THE INITIAL YEARS OF ALLOY 718 - A GE PERSPECTIVE

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ABSTRACT

The state of the art gas turbine engine materials, at the time of Alloy 718's first announcement in early 1959 by the Huntington Alloy Products Division of INCO, are briefly described. The mechanical properties of alloy 718, as announced, are presented relative to the alloys being used then, which showed Alloy 718's promise both as a replacement alloy and as an alloy for new design. Alloy 718 was one of numerous new alloy offerings made by Industry and by internal laboratories that engine manufacturers like GE, P&W and Allison routinely evaluated. Huntington initially promoted Alloy 718 as a moderately priced air melted sheet, bar, and casting alloy suitable for high strength welded structures, however; the alloy's good strength properties to 1200F quickly led to it being evaluated for rotor forging applications as well. Early weldability tests showed Alloy 718 to be a radical improvement over any other precipitation strengthened superalloys available, which because of these alloy's weld cracking problems, was a tremendous advantage. Other producers quickly picked up on Alloy 718, aided by INCO's policy for free licensing. Because they saw advantages for double vacuum melting this became the preferred melting method within a very short time period.

At GE, the J93 (XB70 bomber engine) and the X211 (nuclear engine) provided most of the early evaluation support though they were committed to other alloys. The GE4 program (Super Sonic Transport engine) was to be a major user of Alloy 718 and funded long time (10,000 hrs.) stability evaluations, but this engine was not put into production. Alloy 718 got its real push from the GE-1 Core Engine Program (a building block development engine) in 1965 when it was selected over other candidate alloys for most of the rotor forgings as well as static structures. Alloy 718 was highly successful in this engine which was the forerunner of the TF39 (C5A Air Force Transport engine) and the entire CF6 family of commercial engines. Today Alloy 718 is used extensively in both wrought and cast forms, in engine frames, casings, exhaust nozzles, shafts, compressor & turbine disks, seals, spacers, compressor blades and vanes, and fasteners in all of GE's stable of engines.

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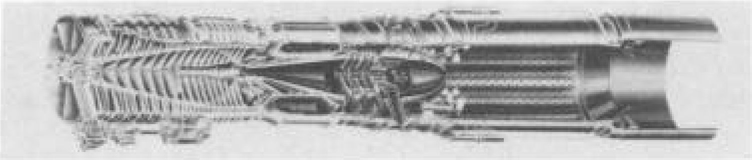
Background

In the late 50's and early 60's, General Electric's prime engine was the J79 (still in service) that utilized B5F5, A286 and V57 in rotor disks and Chromaloy and A286 in fabricated structures. Aside from hot cracking in A286 weldments and occasional notch failures in V57, there were few real material problems. With the next engine, the J93 for the XB70 Supersonic Bomber, all of this changed. Rene'41, because of its enhanced strength and temperature capabilities, replaced the above alloys in most of the rotor forgings and static structures as shown in Figure 1. Rene'41 in rotor forgings was difficult but not impossible. Rene'41 in welded fabrications, such as the turbine frame shown in Figure 2, almost became a show stopper. Strain age cracking of weldments as illustrated by the TIG weld patch test in Figure 3, was a very severe problem. It took an enormous effort and several years on the part of GE and others to understand strain age cracking and how to avoid it.

Materials Used in Early Engines



J79 Engine

Component	Compressor		Turbine	
J79 J93	J79	J93	J79	J93
Blades	40355	A286	U500/M252	U700
Rotors	B5F5	Ti7-4/A286	A286/V57	Rene' 41
Frames/Casings	Chromoloy	Rene'41	A286	Rene'41

Figure 1

J93 Turbine Frame Rene' 41

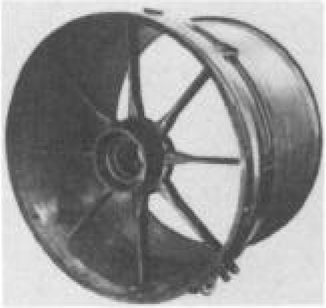


Figure 2

Examples of Strain - Age Cracking in Weld Patch Test

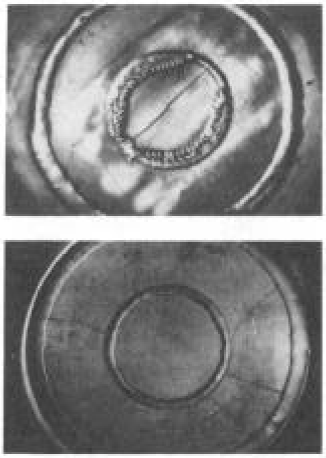
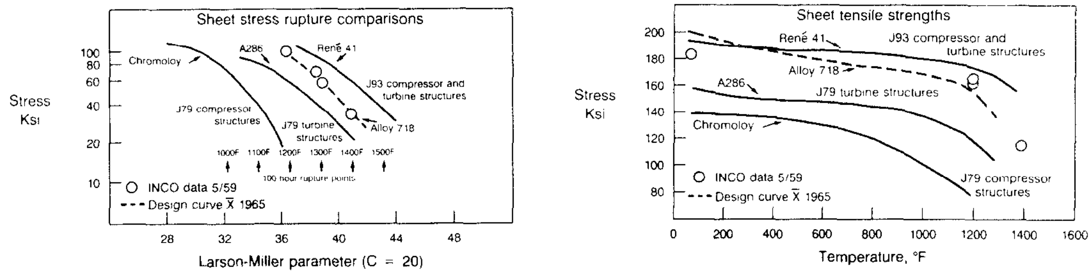


Figure 3

It was at this time that the Huntington Alloys Division of INCO introduced Alloy 718 in both wrought and cast forms. The initial data taken from an INCO introductory report dated May 16, 1959, is presented in Figures 4 and 5, respectively for sheet and castings relative to the alloys used in the J79 and J93 engines. The compositions of these alloys in comparison with Alloy 718 are given in Table I.



Sheet Rupture Properties of Alloy 718 Relative to J79 and J93 Engine Materials

Sheet Tensile Properties of Alloy 718 Relative to J79 and J93 Engine Materials

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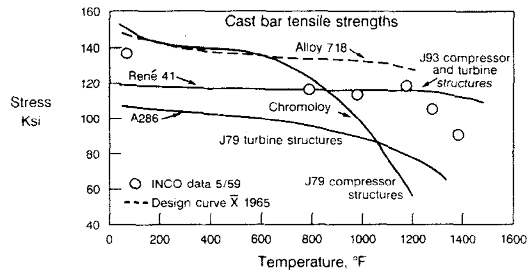
Figure 4



Cast Tensile Properties of Alloy 718 Relative to J79 and J93 Engine Materials

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Figure 5

Wrought Products

At the time of Alloy 718's release, Huntington produced sheet (cold rolled and annealed) and bar (hot rolled) from single air melted static cast ingots. It was on this product that GE performed the first mechanical property and welding evaluations that looked attractive. Because of INCO's free licensing policy, other companies quickly became involved in the evaluation programs. Latrobe Steel produced Alloy 718 bar and billet in late 1961 using an air melt electrode plus VAR process. Special Metals and Wyman Gordon followed within a year using VIM plus VAR processes. Haynes Stellite became an early producer of Alloy 718 sheet using static cast VIM ingots. Within a short while, however, the advantages of double vacuum melting (VIM plus VAR) for composition, cleanliness and structure control became apparent and this became the preferred production method. Later, ESR slab ingot practices were developed that when coupled with VIM electrodes also became one of the preferred methods for producing sheet and plate products.

TABLE I

COMPOSITION OF ALLOYS USED IN J79 AND J93 ENGINES COMPARED WITH ALLOY 718

IRON BASE			Ni/Fe AND Ni BASE SUPER ALLOYS			
ELEMENTS	CHROMOLOY	B5F5	ELEMENTS	A286/V57	RENE'41	ALLOY 718
C	0.2	0.45	C	0.04/0.08	0.10	0.04
Cr	1.0	1.0	Cr	15.0/14.75	19.0	19.0
Mo	1.0	0.55	Mo	1.3/1.35	9.75	3.0
V	---	0.3	Co	--- ---	11.0	---
Mn	---	0.55	Al	0.3/0.22	3.15	0.5
Si	---	0.30	Ti	2.1/2.95	1.5	1.0
Fe	Bal	Bal	Cb	--- ---	---	5.3
			V	0.3/0.3	---	---
			Mn	1.5/0.35	0.1	0.45
			Si	0.7/0.57	0.5	0.45
			Fe	Bal./Bal.	5.0	Bal.
			Ni	26.0/27.0	Bal	52.5
Applications	Frames Casings Castings	Disks Shafts		Frames Casings Disks Shafts Blades	Frames Casings Disks Shafts Casings	Frames Casings Disks Shafts Blades Castings
	J79			J79	J93	

Early experimental forgings were made in 1962 by Ladish and Kropp Forge from Latrobe Steel's air plus VAR billet. These forgings, 15" diameter by 1" thick pancakes by Ladish and 35 lb closed die impeller type forgings with a stub shaft on each side of a "vane" disk by Kropp, were successful in that they showed the capability to meet GE first forging specification, C50T69, that was based upon Huntington Alloy's bar stock data. This success led to forging evaluations of J79 3rd stage turbine disks, normally V57, by both Cameron Iron Works and Wyman Gordon using Special Metals and Wyman/Latrobe billet, respectively. While not an unqualified success, these studies showed excellent properties in properly worked areas and low strengths, low ductilities and notch brittleness in coarse grained areas receiving too little deformation. Confidence, however, was established that fully acceptable contour disk forgings could be made with proper development. The notch brittle problem (in stress rupture) lingered on a few years before it was reproducibly brought under control. Melting refinements to limit impurity elements like sulfur and forge processing improvements to consistently produce well worked fine grained structures have made such problems almost non existent.

Cast Products

The initial cast properties were determined on Cast To Size test bars made by the Bayonne Works of the International Nickel Co. These bars were described as being made from 25 lb. slag covered air melt heats cast in Roll-Over carbon arc furnaces under Argon cover. Shortly after, the Bayonne foundry was closed, therefore, other casting sources were sought. To this end, casting evaluation programs were initiated at Austenal, Misco, Haynes Stellite, and Arwood. These programs utilized existing investment cast tooling for strut ends and other hardware type castings used in fabricated jet engine frames. Initially, GE insisted that they follow INCO's lead in casting in air under an Argon blanket; however, all of them quickly demonstrated much better yield (freedom from Zyglo defects) by vacuum casting processes.

Mechanical property testing showed properties inferior to the wrought product as shown in Figures 4 and 5. Microstructural examination revealed Cb segregation, evidenced by large pools of dark etching Delta Phase (Ni_3Cb), throughout the castings that detracted from the strength. Subsequent homogenization studies showed that most of this disappeared with a 2000°F homogenization treatment prior to heat treatment and that strengths were improved. The Alloy 718 tensile curve plotted in Figure 5 for homogenized and heat treated specimens show this improvement over the initial data points without homogenization.

Initial Engine Programs

Huntington Alloy's property data plus their report of good welding characteristics immediately encouraged the J93 Project at GE to support design data and weldability investigations directed toward welded structures even though they were committed to Rene'41. Weld patch tests confirmed Huntington's report for good weldability and the freedom from strain age cracking susceptibility. Alloy 718 became a model to aid in the study of the Rene'41 strain age cracking problem where it was found that Alloy 718's slow response to aging was key for enabling weldments to be solution treated (thermally stress relieved) without cracking. This sluggish aging response is illustrated by the plot of hardness response to isothermal aging in Figure 6 that compares the Cb containing Alloy 718 versus Rene'41, and Astroloy that obtain their strengths due to Al and Ti alone.

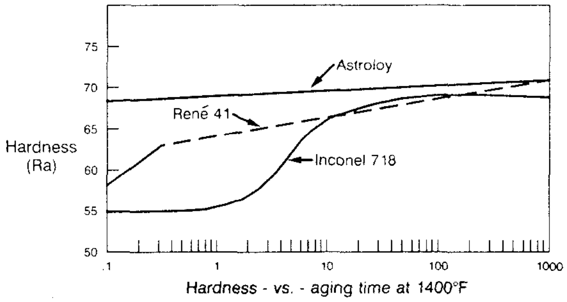


Figure 6

The J93 design was too far along for Alloy 718 to be substituted for Rene'41 in the Turbine Frame, but the Compressor Rear Frame shown in Figure 7 that operated at somewhat lower temperatures was a candidate. With only preliminary data, the outer casing skin was made from Alloy 718 sheet and the strut ends (inner and outer) and fuel inlet bosses were made from Alloy 718 investment castings. The rest of the frame was made from Inconel 722.

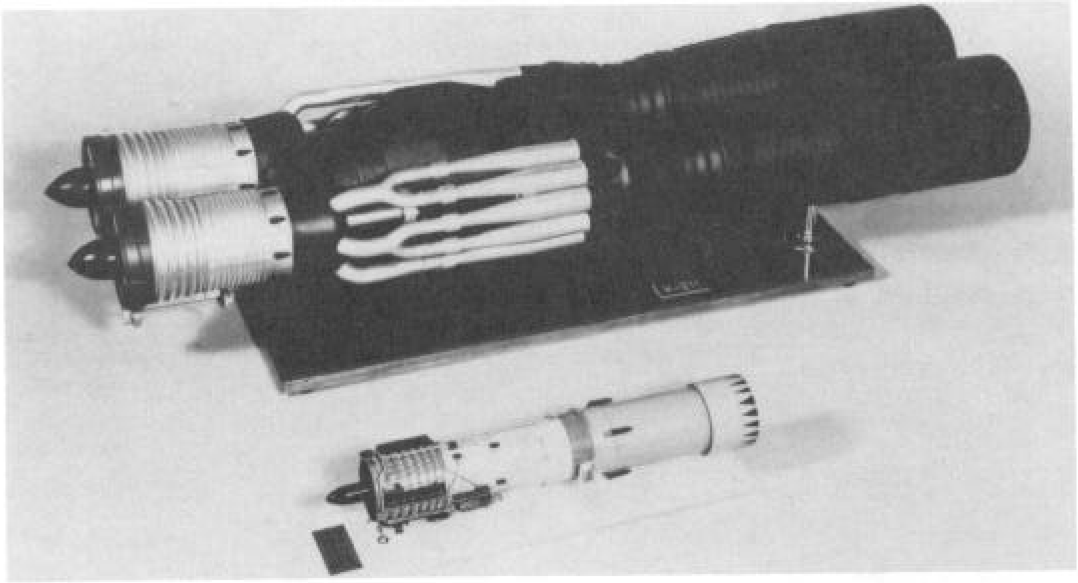
This frame proved to be much more fabricable than the prior Rene'41 frame and was successfully used throughout the balance of the short lived J93 program.

Welded Engine Frame Fabrication Prior To Machining Containing Alloy 718C Castings, Alloy 718 Outer Casing Skin and Inconel 722 Flanges, Struts, Etc.

Figure 7

The X211 nuclear engine program also provided early support. This was a huge engine even by today's standards as shown by the photograph in Figure 8 contrasting it with a J79. The frames and casings on this engine were heavy section A286 (~1/4" thick) that were extremely difficult to fabricate. Hot short weld cracking was the main problem. As such, the X211 Program sponsored design data and weldability investigations on 1/4 and 1/2" thick Alloy 718 sheet and plate, produced by Huntington Alloys. Welds were made by multipass TIG and the then new Electron Beam process. Again, Alloy 718 was free of hot cracking tendencies and much more easily fabricated than A286. Tensile property stability tests conducted on 1/4" thick sheet also indicated that the alloy seemed to have much more strength capability than originally believed. This data, presented in Table II, comparing as heat treated material using the recommended 1700F solution plus 1325F/16 hr age treatments versus material heat treated plus thermally exposed at 1200F for 200 hrs. (a summation of the worst expected conditions for the X211 components) showed that tensile strengths were increased to over 200 ksi with little reduction in ductility. This information was relayed to Herb Eiselstein at Huntington Alloys, the alloy's inventor, who found that residual strain in the heavy sheet, that would not be present in thinner gages, was responsible for the increased strength upon prolonged aging. This was a disappointment, but as a result of this investigation, Eiselstein did develop the 1325F furnace cool to 1150°F treatment, applicable to all forms of Alloy 718, that provided a more modest increase in strength. This treatment is universally used today for Alloy 718.

With the election of President Kennedy in 1960, the X211 Nuclear Engine Program was cancelled. Therefore, despite its early promise, all further heavy section fabrication work on Alloy 718 was stopped before any parts were built for this engine.



X211 and J79 Engines

Figure 8

TABLE II

EFFECT OF 1200F EXPOSURE ON TENSILE PROPERTIES OF 1/4" THICK ALLOY 718 SHEET

PROPERTY	TEMPERATURE	AS HEAT TREATED	HEAT TREATED PLUS 1200F/200 HR EXPOSURE
Tensile Strength (ksi)	RT	181.1	240.1
Tensile Strength (ksi)	1200	146.5	195.7
.2% Yield Strength (ksi)	RT	147.2	214.4
.2% Yield Strength (ksi)	1200	130.3	172.7
% Elongation	RT	21.2	19.0
	1200	9.2	8.5

The GE4 Supersonic Transport (SST) engine, a new engine program in the early 60's, sponsored long time stability testing of three candidate disk alloys preliminary to alloy selection. The alloys were Rene'41, Astroloy as well as Alloy 718. In this program, test material from disk forgings were creep-rupture tested at stresses intended to produce lives to 10,000 hrs. The stresses chosen for the longer lives were based upon projections from shorter time tests using the Larson Miller (C=20) parameter. This method was reasonably accurate for Rene'41 and Astroloy but under predicted Alloy 718 in the 1000 to 1200°F range where actual lives exceeded 30,000 hrs. A stress versus life plot of the data is shown in Figure 9. A subsequent data analysis showed that a LM constant of 25 provided a better data fit, Figure 10. Thus, the creep-rupture stability exhibited for Alloy 718 in this temperature range was better than current alloys of the time and was considered a plus for design of long life engines. Residual strength and ductility properties also were not impaired by this kind of exposure.

Log-log Plot of Alloy 718 Stress Rupture Strengths

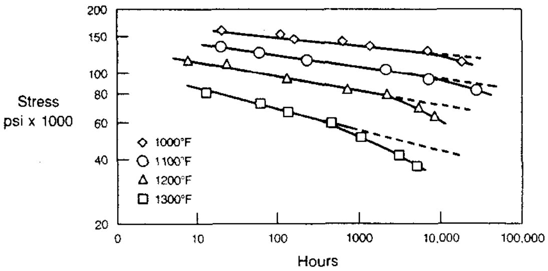


Figure 9

Alloy 718 Stress Rupture

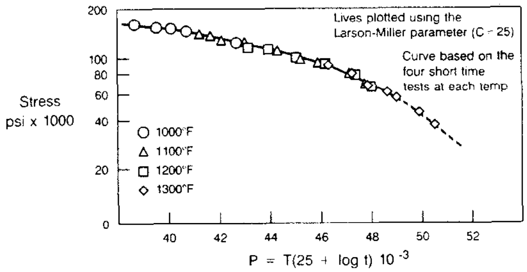


Figure 10

Production Application

By early 1965, design data, fabrication, and property and structural stability evaluations had been successfully completed on Alloy 718, but with the exception of a few J93 compressor rear frames, where only a portion of the frame was Alloy 718, there were no volume applications. In 1965, however, work began in earnest on two new engines; (1) The GE-1, a building block demonstration engine that was to become the core of the TF39 (for Air Force C5A Heavy Transport) and the CF6 commercial family of engines and (2) the GE-4 Super Sonic Transport (SST) engine that had earlier sponsored the long time stability work. Alloy 718 was immediately chosen for static structure fabrications in both engines but there was still an internal competition going on for the critical rotor forgings. Astroloy was chosen for the GE4 high pressure turbine disks for temperature reasons. For the rest of the GE4 and all of the GE1 superalloy rotor forgings, there were two other candidates in addition to Alloy 718 that were under consideration. They were:

- Udimet 630, a Special Metal developed alloy similar to Alloy 718 but having a higher Cb content.
- CG27, a joint Crucible Steel-GE nickel/iron superalloy that was an extension of A286 technology.

All three alloys had comparable strengths in the 1000 to 1200F temperature range though Udimet 630 was considerably stronger at RT. CG27, while cheaper than the other two because of lower raw material costs, was eliminated because of poor property stability where half its ductility was lost after 1200F/1000 hr exposure. Alloy 718 was eventually chosen over Udimet 630 mainly because of its widespread availability and extensive data base compared to Udimet 630 that was single sourced and its characteristics relatively unknown.

This decision, made in January of 1965, committed GE and the industry to focus a significant part of their energies and resources over the next decade to make Alloy 718 work in all of its forms and to become the backbone of the superalloy business. The application of Alloy 718 in the GE4 was successful in that all of the components (forged disks, shafts, frames, casings, compressor blades and vanes et al) were produced with a minimum of difficulty and performed well in the engine. The program, however, was stopped by the Government after only a few engines were built. Alloy 718 in the GE1 Program was equally successful in all of its component applications, but in contrast to the GE4 program, this program led directly to the highly successful TF39 Military, CF6 Commercial Aircraft, and LM2500 and 5000 Marine and Industrial engine programs that are still going strong today.

In addition to the above engines, Alloy 718 is used in major amounts in all its forms in the following GE engines:

F101
F110
F404
TF34
T700
CT7
CFM56

The relative amounts of Alloy 718 used in a typical CF6 commercial engine is shown below: where 48% of the material input weights are nickel base superalloys and 71% of this amount is Alloy 718.

Relative Material Input Weight

Material	Percentage
Ni Superalloys*	48%
Ti Alloys	25%
Steels	16%
Aluminum	8%
Composites	4%

*Alloy 718 alone is 34% of the total

In terms of Alloy 718 forms used in this engine, 82% is in forging billet, 12% is bar and sheet, and 6% castings.

Summary

At the time of Alloy 718 introduction, there was an urgent need for an improved superalloy for aircraft gas turbine engines. The increasing temperatures and stress requirements of the new engines clearly out stretched the capabilities of the materials then in use. Alloy 718 was one of numerous offerings at the time, both external and internal, that was investigated to fill this need. In the course of about five years, these materials competed, as it were, with one another against a set of rapidly evolving criteria until Alloy 718 emerged the winner. In addition to its outstanding capabilities, Alloy 718 was given a great advantage over its competitors by INCO's free licensing policy which enabled everyone to participate on an equal footing. As such, the resources of the whole superalloy community, both producer and user alike, as well as universities and government laboratories were concentrated and brought to bear in making Alloy 718 a mature engineering material. When this happened, the applications and production literally exploded and Alloy 718 became the alloy of the Gas Turbine Era as evidenced by this Symposium.