AN OVERVIEW OF ALLOY 718 IN

LARGE STRUCTURAL CASTINGS

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Abstract

   Since its arrival in the aerospace arena a quarter of a
century ago, cast alloy 718 has become the predominant material
for large structures used in aircraft engines. It belongs to
that nucleus of superalloys which has successfully met the
material demands of high performance, high reliability engines.
Users of cast alloy 718 have benefited from continual efforts to
understand its metallurgical characteristics, processing response
and capabilities as an engineering material. The alloy has
returned millions of service hours in a predictable manner.

Introduction

Cast alloy 718 has filled the need for a low-cost material with good mechanical properties suitable for structural components, for use at temperatures up to 300°F beyond that for stainless steels or conventional titanium alloys. It possesses good manufacturing flexibility and has proven to be well suited to casting with minimal adaptation.

This paper attempts to explain how alloy 718 is regarded today through an outline of the scope of application of the alloy in structural castings and a description of the foundries' contribution towards bringing that about. Mechanical property behavior issues involved in designing with real materials - as investigated with alloy 718 - are discussed as are methods for assuring the highest levels of structure integrity in structural components. The competition with wrought 718, cast 718's nearest rival, is mentioned followed by an impression of structural castings of the future.

Alloy 718 in Large Structural Castings - Some Figures

Approximately one quarter of the weight of today's aircraft engine is made up of castings. Of that, two thirds is accounted for by structural castings, of which about three quarters is produced in alloy 718. On the CF6-80C2 engine, the smallest 718 casting is a mount bracket of weight 2 lbs. One of the largest, shown in Figure 1, weighs close to 200 lbs. and is of size 24" high and 38" diameter.
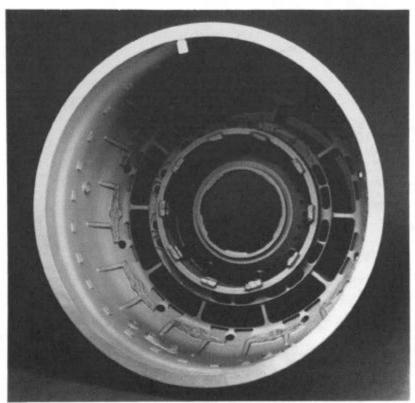

Figure 1:   Compressor Rear Frame from the type CF6-80 engine.

A typical 718 structural component may weigh 160 lbs., having been supplied as a 350 lb. casting, and having been produced from a 1200 lb. pour. Alloy cost makes up one quarter of the cost of an as-supplied casting. Hot isostatic pressing, if used, will account for up to a 25% cost increase. At the point of engine assembly, the value added by manufacturing is between 25 and 40% of the cost of the casting, depending upon part type.

Alloy 718 in Large Structural Castings - A History

The use of alloy 718 in structural castings dates back to 1964 and the TF39 turbine rear frame hub. The alternative material choice at that time was stainless steel, but the weight penalty associated with that choice ruled it out. To make the part as a wrought and fabricated 718 component would have been prohibitively expensive, thus attention was turned to making the hub, from conception, as a one-piece alloy 718 casting (1).

The late 1970's saw a dramatic increase in the application of 718 structural castings, particularly for new applications in the CF6-80 and CFM-56 families of engines. Compared with the previous generation of engines, the number and weight of structural castings per engine doubled. This was brought about partly by needs of the business, but was made successful by re-emphasis of the design-for-casting philosophy and the pursuit of that aim by members of the design and casting technology communities. The choice of material and processing route for a new or growth structural casting application is determined by several factors; most importantly, performance and reliability criteria and the need to design and manufacture components to target costs. Castings proved their value through the freedom of design allowed to frames, supports, pressure vessels and so on coupled with the reduced cost of casting complex components; Figure 2 highlights the application of the 718 structural castings in the CF6-80 engine.
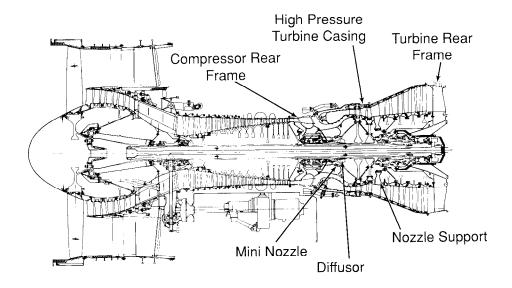

Figure 2: Applications for cast + HIP 718 in the type CF6-80 engine.

The As-Cast Microstructure

Like most highly alloyed cast nickel base alloys, 718 in the as cast condition can be highly segregated, as illustrated in Figure 3. Of relevance to the mechanical property levels that can be generated from the as cast state is the distribution of niobium within the microstructure. Niobium preferentially partitions to the interdendritic regions 5:1, where it is tied up almost exclusively as undesirable Laves phase. The slower the cooling rate of the casting section, the greater the volume fraction of Laves phase that is formed. For optimum strengthening, it is required that as much as possible, the niobium is homogeneously distributed to promote maximum γ''/γ' precipitation. This is not readily achieved through standard heat treatment because niobium has relatively low diffusivity in nickel.
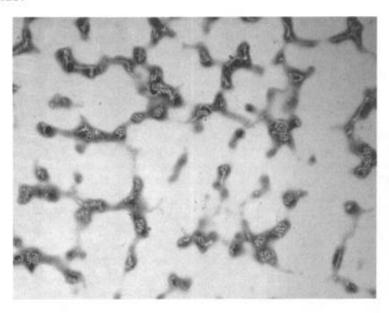

Figure 3: The microstructure of Alloy 718 - as cast, 200x

Also visible in the as cast microstructure, is the niobium-rich delta phase, which precipitates as platelets in the solid state between approximately 1950 and 1600°F. Some delta is beneficial to time-dependent properties i.e. fatigue and rupture, however it too ties up niobium and has to be solutioned to permit more γ''/γ' precipitation. For rupture, the size, shape and distribution of delta is important. MC - type carbides are observed at the grain boundaries; as discrete precipitates they impart some grain boundary strengthening.
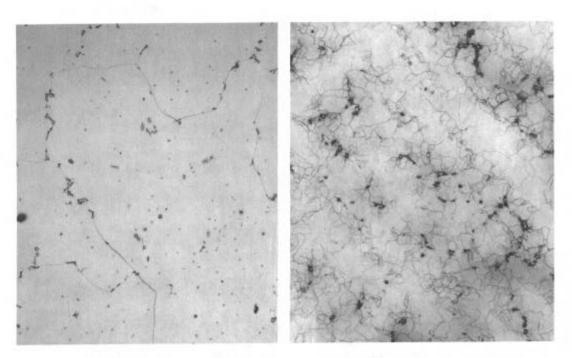
A common feature of as cast 718 is microshrinkage, which is a most critical microstructural constituent because of the potential adverse effect on mechanical properties. It forms during the liquid to solid contraction of the final few percent of liquid remaining at the local solidus temperature, i.e. between 2100 and 2200°F, and is therefore found in the interdendritic region with the Laves phase.

Sections taken parallel to the casting surface show grain
sizes ranging from .008" nominal diameter for fine grain products
to .250" nominal diameter for conventionally cast 718. The
secondary dendritic arm spacing for conventionally cast material
ranges from 40 to 100 microns. The finer the dendrite arm
spacing, the easier it will be to produce consistent and high
property levels through heat treatment.

Generating Useful Microstructures through HIP and Heat Treatment

Hot isostatic pressing causes a number of important changes
to the cast 718 microstructure. Through the HIP cycle, the
majority of delta and some of the Laves phase are taken into
solution, beginning a modest reduction in chemical inhomogeneity.
HIP closes non-surface connected voids and microshrink and also
promotes the formation of patterned γ'' precipitation on the
dislocations of sub grain boundaries, which may be useful for
post-HIP processing of castings. HIP temperature is important;
less than 1950°F at 15 ksi and void closure does not occur,
higher than 2150°F and incipient melting occurs, which can lead
to processing difficulties later on. The appearance of the HIPed
718 microstructure is shown in Figure 4.

The slow cool down from the HIP temperature promotes
non-optimized γ''/γ' precipitation, therefore a short time
delta solution and quench has to be used before aging. HIP
quench may in the future eliminate this step. Aging is intended
to produce a bimodal γ''/γ' precipitate size distribution. For
most 718 applications, the 8 + 8 hour two temperature, two stage
age can be replaced by a 5 + 1 hour treatment which uses slightly
higher temperatures. Figure 5 shows the resulting fully heat
treated, cast + HIP 718 microstructure.

Figures 4 & 5: The Microstructure of Alloy 718 as HIPed (left)
and fully Heat Treated (right), 200x

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Structural Castings - The Challenge to the Foundries

For any structural casting, the technological and engineering approach required of the foundries is one that will result in parts whose physical and mechanical characteristics have zero or minimum deviation from our expectations, that is, castings should be usable as planned. A casting user wants:

o   sound castings
o   reproducible minimum properties
o   continuance of the cost-effectiveness of castings

As a general rule, the larger and more complex the configuration, the greater the number of casting defects produced and the larger the number of defects that will not be detected with conventional NDT methods. It is also more difficult to control microstructure in a large casting of complex geometry. The success achieved by the foundries in limiting specifically microshrinkage and chemical segregation has turned out to be a critical factor in influencing the number and variety of structural castings employed in aircraft engines. Some problems with casting manufacture can be avoided depending on the extent to which the user can design the component as a castable shape.

Working with Alloy 718 in the Foundry

Alloy 718 is treated much the same way as other non-airfoil vacuum cast superalloys with regard to remelting and casting. There are no widespread techniques applied to influence solidification structure in conventional 718 castings; the melt is typically cleaned to reduce dross by superheating at approximately 2850°F and poured at between 2600 and 2750°F. Filters are customarily used to keep transfer of non-metallics from the melt to the mold at a minimum. Higher pour temperatures have been avoided because of unacceptable surface finishes produced by reaction with silica - containing mold materials and difficulty in interpreting x-ray film because of increased diffraction mottle caused by heavy microstructural segregation and large grain size.

718 was not designed as a casting alloy and only limited success has been achieved in attempts to improve its foundry response through chemistry modification control within specification limits. Formation of microshrinkage has been linked to the volume fraction of Laves phase, which would be a function of the degree of localized segregation. However, macro influences on the casting process such as section thickness and post-cast cooling rate would always dominate microstructure development and alternative means have had to be used to produce sound, shrink-free sections, for example by progressive solidification within local features. Unfortunately, these alternatives cannot alleviate the problem of segregation, specifically the niobium tied up in Laves phase.

Similarly, control of the charge mix employed for remelt stock to minimize microshrink has shown limited success. Using today's foundry technology, a negligible difference in casting quality has been observed between castings produced from virgin and virgin-revert mixtures.

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Nearly all structural 718 castings have to be reworked in order that the part meet blueprint and specification requirements. Most rework effort is expended in weld repair of casting defects; tracking of rework hours and a breaking down of rework into defect types, size and location yields much information as to the degree to which the casting method of manufacture is under control and the effectiveness of the chosen gating system in producing sound, clean castings.

Debate still continues over where in the casting manufacturing cycle HIP and in-process welding should be in order to gain the maximum benefit of HIP on the 718 microstructure and to minimize weld repair time. Proponents of welding prior to HIP claim that the HIP cycle assures closure of HAZ microfissures and avoids possible problems with outgassing, if welding after HIP. Proponents of welding after HIP cite improved hot ductility and increased chemical homogeneity, both of which might lessen significantly the cause of microfissuring i.e. grain boundary liquation.

Designing with Real Materials

Another factor that determines how successfully a material such as cast 718 can be used for structural components is the degree to which the mechanical behavior of that material is understood. We attempt to maximize the highest fraction of the alloy's full material capabilities that can be used in a given design; that fraction is governed by:

o the closeness with which mechanical properties measured through testing of samples reflect the properties of real structures, e.g. grain size effects, hold time effects and the confidence level with which those results can be applied
o the presence of defects in real structures
o inherent scatter in properties caused by chemical and microstructural inhomogeneity

Low cycle fatigue has been traditionally the principal mechanical property employed in the design of structural castings and much effort has been put into producing well characterized, statistically validated design data. The 'standard' S-N curves are based on the performance of microstructurally sound, machined and polished samples. In reality, structural castings contain flaws such as the pocket of microshrink shown in Figure 6. The effect of microshrink on LCF of cast + HIP 718 is given in Figure 7. Knowing this, it is possible to predict with greater certainty the life of a real 718 structure and hence better assure the component design.
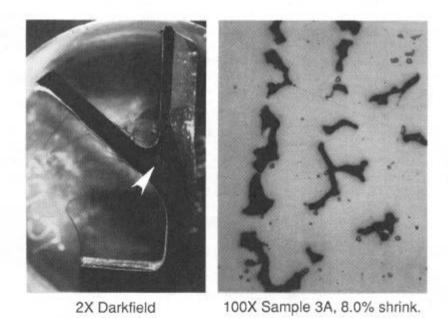
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2X Darkfield   100X Sample 3A, 8.0% shrink.

Figure 6:   Casting Microshrink Associated with Mold Hotspot.
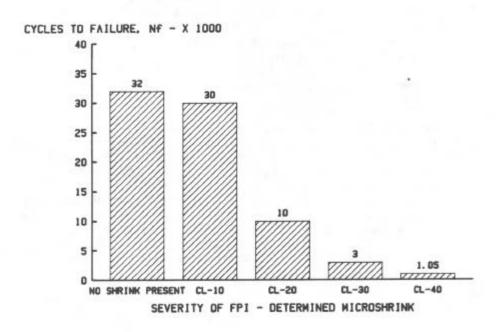

CYCLES TO FAILURE. Nf - X 1000

Figure 7:   The Effect of Microshrink on Average LCF life of
            Cast + HIP 718 Testbars at 1000F, 50 ksi, A=1.0

The alternative way to use flawed material is to repair the
flaws. However, in doing this, defects can be introduced whose
impact on properties is far more serious than with the original
flaw. How does alloy 718 fare? LCF testing of GTA welded cast +
HIP 718 showed that HAZ microcracks of the maximum size ever
likely to be encountered in production weldments not surprisingly
lowered the average number of cycles to failure compared with
standard material, but not sufficiently to impact component life
expectancy (2). When microshrinkage was eliminated in cast + HIP
718 by a new (and less expensive) repair technique, it was found
that rejectable shrink could be eliminated to yield material of
LCF capability between class-10 and -20 material thus allowing
application of the technique to non-critically stressed areas of
components (3).

Erratic Stress Rupture Behavior of Cast + HIP 718

As Figure 8 shows, cast + HIP 718 exhibits a large scatter in
stress rupture life at high stresses and between 1150 and 1250°F.
The reason for the extreme flatness of the rupture curve is not
clear and consequently no structural casting is exposed to a
stress-temperature regime where life would be rupture-limited.
The behavior may be related to the heat treat response of a
certain form of microstructure, which results in an ineffectual
distribution of delta phase around the grain boundaries and/or an
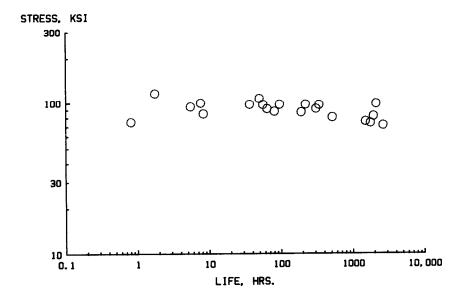interaction with oxygen.

Figure 8: The Scatter in Rupture Life for Cast + HIP Alloy 718
at 1200°F

The Application of Fracture Mechanics to
Structural Components' Design

Residual life calculation, based on for example detectable
flaw size, is applied to structural castings as part of the
design process. Much fatigue crack growth rate data has been

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developed for cast + HIP 718, most by the potential drop method. Figure 9 shows the 1000°F da/dn curve for cast + HIP 718 and upper and lower bounds for the data. The scatter observed in wrought 718 has resulted in the adoption of a design safety factor of roughly 2. For cast + HIP 718, the safety factor is 6. Note that cast 718 has the same fatigue crack growth rate characteristics and safety factor as cast + HIP 718.
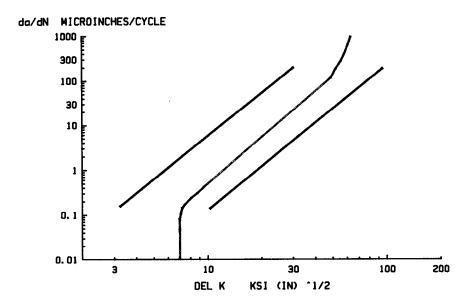

da/dN MICROINCHES/CYCLE

Figure 9: Fatigue Crack Growth Rate in Cast + HIP Alloy 718 at 1000°F, 20 cpm and A=1.0, Showing Upper and Lower Bounds

Component Integrity

The use of 718 structural castings in engine - critical applications and the consumption of property margins in the newer, higher thrust engines has necessitated the finding of ways to improve and further assure product integrity.

Twenty-five years ago, casting quality was assured through x-ray and fluorescent penetrant inspection and source substantiation (freezing) of the method of manufacture. The concept of product assurance has since been widened and the emphasis moved to superior integrity through process improvement (process control) and process innovation rather than inspection. The use of HIP to eliminate sub-surface shrink, begun in the late 70's is one example. Even so, up to one-fifth of the cost of a structural casting can be accounted for by inspection, and more powerful inspection tools have become available such as CATSCAN, or existing processes have been improved, such as pre-FPI surface enhancement procedures [1].

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[1] The ratio of shrink-type defects with and without pre-FPI enhancement processing can be higher than 5:1

Lastly, the snapshot source substantiation has become part of a total product audit plan which includes periodic destructive evaluation of castings.

The Competition with Forgings

Modern processing methods for working and machining wrought 718 have made today's forgings cost-competitive with simple casting configurations. A cast 718 component could be replaced by a wrought version if, as with a high thrust model engine, cast material property margins were exhausted and where for manufacturing reasons a simple alloy substitution to a cast material of greater strength or fatigue capability was not feasible. A cast to wrought substitution might alternatively be made for weight savings in order to increase engine performance. To illustrate the possibilities, a comparison amongst wrought and cast 718, and cast Rene'41 is given in Table I.

The Future

What of structural castings of the 1990's? They will be more complex and probably contain more thin wall, and more internal passageways than previously. The maximum dimensions will be much the same as today (sized by the 70-75,000 lb. thrust-class engines). They will need to possess greater metallurgical and dimensional consistency, they must meet the new standards for high integrity cast components and they will have to be supplied to higher dimensional tolerances.

To meet this demand, we will see an increase in the amount of engineering time put into structural castings to understand and control the processes involved in casting manufacture. This has already begun through SPC implementation, designed experimentation and, to a modest degree with structural castings, process modeling. Additionally, we will see production-scale application of new processing techniques for the production of shaped microstructures - for example fine grain and centrifugal casting, cleaner products, that is, being able to take advantage of clean alloys and ceramicless melting, and new in-process casting repair processes.

Much of the ongoing development and investigatory work by the casting suppliers and consumers respectively will involve alloy 718. This will extend its useful life for some years to come. In terms of usage by weight, alloy 718 will be the predominant alloy for structural castings of the near future. However, as our engine designs change, the number of cast 718 applications will decrease through the challenge of alternative high temperature alloys.

References

(1) R.T. Murach, private communication, General Electric Aircraft Engines, 1989

(2) B. Martin, private communication, General Electric Aircraft Engines, 1987

(3) R. Dzugan, private communication, General Electric Aircraft Engines, 1988

Table I: A Comparison of Potential Materials
for Structural Components

	Wrought 718	Cast + HIP 718	Cast Rene'41
ρ lb/in^3 @ RT	.298	.297	.298
cost $/lb @ Dec. 88[1]	-----	3.72	5.63
tmax application, °F	1100	1100	1400
E dyn x10^6 psi[2]	24-26	23-29	23-28
α x10^{-6} in/in.F[2]	8.3	8.2	7.8
T solidus, °F	2275-2300	2300-2375	2370-2400
T liquidus, °F	2450-2475	2450-2500	2430-2460
castability index[3]	-----	1.0	0.8
weldability index[4]	1.7	1.0	0.8 (after pre-weld conditioning
machinability index[5]	2.0	1.0[6]	0.8
typical material properties @ 1000°F[7]			
σ 0.2, ksi	152	107	100
σ UTS, ksi	173	121	117
EL, %	18	12	5
σ for 10^4 LCF, ksi cycles	96	90	63
σ for rupture @, ksi 200°F in 1000 hrs.	84	76	95

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1. 50% virgin/50% revert
2. Properties quoted are at 1000°F
3. Ability to fill shapes, without significant shrinkage or hot tearing
4. Ability to produce sound GTA welds under production conditions
5. Ability to attain high cutting rates with minimum tool wear in solutioned condition
6. Cast 718 has poorer machinability than cast + HIP 718
7. Wrought 718 of ASTM grain size 4