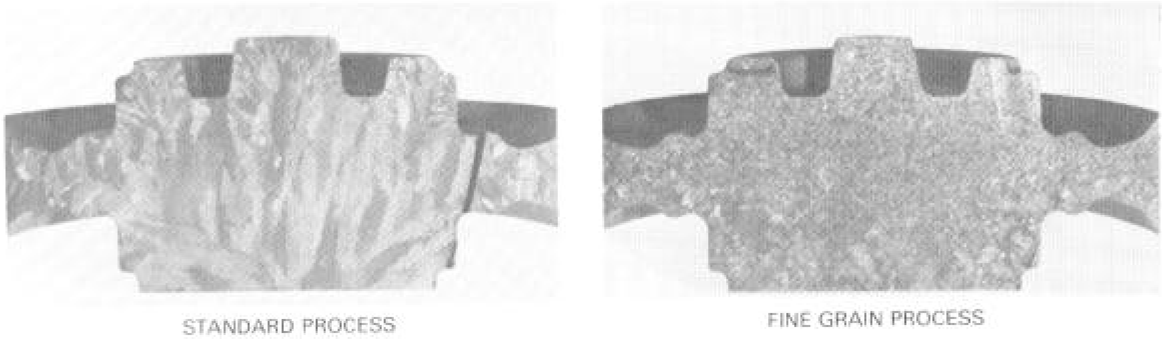

Figure 3 - Comparison of grain size of axial turbine wheel castings made with Mar-M247. (Magnification, 2/3X)

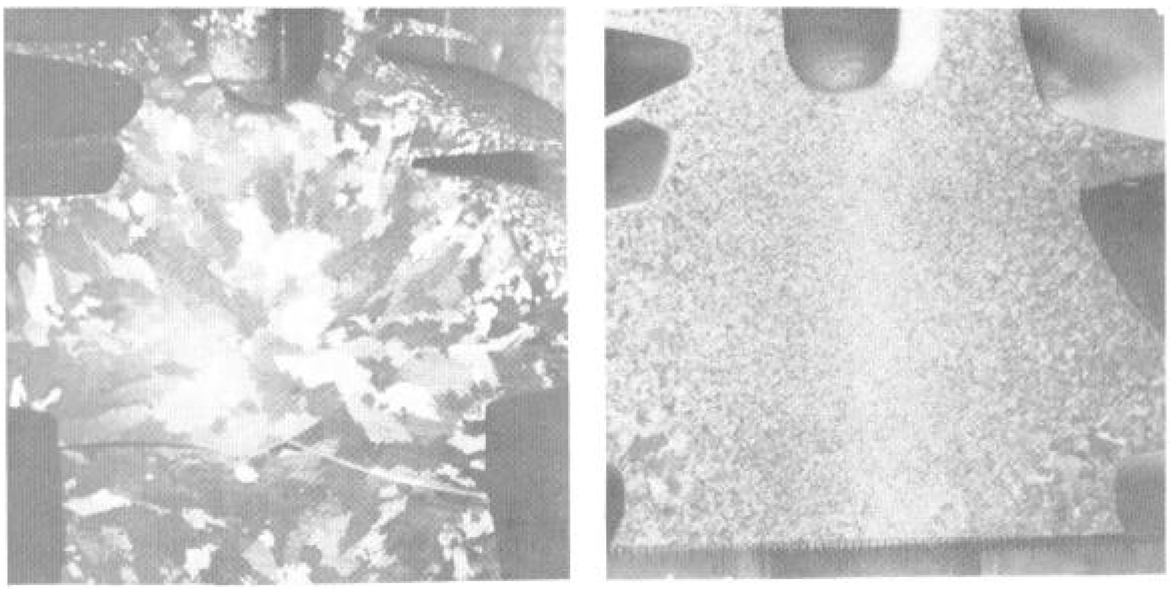

Figure 4 - Radial turbine wheels. (Left) Cast by conventional production process using IN713LC. (Right) Cast by Fine Grain Process using Mar-M247. (Magnification, 2/3X)

Coarser grains were encountered in certain sections of the FGP castings. To control the formation of these and reduce their size, local chills were installed. Localized face coats of cobalt-oxide-innoculated slurry were added to investment molds. With a constant shell preheat, localized fine grain near the casting surface can be nucleated.

Cooling Rate in the Mold

In all metal solidification processes, it is necessary to provide a reservoir of liquid metal to compensate for the contraction during the liquid-solid phase transformation. In most casting operations this is achieved by providing an additional volume of metal. Thus, the casting is sound and the last metal to solidify is in the riser (which is subsequently removed).

The time that the metal remains molten is critical to the feeding of the solidifying casting; this time is dependent on the size and location of the riser. If the time is too short, shrink could occur in the casting. If the time is too long, grain growth could occur. Thus, it is essential to control the solidification in the mold and particularly within the riser. This was accomplished in two ways: thermal wrapping or the application of exothermic material (hot top).

Certain casting configurations were thermally wrapped with Kaowool to slow down the cooling in designated areas, specifically, around the sprue (or riser) and at airfoil locations. Hot top application was the most effective method of controlling riser solidification and grain growth.

Based on the results of a development program, a rapid-burning exothermic compound was selected. It was applied to the sprue after the casting had been removed from the melt chamber. The process required careful additions of known quantities of compound at set time intervals, these latter parameters being specific to the casting being produced. Each type of casting, depending on dimension, configuration, and mass, required its own set of hot top applications. These specifications had to be established initially. Too much compound applied too soon after pouring would result in columnar grain growth; insufficient compound applied too late or infrequently would lead to microshrink. The FGP used a specially designed, larger volume sprue to provide a higher metallostatic pressure head and to ensure a larger volume of available liquid feed metal. Work is presently under way to develop a system whereby this solidification control procedure may be performed in the melt chamber using an induction coil rather than an exothermic compound. The development of such a system is particularly important to the fine grain hub/directionally solidified blade casting program.

Hot Isostatic Processing

Wheels produced by the FGP were sectioned and examined by X-ray and dye penetrant techniques. No microporosity or shrink was observed. However, when low-cycle fatigue tests were run, data scatter indicated that premature failure was occurring. Failure analysis showed that microporosity was the cause.

Numerous sections were taken and metallographic studies performed. It was found that despite all precautions, small areas of microshrink were present. It was further discovered that the smaller the casting the less the incidence of microshrink. Wheels with hub sections of 3 in.-diameter or less, were free of microporosity. However, it was felt that, due to the criticality of the low-cycle fatigue requirement, it would be preferable to hot isostatically process (HIP) the wheels to eliminate all possible microporosity. The HIP cycles used were those established by the various customers and were based on prior experimentation. After HIP cycles, the castings were given heat treatments to restore the properties as well as to satisfy the respective specification heat treatment requirements.

Evaluation

Grain Size

Using the standard P+40°F pouring temperature, grain sizes in the range of ASTM 1-2 are obtained. By contrast, the mechanical agitation process results in grains of ASTM 00. In standard production process, grains of 0.25 in. and larger are common. Table I shows the comparison for the three processes and the number of grains per unit volume.

Table I. Process vs Grain Size Relationships

Casting Process	ASTM Grain Size	Grain Diameter (in.)	Grains/cu mm
Standard Process	0.25 in. +	0.25	1
Mechanical Agitation	00	0.020	7
FGP	1-2	0.007	170

Casting Quality

Castings were subjected to standard foundry inspection techniques such as x-ray, zyglo, and dimensional and visual checks. Once the process parameters had been established, the non-fill problem was resolved and casting rejections were minimal. Numerous wheels were sectioned and examined in both x-ray and zyglo, but microshrink was not observed. However, as explained earlier, detailed metallography will reveal areas of microporosity in castings that have not been HIP cycled, and this is probably the most significant inspection problem facing the industry.

There are no satisfactory non-destructive tests that reveal the presence of internal microshrink or inclusions. X-ray, ultrasonic, and neutron radiation inspection will not reveal the presence of small imperfections in these relatively large section castings. It is imperative that strict process control be adhered to and that a fixed process be established for each casting configuration. Casting lot inspection and control are necessary, albeit expensive, methods of maintaining reproducibility and repeatability within lots.

Mechanical Properties

The major advantage of the fine-grain structure over conventional cast structures is the improvement in low-cycle fatigue life. Certain tensile properties are improved, but the predominant mode of failure in these castings is fatigue; hence, most of the testing has been in this area.

Table II shows the 500°F low-cycle fatigue results and the room temperature tensile data for a small IN713C integral casting. All tests were performed on bars cut from the hub sections after the processing described in previous sections has been performed. It can be seen that there is an approximate 30 percent improvement in fatigue life for Fine Grain Process castings as well as improvements in tensile properties.

Figure 4 shows a wheel that was conventionally cast with IN713LC. When the wheel was made as a fine grain casting using Mar-M247, there was an increase in low-cycle fatigue life of 2 to 4 times, depending on test conditions. At constant strain, conventionally cast IN713LC exhibited approximately 20,000 cycles to failure, whereas for fine grain Mar-M247, up to 80,000 cycles are fairly common. Moreover, the scatter in cycles to failure is greatly reduced with the fine grain castings; the log of standard deviation is about 0.1, compared to 0.45 for conventionally cast wheels.

Table II. IN713C Small Wheel Average Mechanical Properties

	Conventional Production Process	Mechanical Agitation Process	Fine Grain Process (FGP)
Low-Cycle Fatigue Life (N_f) cycles @ 500°F	20,000 cycles	35,000 cycles	35,000
Room Temp. Tensile			
U.T.S. (ksi)	123.0	123.0	133.0
Elongation, %	6.1	5.1	6.9
R.A., %	10.5	8.7	9.4
1800°F/22 ksi	109.8 hours	47.0 hours	97.1 hours
Airfoil Stress-Rupture	5.2% El	6.0% El	15.0% El

Conclusions

An economical process has been developed to produce integrally cast turbine wheels possessing fine grain structures in the critically stressed hub areas. This grain-control process produces castings that have superior low-cycle fatigue properties in the large center sections without detriment to the rupture properties in the airfoils. Work is currently in progress to produce a directionally solidified structure in the airfoils for improved properties, the Fine Grain Process (FGP) being quite adaptable for this purpose.

Several superalloys have been successfully cast, including those containing hafnium. The hafnium-bearing alloys are melted in a nonreactive crucible to precent the formation of hafnium oxide.

A significant achievement of the Fine Grain Process is the reproducibility of properties. Because of the problem of unreliable nondestructive testing methods, it is necessary to rely on tight process control to guarantee the consistency of castings. The Fine Grain Process produces a uniform grain and enables greater reliance to be placed on the manufacturing process.