EFFECT OF CHEMISTRY AND PROCESSING ON THE STRUCTURE AND MECHANICAL PROPERTIES OF INCONEL ALLOY 718

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Abstract

Alloy 718 has been utilized in gas turbine engines for almost 30 years because of its extremely good mechanical properties.[1-3] Over the years the property levels attained with the alloy have been increased by altering the thermomechanical history as discussed by Loria.[5] The chemical composition range for the alloy has remained relatively stable over the years, although there has been a tightening of the columbium range along with tighter control of minor elements such as magnesium and sulfur. Recently there has been interest in the stabilizing of γ'' by adjustments of aluminum, titanium, and columbium.

Superalloy 718—Metallurgy and Applications
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The Minerals, Metals & Materials Society, 1989

Introduction

As Alloy 718 has been upgraded, the influence of thermomechanical processing has become even more important, and as the schematic shown in Table I indicates, each step is important and the effects are cumulative.

Table I - Property/Process Schematic

Property/Process Step Showing Interdependence	Some of the Properties/Process Variables of Interest
Mechanical Properties	Tensile, Creep/Rupture, LCF, etc.
=	
Metallurgical Structure	Grain Size, γ, δ, Dislocations
=	
Heat Treatment Procedure	Time, Temperature, Cooling Rate
+	
Forging Procedure	Strain, Strain Rate, Temperature
+	
Consolidation	Strain, Strain Rate, Temperature
+	
Remelting	Arc gap, Current, Voltage, Cooling
+	
Vacuum Melting	Refractories, Leak Rate
+	
Chemistry	Cb, Ti, Al, Mg, S, Ni, Fe, Cr, Mo

Because of space limitations, this paper will only discuss the relationship of room temperature yield strength with metallurgical microstructure, processing history, and alloy chemistry for direct aged Alloy 718 which is the most process dependent of the commercial grades.

Effect of Structure on Yield Strength

As shown in Table I, the room temperature yield strength is controlled by such microstructural variables as grain size, γ'' and δ precipitation, and dislocation density. The relative effect of each of these variables is important as it determines what thermomechanical and chemistry variables must be controlled.

In the case of direct aged Alloy 718, the effect of γ'' resulting from the aging treatment can be eliminated by studying the variation of yield strength in the unaged condition. The effects of the other variables can be at least partially isolated by heat treating the as forged structure. Heating to 927°C removes the dislocation strengthening effect on yield strength. Heating to 996°C removes most of the effect of δ precipitation and increases grain size. Heating to 1065°C gives the base strength of the alloy and results in a very large grain size. When one plots the yield strength of samples treated as above, the result is the yield strength versus grain size plot shown in Figure 1. This indicates that grain size plays a very large role in determining yield strength of the alloy.

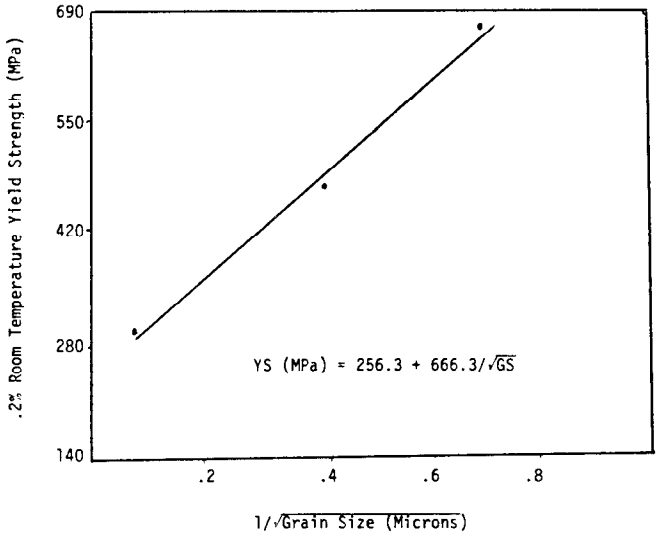

Figure 1 - Room Temperature Yield Strength Variation as Function of Grain Size in Alloy 718 in Unaged Condition.

Carrying this a step further, material forged at various temperatures, strain rates, and strains can be studied to see if the above correlation holds in the as forged and/or direct aged conditions.

The yield strength data from samples in the as forged state is plotted in Figure 2 along with the data from Figure 1. It can be seen that the same regression equation holds, and that grain size is again controlling the strength in the as forged state.

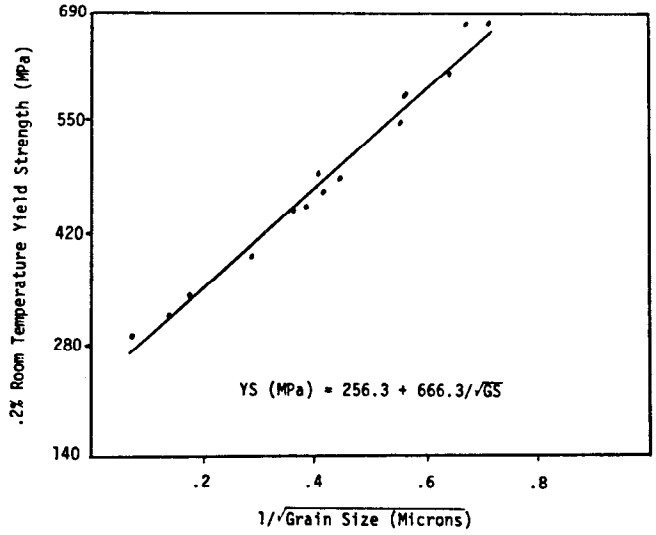

Figure 2 - As Forged Room Temperature Yield Strength as Function of Grain Size.

Similar data for some of the forgings of Figure 2 after direct aging to precipitate γ'' is shown in Figure 3. A straight trend line has been drawn through some of the data, but it can be seen that with fine grain, the yield strength is below the line and there is much scatter in the results. In general, this data shows that the contribution of γ'' to the strength is about 750 MPa, but with fine grain size the contribution can decrease. This is due to the precipitation of δ which consumes part of the columbium that could participate in the γ'' reaction. Quantitative extraction of the δ phase allows one to develop the regression equation shown in Figure 3 which takes into consideration this precipitation.

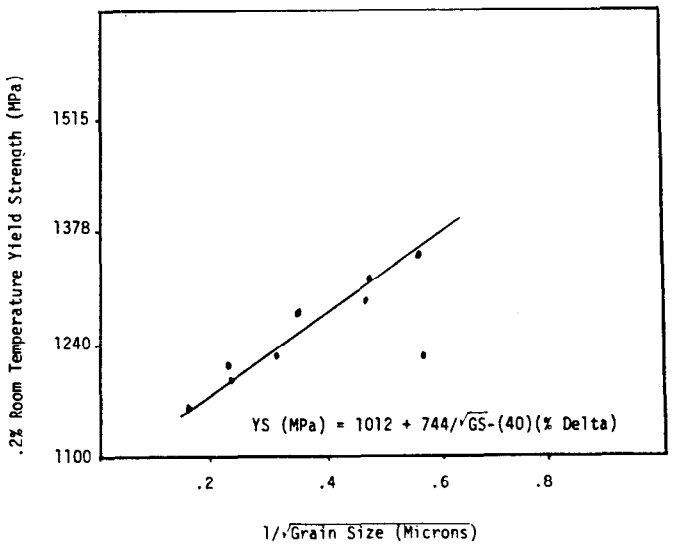

Figure 3 - Direct Aged Room Temperature Yield Strength As Function of Grain Size.

Engine builders are now concerned as much with the scatter in mechanical properties as they are in meeting the minimum mechanical property requirement. They tend to design to average property values minus two sigma or minus three sigma to be conservative with their design. The consequence of this is that the part manufacturer must be as concerned with the reproducibility of properties as well as just meeting the specification minimum. As an example of what this can mean to the forger, Table II shows room temperature yield strength data for samples taken from forgings made from two billets of Alloy 718 forged as identically as possible. It can be seen that the level of properties in the as forged and direct aged conditions differ by some 70 MPa, and it can be shown that this is directly related to a variation in grain size. It is important for the forging vendor to understand the causes for such variations in order to minimize property variation.

Table II - Room Temperature Yield Strength of Similar Forgings From Two Billets of 718

Pancake	Condition	.2% Yield (MPa)
1	As forged	558
1	Direct Aged	1350
2	As forged	496
2	Direct Aged	1274

The macro chemistries of the above two forgings are shown in Table III along with the generally accepted specification minimum and maximums for the elements shown. It can be seen that the elements are all well within the specification, and the "hardeners" are almost identical. The major differences are in the nickel, iron, and chromium contents. The balance of this paper will discuss the effects of these differences.

Table III - Billet Chemistries

Pancake	C	Cr	Ni	Mo	Ti	Al	Fe	Cb
1	.032	18.05	53.15	2.98	.98	.52	18.00	5.29
2	.037	17.71	52.52	3.30	.97	.56	19.36	5.32
Minimum	.02	17.00	50.00	2.80	.85	.40	15.00	5.25
Maximum	.05	21.00	55.00	3.30	1.15	.70	21.00	5.50

Effect of Chemistry on Structure of Alloy 718

During the development of Alloy 718, literally hundreds of chemistries were examined for mechanical properties and metallurgical phases. The results of these unpublished investigations are critical to the understanding of the effects of each element on each step of the thermomechanical processing and resultant structure and properties.

The basic cast structure of Alloy 718 has been the topic of numerous publications over the years. The typical cast structure of Alloy 718 is shown in Figures 4 and 5. It consists of a dendritic structure with the interdendritic channels containing the ternary eutectic phase laves (A_2B).

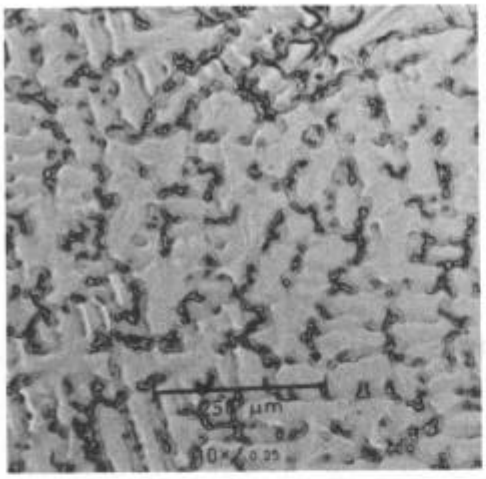

Figure 4 - Cast Structure of Alloy 718.

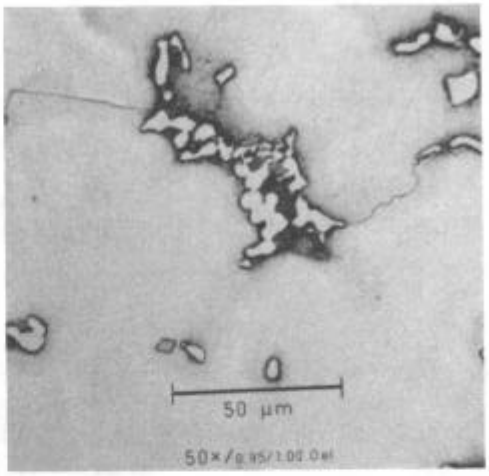

Figure 5 - Higher Magnification of Figure 4.

One can better understand the solidification mechanics of the alloy with the help of electron probe studies. A quantitative model of the cast structure can be developed by analyzing a large number of randomly selected 20 square micron areas. Six such analyses from a 200 area study are shown in Table IV. This type of data can be analyzed in several ways to study the effect of casting parameters, base chemistry, and thermomechanical processing.

One method of data analysis is to look at the statistical distribution of each element shown in Table IV and see how they are affected by processing and chemistry changes. The mean value, standard deviation, and minimum and maximum values for each element are listed in Table V. As can be seen, the elements vary quite drastically in the cast structure. Of particular note is the large standard deviation for columbium.

Table IV - Selected Microprobe Analysis of 20 Micron Square Areas

	Percent of Element								
Area	Mn	Fe	Ti	Al	Si	Cb	Mo	Cr	Ni
4	0.35	17.94	0.66	0.77	0.22	2.45	2.84	19.76	54.05
23	0.43	14.93	1.19	0.72	0.41	6.82	3.43	17.55	53.17
63	0.40	14.94	1.17	0.70	0.42	7.05	3.43	16.95	52.35
91	0.35	17.83	0.62	0.71	0.20	2.21	2.74	19.42	53.46
93	0.38	12.75	1.29	0.52	0.80	12.80	4.27	15.11	49.13
95	0.39	15.66	1.03	0.75	0.26	4.65	3.02	18.24	53.45

Table V - Statistical Analysis of a 200 Area Sample

	Percent of Element								
	Mn	Fe	Ti	Al	Si	Cb	Mo	Cr	Ni
Mean	0.37	16.48	0.89	0.73	0.30	4.48	3.06	18.51	53.12
Std. Dev.	0.03	1.55	0.26	0.05	0.14	2.72	0.40	1.23	1.13
Min.Value	0.31	12.75	0.53	0.52	0.15	1.59	2.45	15.11	48.60
Max.Value	0.43	18.77	1.66	0.82	0.82	12.80	4.55	20.07	54.41

A second way to utilize the data in Table IV is to determine how one element varies with another. This is a key to understanding solidification behavior and the effect of changes in composition on segregation. Table VI shows a partial correlation coefficient matrix for the cast structure of Table IV. A correlation coefficient of plus one would indicate that one element segregates perfectly with the second element while a coefficient of minus one indicates perfect inverse segregation. For example, the correlation coefficient between Cb and Ti is .88. These results show a strong tendency for Cb, Si, Ti, and Mo to segregate together while Cr, Ni, and Fe tend to segregate together. These first two methods provide a quantitative measure of the effects of remelting parameters and thermomechanical work on the homogeneity of the material. This will be discussed later.

Table VI - Interelement Segregation Coefficients

Element	Partial Correlation Coefficient Matrix							
Fe	-0.77							
Ti	0.84	-0.94						
Al	-0.03	0.59	-0.40					
Si	0.58	-0.90	0.81	-0.73				
Cb	0.65	-0.95	0.88	-0.69	0.95			
Mo	0.66	-0.88	0.80	-0.58	0.92	0.89		
Cr	-0.64	0.95	-0.89	0.71	-0.92	-0.97	-0.84	
Ni	-0.43	0.85	-0.72	0.84	-0.91	-0.89	-0.80	0.90
	Mn	Fe	Ti	Al	Si	Cb	Mo	Cr
	Element							

A third way to display the data is in the form of a pseudo binary or pseudo ternary isotherm. If the Ni and Fe + Cr contents of Table IV are plotted on a pseudo ternary diagram as shown in Figure 6, a straight line results. This line points to the composition of laves as shown in Eiselstein's work which was obtained by electrolytically isolating a freckle containing laves. This type analysis allowed the construction of the pseudo binary shown in Eiselstein's paper as shown in Figure 7.

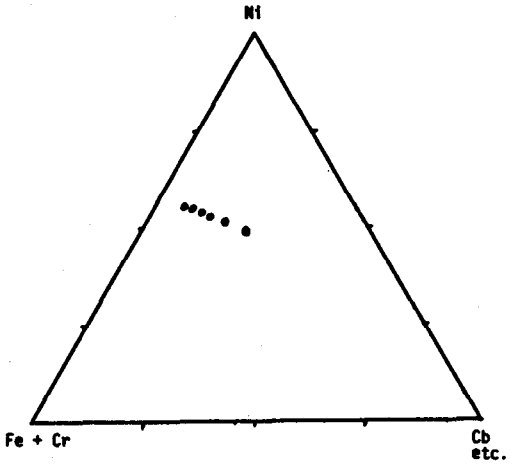

Figure 6 - Pseudo Ternary Diagram for Probe Data of Table IV.

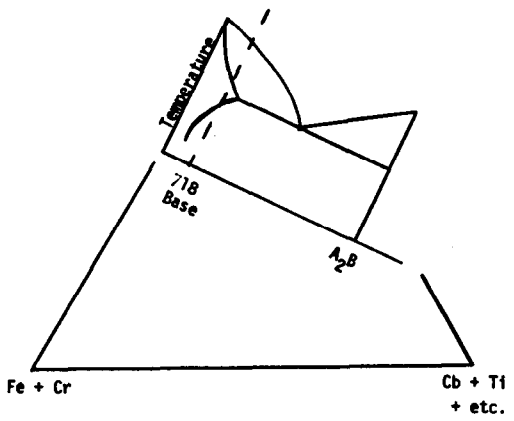

Figure 7 - Pseudo Binary Slice for Alloy 718.

The development of TTT diagrams, one of which is shown in Eiselstein's paper, then allows the construction of pseudo ternary phase diagram isotherms such as shown in Figure 8 to picture the effect of the various elements on the phases seen in Alloy 718. As the years have progressed people have raised the nickel aim points, and as can be seen from the pseudo ternary, this can have the effect of moving from a three phase field into a two phase field, particularly if segregation is present. It can also effect the thermomechanical processing temperature on δ precipitation and grain size.

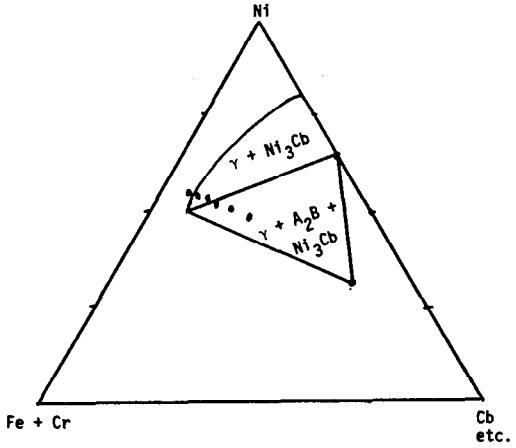

Figure 8 - Pseudo Ternary Isotherm for Alloy 718 Type Alloy.

Over the years extensive work has been done on remelt parameters, homogenization, and billet processing to reduce the amount of segregation in the alloy. Segregation analysis done on typical present day fine grained billet in the same manner as for the cast structure of Table V is shown in Table VII. The statistical analysis of the variation of columbium is particularly impressive when compared to the cast structure value of Table IV.

Table VII - Statistical Analysis of 200 Area Sample of Fine Grain Alloy 718 Billet

Element	Cr	Ti	Mo	Fe	Cb	Al	Ni
Mean	18.63	0.94	2.93	18.15	4.86	0.75	52.67
Std. Dev.	0.25	0.02	0.04	0.11	0.08	0.02	0.36
Min.Value	17.95	0.88	2.82	17.72	4.62	0.70	51.44
Max.Value	19.13	1.02	3.03	18.42	5.09	0.86	53.25

The partial correlation coefficient matrix in Table VIII shows almost random variation of all elements with one another. In effect a very homogeneous billet has been produced.

Table VIII - Interelemental Segregation Analysis for Fine Grain Alloy 718 Billet

	Partial Coefficient Matrix					
Ti	-.25					
Mo	.09	.23				
Fe	.42	-.48	-.29			
Cb	-.17	.44	.30	-.62		
Al	.57	-.08	.11	.07	.16	
Ni	.67	-.02	.25	-.04	.28	.62
Element	Cr	Ti	Mo	Fe	Cb	Al

Once the homogeneity of the billet is established by such techniques, the effect of base chemistry on thermomechanical processing can be established. Figures 9A through 9D show the effect of nickel content of the alloy on the delta precipitation. In the as received condition, the amount of delta as measured by quantitative electrolytic extraction, is independent of nickel content. This results from the variation in billet production. Heating the billet to 968°C for 16 hours is a great equalizing treatment since it is enough below the δ solvus that all compositions produce about the same amount of δ. Heating the same billets to 982°C and 996°C for 16 hours accentuates the effect of nickel on the δ solvus of the alloy.

Mechanical properties shown in Table II can now be accounted for in terms of the effect of Ni content on δ solvus and grain size. This is particularly important to the forger of direct aged 718 because the forging operation is normally done with the billet heated at 1775-1825°F. This effect of nickel on the δ solvus grain size and property scatter is illustrated by the data in Table II for the two experimental forgings described previously. This type scatter in properties can be disastrous.

This is not to say nickel content is the only variable effecting yield strength or other properties. A book would be required to discuss all of them. It does, however, show how the effect of minor changes in chemistry well within the specification must be isolated to enable the property control now required by the jet engine builders.

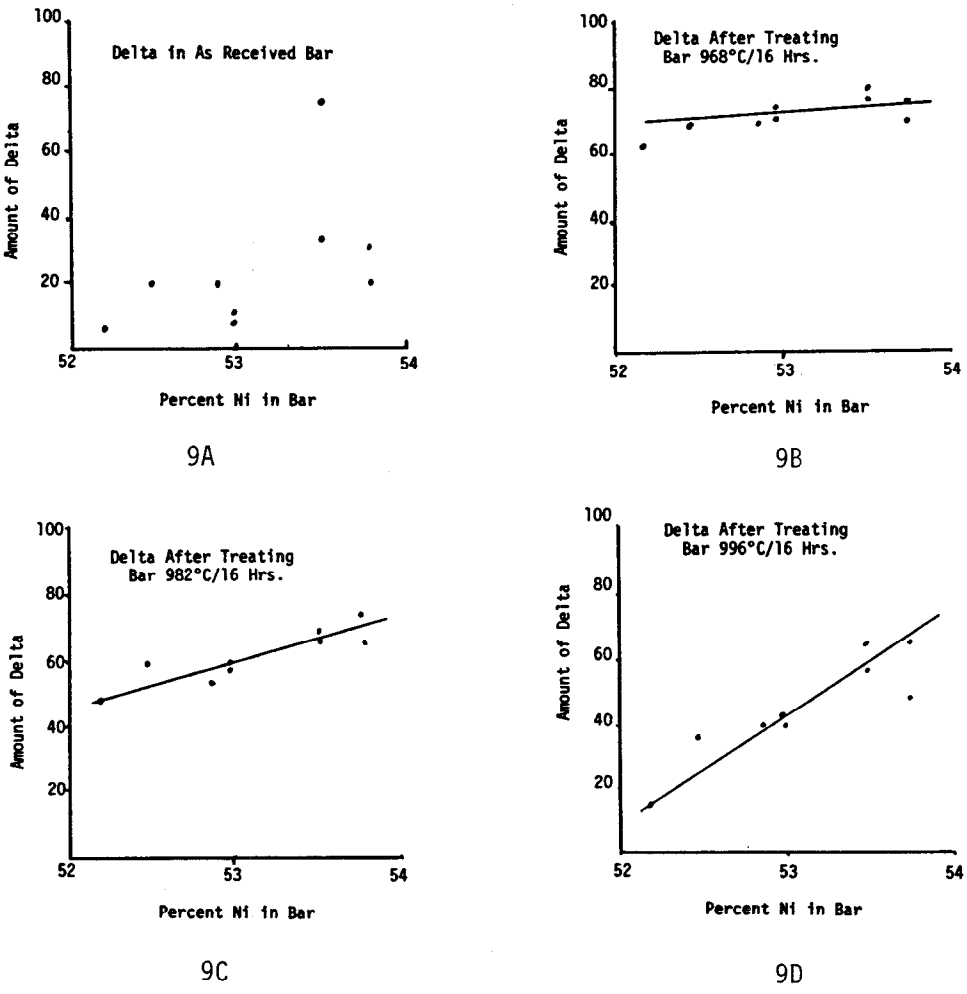

Figure 9 - Variation of δ in 718 Billet With Bulk Ni Content.

Summary

This paper only presents the effect of one element, nickel, on the structure and tensile properties of alloy 718. Many other element combinations have equally important effects on tensile and other properties. For example, the effects of aluminum content on the structure of gamma prime, the optimum aging treatment, and tensile properties are discussed for sister alloy 706 in the 1972 publication by D. A. Wells and myself.[4] This also applies to alloy 718.

A second area not covered is the effect of deoxidation practice on stabilization of sulfur as MgS or CaS. These have drastic effects on 1200°F ductility and notch stress rupture ductility.

The most interesting observation to me is that these relationships are still being explored after the alloy has been in production for thirty years. It appears we will never understand all these relations.

References

1. H. L. Eiselstein, American Society of Testing Materials, Special Technical Report, 1965, No. 369.

2. H. J. Wagner and A. M. Hall, DMIC Report, 1965, No. 217.

3. W. J. Boesch and H. B. Canada, "Precipitation Reactions and Stability of Ni_3Cb in Inconel Alloy 718", Journal of Metals, October 1969, 34-38.

4. E. L. Raymond and D. A. Wells, "Effects of Aluminum Content and Heat Treatment on Gamma Prime Structure and Yield Strength of Inconel Nickel Chromium Alloy 706", Superalloys 72, Proceedings of Second International Symposium, ASM (1972), N1-N21.

5. E. A. Loria, "The Status and Prospects of Alloy 718", Journal of Metals, July 1988, 36-41.