Elemental Effects on Cast 718 Weldability

Boron, an essential element in Alloy 718, appears to cause the most detriment to weldability, creating a dilemma for improvement

BY. T. J. KELLY

ABSTRACT. In order to reduce the cost of gas turbine engines, the aerospace industry has gone to extensive use of investment castings in place of fabricated machined components. Alloy 718 is a commonly used cast alloy intended for 482° to 649°C (900° to 1200°F) service. Though Alloy 718 was developed to be free of the strain age cracking phenomena present in most nickel-based superalloys, it still is prone to microcracking in the heat-affected zone (HAZ) of weldments. In the wrought form, this can be controlled by limiting its grain size to ASTM 6 or finer, but such a small grain size is difficult to achieve in investment castings. Therefore, a great deal of work has been performed to determine the origin of the microcracking problem. Most of this work has centered around the effects of tramp elements, such as sulfur. This paper demonstrates that the microcracking problem with cast Alloy 718 is due to its principal alloying elements and is judged to be unavoidable without a major change in alloy chemistry. The primary cause of microcracking in cast Alloy 718 is the boron content followed by the iron and columbium content, all of which are required alloying elements. The current tramp element range is more than adequate to prevent elements such as sulfur and phosphorus from influencing weldability.

Introduction

The first nickel-based superalloys to be invented were based on the precipitation of gamma prime (Ni_3Al or Ni_3Ti), which depended on the Al plus Ti content of the alloy. This precipitation reaction is very effective, but also very rapid. It can occur in the heat-affected zone (HAZ) of weldments during the cooling process. When the gamma prime reaction occurred in the HAZ during cooling or on subsequent reheating after welding, it caused cracking in the HAZ known as strain age cracking.

H. Einselstein (Ref. 1) of Huntington Alloys invented a new superalloy in 1962 that was based on a much slower precipitation reaction known as the gamma double prime reaction (Ni_3Cb). This alloy, with its much slower precipitation reaction, avoided the strain aging phenomenon and was heralded as the first weldable nickel-based superalloy. It still suffered from HAZ microcracking of undetermined origin, but it was determined through experience that this could be prevented by maintaining a controlled grain size of ASTM 6 or finer.

At about the same time as the discovery of microcracking in the HAZ of Alloy 718 weldments, but not solely due to the discovery of microcracking in Alloy 718, a great deal of research was focused on the HAZ microcracking problem in wrought nickel-based superalloys (Ref. 2). Pease (Ref. 3) published a list of elements and their effects on weldability. This list is shown in Table 1, and shows Cb to be beneficial to weldability (presumably because it did not cause strain age cracking). It also shows boron (upper limit 300 ppm) and other tramp elements such as sulfur to be harmful. About the same time, Owczarski (Refs. 4, 5) and Shira (Ref. 6) had determined liquation of grain boundary CbC could cause microcracking in the HAZ of superalloys due to the presence of various minor elements, such as sulfur. The work of Pease, Owczarski and Shira basically resulted in current tramp element specifications for welding of nickel-based superalloys.

Recent work by Baeslack (Refs. 7, 8), Thompson (Refs. 9, 10) and Kelly (Ref. 11) focused on the problem of microcracking in cast Alloy 718. A typical HAZ microcrack from a cast 718 weldment is shown in Fig. 1. Baeslack showed that the constitutional liquation of both CbC and the liquation of a Nb-rich Laves phase contribute to HAZ liquation and microcracking. Thompson theorized that minor element segregation due to heat treatment was the cause of microcracking. Kelly showed that the cause of HAZ microcracking in a generic nickel-based superalloy (based on Alloy 718 but containing cobalt) was associated primarily with boron content exacerbated by the Cb and iron content.

When Alloy 718 was originally developed, it was intended to be used as a wrought alloy. It was not until many years later that the gas turbine industry began using it as an investment casting alloy. In the investment cast form, the microstructure of the alloy is greatly different than in the wrought form—Fig. 2. Generally, the Cb content concentrates in the low-melting Laves phase (Ni_3Cb) eutectic forming at the interdendritic sites and along grain boundaries. The Cb will also segregate to form carbides (CbC).

Due to the relative immobility of the larger Cb atoms in the Ni lattice, it is difficult to really homogenize the cast structure using only thermal cycles; therefore, it should be expected that the welding metallurgy of the system would

Table 1—List of the Effects of Alloying and Tramp Elements on the Weldability of Nickel-Based Superalloys Compiled by Pease

Beneficial	No effect	Variable	Harmful
Nb	Mn	Al	Pb
Mg	Cu	Ti	S
–	Cr	C	P
–	Fe	Mo	Zr
–	Co	Si	B

KEY WORDS

Cast Alloy 718
Alloy 718 Weldability
Tramp Element Effects
Element Effects
Investment Castings
Boron/Microcracking
Specification Limits
Tensile/Stress
Statistical Matrix
20-Run Matrix

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change in going from wrought to cast form. In fact, Radavich and Carlson (Ref. 12) have shown that even though the Laves phase can be solutioned into the matrix, and carbides can be reduced, the elemental segregation diminishes very little. This results in a microstructure that appears optically homogeneous, but is actually almost as segregated as the original casting and prone to the formation of low-melting phases and regions during the welding thermal cycle.

Experimental Procedure

The concept of weldability in this study was the ability to resist HAZ microcracking during fusion welding. This was measured by the number of cracks and the total crack length produced in a 2% augmented strain Spot Varestraint test.

In order to evaluate the effects of both alloying and tramp elements on the weldability of cast Alloy 718, a statistically designed matrix (Plackett-Burman 20-run design) was employed. This matrix consisted of 20 heats of 718 melted to the compositions shown in Table 2. The elements evaluated in the matrix were C, Si, S, P, Cb, B, Fe, Mo, Hf and Zr. Additionally, one column in the matrix was used to evaluate the effect of heat treatment on Alloy 718 weldability and on tramp element response to heat treatment.

The 20-run matrix used in this evaluation of the elemental effects of cast Alloy 718's compositional specification on its weldability is a statistically designed and balanced matrix. This matrix insures that as many high levels of each variable are analyzed as the number of low levels and that no combinations are repeated in a manner that will skew the final analysis. As a result of analyzing the results of an experiment using this approach, all first-order effects from the variable being analyzed can be determined to a known statistical confidence level.

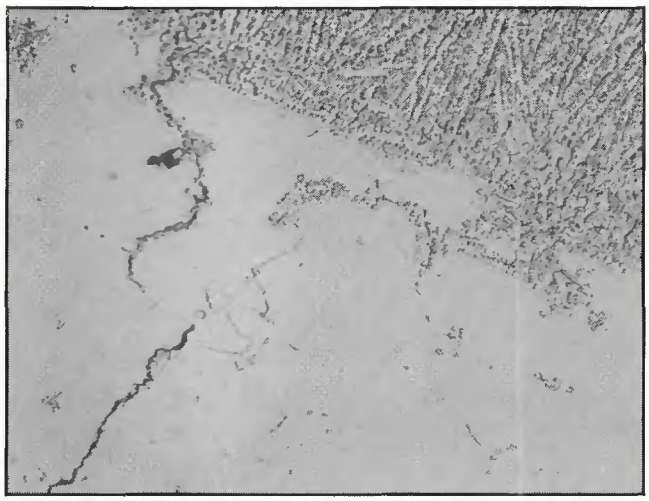

Fig. 1 — Microstructure of a typical microcrack in the HAZ of a cast 718 weldment

Unfortunately, no interaction effects can be determined. However, in this case, the first-order effects of several of the required alloying elements were so strong as to eliminate the need to further investigate the effects of interactions between minor elements, such as S and P. An analysis of this type allows the researcher to see both the significant first-order effects and the responses which are merely above experimental error, but have no statistical confidence level of importance. In the tables that show the results of this work, a simple double plus indicates that the high level of the element had a response level greater than experimental error and likewise, a double minus indicates that the low level of the element had a response level greater than experimental error. However, a response lacking any statistical confidence level of note can usually be discarded as irrelevant or not worthy (cost effective) for further work.

The range of all the elements was selected to be outside of (higher than and lower than) the current specification employed for cast Alloy 718. In general, if the level of an element is called out as LAP (Low As Possible), it means less than 10 ppm. Elements such as Cr, Al and Ti, not included in the matrix shown in Table 2, were held as constants at the mid-range of the specification for Alloy 718. Oxygen and nitrogen were held below 40 ppm and 30 ppm, respectively.

In order to evaluate the effects of heat treatment on the weldability of cast 718, a column not shown in Table 2 was used. The approach used was to assign one heat-treat condition, either temperature or time, as a high level of a variable. An example would be to use heat treatment A from Table 3 as a high-level variable and B as a low level to analyze time effects or A versus C for temperature effects.

All castings were made as 54- × 150- × 6-mm (2- × 6- × 0.25-in.) slabs (approximately 20 per heat) by the Howmet Turbine Casting Corporation. The castings were heat treated according to the treatments shown in Table 3. Following heat treatment, the slabs were then

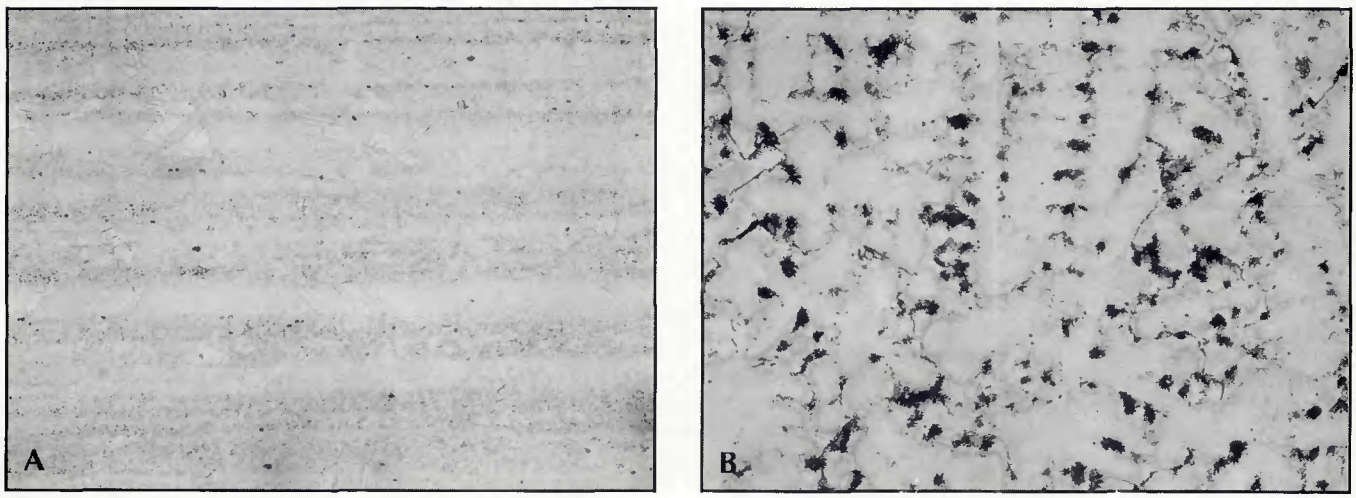

Fig. 2 — Typical microstructures of Alloy 718. A — Wrought Alloy 718; B — cast Alloy 718. Note the massive difference in segregation between the two forms

Table 2—The Compositions of Alloy 718 Heats Used to Evaluate the Effects on Weldability of the Various Alloying and Tramp Elements

Trials	C	Si	S	P	Cb	B	Fe	Mo	Hf	Zr
1	0.1	0.35	LAP	LAP	5.4	0.01	22	3.5	LAP	0.1
2	0.1	LAP	LAP	0.015	5.4	0.01	22	2.5	0.1	LAP
3	LAP	LAP	0.015	0.015	5.4	0.01	17	3.5	LAP	0.1
4	LAP	0.35	0.015	0.015	5.4	LAP	22	2.5	0.1	LAP
5	0.1	0.35	0.015	0.015	4.4	0.01	17	3.5	LAP	LAP
6	0.1	0.35	0.015	LAP	5.4	LAP	22	2.5	LAP	LAP
7	0.1	0.35	LAP	0.015	4.4	0.01	17	2.5	LAP	LAP
8	0.1	LAP	0.015	LAP	5.4	LAP	17	2.5	LAP	0.1
9	LAP	0.35	LAP	0.015	4.4	LAP	17	2.5	0.1	0.1
10	0.1	LAP	0.015	LAP	4.4	LAP	17	3.5	0.1	LAP
11	LAP	0.35	LAP	LAP	4.4	LAP	22	3.5	LAP	0.1
12	0.1	LAP	LAP	LAP	4.4	0.01	22	2.5	0.1	0.1
13	LAP	LAP	LAP	LAP	5.4	0.01	17	3.5	0.1	LAP
14	LAP	LAP	LAP	0.015	5.4	LAP	22	3.5	LAP	LAP
15	LAP	LAP	0.015	0.015	4.4	0.01	22	2.5	LAP	0.1
16	LAP	0.35	0.015	LAP	5.4	0.01	17	2.5	0.1	0.1
17	0.1	0.35	LAP	0.015	5.4	LAP	17	3.5	0.1	0.1
18	0.1	LAP	0.015	0.015	4.4	LAP	22	3.5	0.1	0.1
19	LAP	0.35	0.015	LAP	4.4	0.01	22	3.5	0.1	LAP
20	LAP	LAP	LAP	LAP	4.4	LAP	17	2.5	LAP	LAP

Balance Ni, 20% Cr, 0.5% Al, 1.0% Ti, O-N-Mg LAP

machined into subscale Varestraint specimens 31 × 3 × 150 mm (1.25 × 0.125 × 6 in.), usually two from a slab. All Varestraint specimens were tested at 2% augmented strain so that the resulting data could be compared directly. This augmented strain was selected because it had previously been shown to cause HAZ cracking without inducing cold cracks in cast 718 specimens. In each case, the data used in the statistical computations were the average of three Varestraint tests for each composition evaluated.

The metallography was performed on cuts from Varestraint specimens. Due to the configuration of the slab castings, all mechanical property data were generated using rectangular gauge sections. This means that specimen configuration had a major effect on the absolute results, but since this work measures only relative results, it can be assumed that specimen configuration did not alter the statistical results.

Results

A summary of statistical results of the elemental effects on the weldability of Alloy 718 are shown in Table 4, with a simplified version shown in Table 5. All of the results are shown, so if no result exists for a given element, then that element has no effect on Alloy 718 weldability within the range evaluated. Further, if an effect is shown only as above experimental error, it is unlikely to be of major importance to the weldability of the alloy.

In the first set of data shown in Table 4, which gives the results from heat treatment A, only boron appears as contributing a major negative effect on Alloy 718 weldability. Boron appears to increase both the total crack length and the average crack length, but registered no effect on the number of cracks formed. The only tramp element that appeared detrimental at all was phosphorus, which only indicated a response level above that of experimental error.

When heat treatment B was used, the level of the responses of the various elements increased and the number of elements showing a response increased. Again, boron was the most detrimental element to Alloy 718 weldability. However, iron begins to appear as detrimental, while low levels of sulfur, silicon and columbium appear detrimental to weldability.

The third set of data in Table 4 evaluates the effect of each element after the HIP cycle plus solutioning, heat treatment C. In general, less response is generated from this heat treatment for most of the elements evaluated. The exception is Mo

Table 3—Heat Treatments Used on Alloy 718 Prior to Testing for Weldability

Heat Treatment Code	Conditions Temperature/ Hold Time
A	1093°C (2000°F)/1 h
B	1093°C/10 h
C	1163°C (2125°F) HIP + 1093°C/1 h
D	1168°C (2135°F)/1 h ramp to 1177°C (2150°F)/3 h

Table 4—Effects of Elements on the Weldability of Cast Alloy 718

	C	Si	S	P	Cb	B	Fe	Mo	Hf	Zr	H.T.
Heat treatment A											
Total crack length				++[b]	−−[a]	+2[d]		−−			
Number of cracks											
Average crack length	−−	−−		++		+3[e]			++	+1[c]	
Heat treatment B											
Total crack length		−−	−2	++	−1	+3	+3	−−		++	
Number of cracks	++	−−	−−		−1	++	++				
Average crack length	−2		−−			+3		+1	−−	+1	
Heat treatment C											
Total crack length	−−			++		+3	++	+1			
Number of cracks	++							+2		−−	
Average crack length	−1	++		++	++		++	−−	++		
Heat treatment D vs. heat treatment A											*[f]
Total crack length					++	++	++	−−		−2	++
Number of cracks		−3		++						−−	++
Average crack length				−−	+2	+2	++	−2	++	+3	+3

(a) −− Low range reduces weldability
(b) ++ High range reduces weldability
(c) 1 = 90% confidence level
(d) 2 = 95% confidence level
(e) 3 = 99% confidence level
(f) * = Positive represents heat treatment D

Table 5—The Effect of Elemental Compositional Range Limits of the Cast Alloy 718 Specification on Weldability

Increases Weldability	Decreases Weldability	Neutral to Weldability
Cobalt	Boron	Sulfur[b]
Tantalum	Iron	Carbon
	Molybdenum	Silicon
	Columbium[a]	Phosphorus
	Zirconium[a]	
	Hafnium[a]	

(a) Strongest effect shown after 1149°C (2100°F) heat treatment.
(b) Appears to have a lower limit below which weldability decreases.

Table 6—The Average Varestraint Data from Each of the 20 Chemistries Used in This Program for Heat Treatments A and C

	Total Length		Number of Cracks	
	H.T. C	H.T. A	H.T. C	H.T. A
	0.396	0.132	11.5	4.33
	0.532	0.528	17.5	18.3
	0.412	0.266	7.5	7.3
	0.226	0.149	3	6.7
	0.254	0.091	12	6
	0.126	0.081	4	3.3
	0.552	0.823	19.5	17.7
	0.23	0.297	12	15
	0.162	0.144	3	6
	0.274	0.348	19.5	20.5
	0.44	0.287	17	16
	0.162	0.140	4.5	4
	0.39	0.176	8	5.3
	0.468	0.272	22.5	12.3
	0.39	0.600	8	18.7
	0.464	0.363	15	13
	0.32	0.127	15	8.3
	0.322	0.156	16	5
	0.530	0.345	15	12.7
	0.126	0.052	10	1
Average	0.3388	0.2589	12.025	10.072

which continues to show a significant effect on weldability, though its magnitude and direction are variable. Boron has again the largest detrimental effect on total crack length.

When the effect of each element is evaluated with heat treatment also evaluated as a variable, as in data set 4 from Table 4, the heat treatment becomes a significant variable in every Varestraint measurement evaluated. It appears that the heat treatment D, which is hotter and longer than heat treatment A, is more detrimental than heat treatment A. Moreover, as the time and temperature increase, the response of many of the variables also appears to increase.

In Table 6, the effects of the alloying elements on 649°C (1200°F) tensile and stress rupture properties are shown. The most pronounced are the effects of Cb, B, P, Zr and Fe. Generally, Cb and Fe increase strength, while B increases the hot ductility and stress rupture life. It appears that Hf has no beneficial effect on the mechanical strength or hot ductility of the cast alloy.

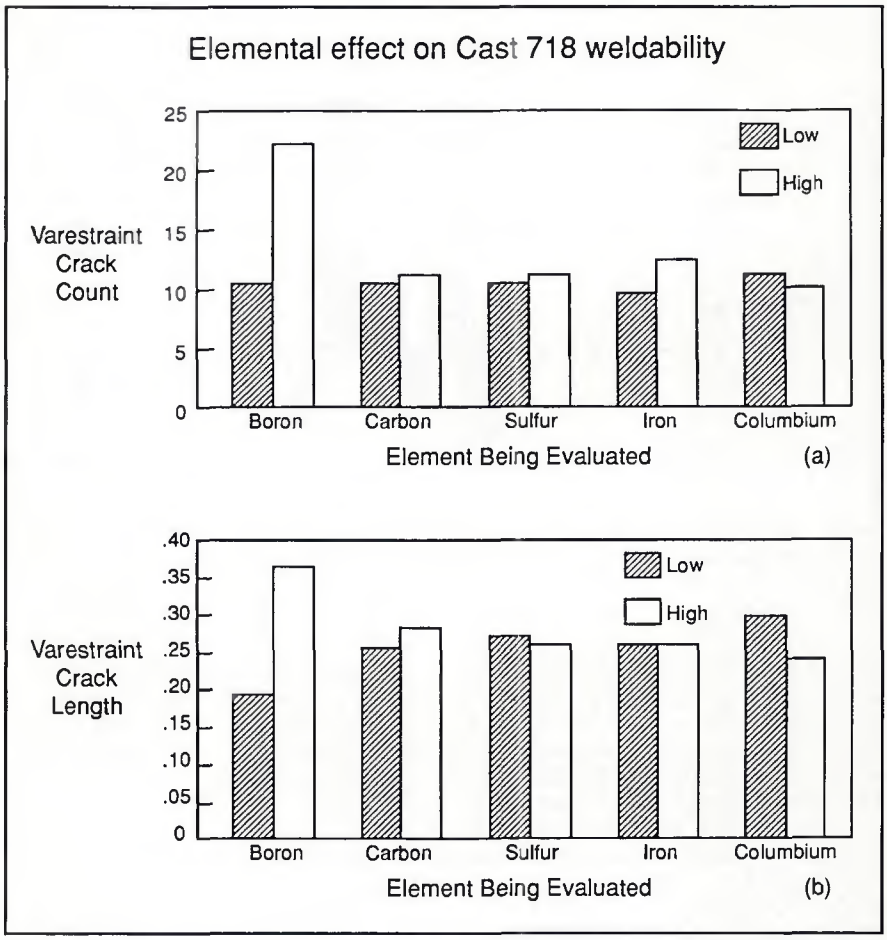

Fig. 3—Elemental effect on cast 718 weldability. A—Average number of cracks counted; B—total length of cracks measured per Varestraint specimen. Each bar is the average of 30 specimens

Discussion

Results shown in Table 4 indicate boron to be the single most detrimental element in Alloy 718 for weldability. This has been shown earlier by Pease, Table 1 (Ref. 3), but he indicated that a level below 300 ppm for nickel-base alloys was not detrimental. However, the lack of influence for Si and Fe was somewhat unexpected. Moreover, the lack of effect for such tramp elements as S, P and Si at the levels tested in this matrix was unexpected. The effects of Mo, Zr and Hf are variable, but only Mo requires any further analysis. It also appears that the higher the heat treatment temperature or the longer the time-at-temperature, the stronger the effect each element had on weldability.

Figure 3 is a graphic illustration of the results for five of the previously identified critical elements (S, B, C, Fe and Cb) in superalloy weldability. These particular graphs consist of an average of 30 Varestraint specimens per bar. The B, S and C vary from low levels of less than 10 ppm to the top of their specification range for Alloy 718, while Fe and Cb vary from 17 to 22% and 4.5 to 5.5%, respectively. Note that only B shows a strong response for the high level of its range. The graphs show that the effect on weldability is the same for both total crack count and total crack length for all five elements.

Boron has a statistically significant effect on Alloy 718 weldability, but only in the measurement of total and average crack length. However, the Spot Varestraint specimen is not the best type of specimen to evaluate the elemental influence on alloy weldability for castings with respect to the number of cracks. This is because the number of cracks measured around a Spot Varestraint specimen is dependent on the number of grain boundaries intersecting the weld spot on the given specimens. Moreover, since the grain size was varied in this experiment, it would be expected to perturb the data for the number of cracks per specimen. Therefore, the results for the number of cracks are diluted and would appear weaker than it is in actuality. However, Fig. 5 does show that B did produce an increase in the average num-

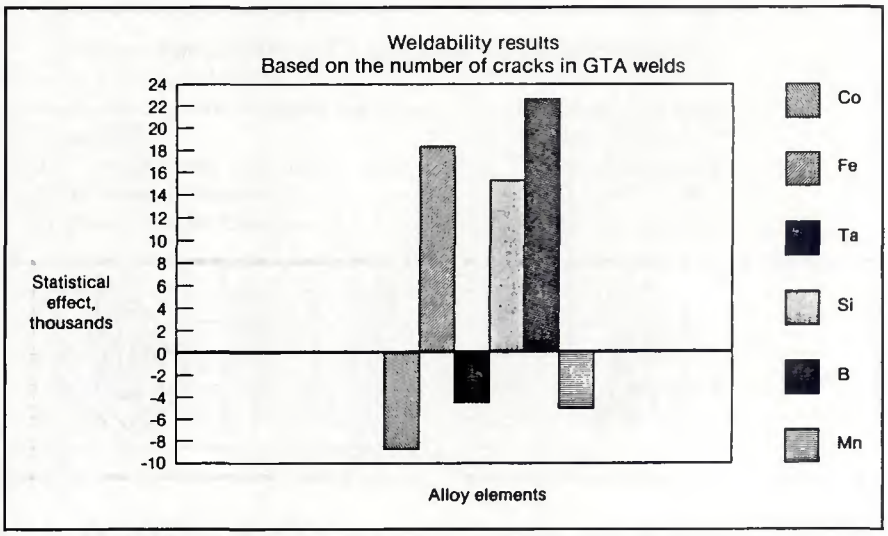

Fig. 4 — The results of a previous study on the effects of major nickel-based superalloy elements on the weldability of a generic nickel-based superalloy designed primarily around the Alloy 718 chemistry

ber of cracks counted per specimen, even though the increase was not statistically significant.

Since an earlier study by Kelly (Ref. 11) was performed using only the total number of microcracks per length of weldment as data, the data from that study gave a 99.5% confidence level that B was responsible for causing the cracks to form, as shown in Fig. 4. Therefore, it is certain that B has a major effect on all aspects of cast Alloy 718 weldability. However, if the earlier study using only the total crack count as data is valid, then why isn't the response for Fe and Si stronger in the total and average crack length measurements? This is probably due to the levels over which the two studies have varied the content of Fe and Si. The current study held to a narrow range around a composition which would be recognized as Alloy 718. In the previous study, the compositions of Fe and Si were varied from 0 to 18.5% and 0 to 0.30%, respectively, which would yield stronger individual responses. In this study, Fe is varied over a range of 17 to 22%, resulting in a large amount of Fe present even for the lowest level being analyzed; therefore, there is always plenty of Fe present to promote Laves-phase formation. Further, with 17% Fe present as a low level, the effect of Si is overwhelmed.

It then appears that as long as Fe is present in the alloy, it has a detrimental effect, but why? Iron is a cheap substitute for Ni and readily soluble in Ni to above the amounts used in Alloy 718. However, Fe promotes the formation of Laves phase, which forms a low-melting eutectic TCP phase in Alloy 718. The wrought form of Alloy 718 can be thermomechanically homogenized to prevent any appreciable Laves-phase formation in the HAZ of weldments, but this is not true of castings.

Though the cast structure can be thermally homogenized to be optically free of second phases (Laves) and as cast structure, it takes heroic efforts to truly homogenize the alloy thermally. Carlson and Radavich (Ref. 12) showed that after 100 h at 1093°C (2000°F) the columbium content in the interdendritic locations remained at about 12%, while the nominal content in the alloy was 5%. Therefore, once Laves phase forms due to a high concentration of Cb at interdendritic locations in the casting, the local concentration of Cb remains high enough to provide areas that will constitutionally liquate and provide liquid metal for grain boundary wetting, which will reduce weldability even though the Laves phase has been solutioned.

The reason silicon did not appear to be harmful to cast Alloy 718 weldability in the present study is that the Fe content (17 to 22%) of all the alloys was always high enough (at least 17%) to promote Laves-phase formation without Si present. Figure 3 shows that there was little, if any, difference in the crack count between the high and low levels of iron. In the previous study, Si, since it is a known Laves-phase promoter, was capable of independently promoting Laves-phase formation in the absence of Fe. This was because Ni and Cb were always present in sufficient amounts to form Laves phase. However, due to the high Fe content found in Alloy 718, the limits for Si are adequate to prevent it from causing noticeable increases in Laves phase or any welding problems.

This explanation is adequate to explain high levels of Si being permissible in Alloy 718, but does not explain why Table 4 shows amounts of Si below 10 ppm to be detrimental to weldability after some heat treatments. A look at Fig. 5 may offer an explanation for this. It appears statistically valid that the level of Si in cast Alloy 718 controls the carbide morphology. At some low level of Si, the carbide morphology changes from blocky to script. After a heat treatment that will only promote the Laves phase, the carbides would be left to initiate fracture and the script carbides being more angular are more likely to be fracture-initiation sites. Therefore, the low Si level would cause more angular carbides and show reduced weldability, as it did.

None of this has yet to shed any light

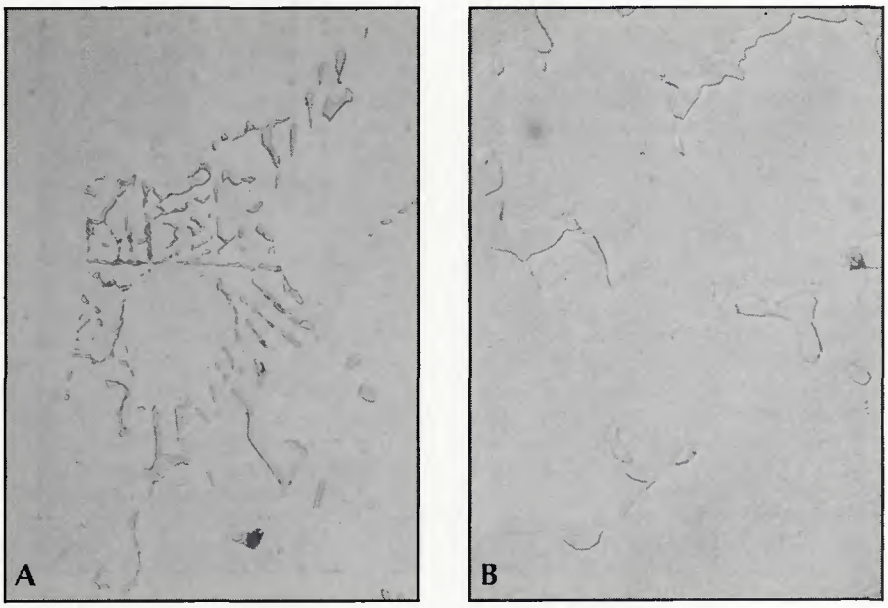

Fig. 5 — Two microstructures demonstrate the effects of Si on the morphology of the carbides formed in cast Alloy 718. A — Script carbides produced in heats with less than 10 ppm Si; B — script carbides produced in heats with a nominal to high Si content

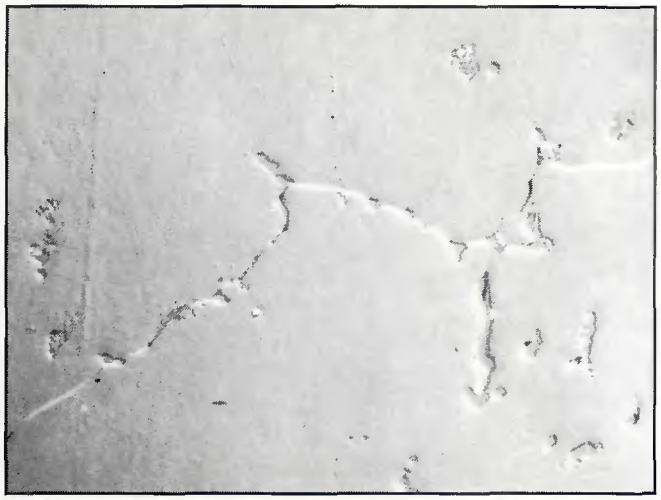

Fig. 6 — Microstructure of the grain boundary film that can form in cast Alloy 718 after a HIP cycle at 1163°C (2125°F)

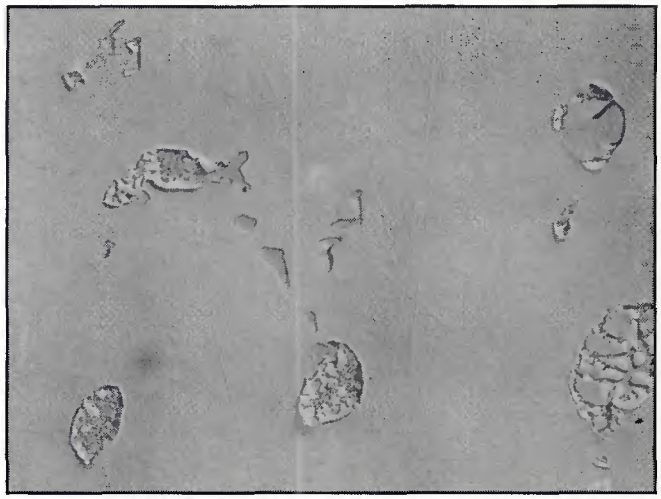

Fig. 7 — Typical microstructure of a HAZ very near the fusion zone in cast 718. Note the pools of liquated Laves phase with fully solid carbides interspersed

on why Cb appears to have a positive effect on weldability when heat treated according to treatments A and B, and a negative effect on weldability when treated according to C and D. Since Cb is a required constituent in the Laves phase and carbides formed in Alloy 718, why isn't it always detrimental to weldability? Theories which would attribute cracking to constitutional liquation of carbides and liquation of Laves phase would place Cb as a major factor in reducing weldability, but the statistical analysis does not support this relationship.

Again, the previous study holds the evidence that explains the absence of Cb from the ranks of the totally detrimental elements in Alloy 718. In the previous study, Laves phase was observed liquating on grain boundaries of two separate heats of Alloy 718. One heat of Alloy 718 had 100 ppm of boron, while the second had less than 10 ppm boron. The liquid Laves phase immediately wet the grain boundary in the B-containing heat, but melted in situ in the non-boron heat. Therefore, by increasing the grain boundary wetting of the always available Laves eutectic liquid, it is B which is the cause of the microcracking in cast Alloy 718 and not the Cb, which only forms low-melting phases that provide a liquid film for boron-affected grain boundaries.

This explanation also fits with the difference in response with respect to heat treatment. In the case of the heat treatments A and B, the maximum temperature was 1093°C (2000°F), which is lower than the Laves-phase liquation temperature, whereas the 1162°C (2125°F) and 1177°C (2150°F) temperatures achieved in heat treatments C and D, respectively, are at or above the Laves-phase liquation temperature. Therefore, the Laves phase in treatments A and B is put into solid solution without liquating, or at least does not liquate and spread down grain boundaries, but in treatments C and D the Laves phase liquates during heat treatment and wets the grain boundaries, as shown in Fig. 6. Then, due to the tendency of Alloy 718 to form Laves phase in the last material to solidify, a thin film of Laves phase, therefore, would probably solidify on the grain boundaries. However, this film is too fine to be resolved optically and likely would require careful scanning transmission electron microscopy to resolve. This causes results for Cb to be reversed based on the maximum temperature observed during heat treatment.

The response for S, the most frequently written-about denizen of the nickel-based superalloys, is amazingly free of any detrimental aspect, and indications even exist that there is a lower limit to S content beyond which weldability drops off. In a previous study (Ref. 13) of the effects of S in 718 welding filler metal on the weldability of cast Alloy 718, it was found that at the lower limits of S in the filler metal (6 ppm) the LCF life of the weld deposit dropped off and the number of cracks counted in the actual HAZ of weldments increased. This is further evidence that a lower limit to S content may exist, but even if it doesn't, it is clear no welding rationale exists to justify work toward lower S limits in cast Alloy 718.

Since S is a surface active element, it may be that a minimum amount is required to allow for proper coherency (wetting) of the matrix to carbides, nitrides, etc. However, beyond a given S concentration limit, sulfide films begin to form and weldability is reduced. Regardless of the possible validity of a required minimum amount of S for weldability, it is clear that the upper limit of S contents currently established for Alloy 718 is adequate for weldability and needs no further investigation.

The response for P is less clear, in that at its upper limit it does appear to reduce weldability, but the response is just above the level of experimental error that should even be considered valid. Moreover, the level of P in commercial alloys rarely approaches the 0.015% level evaluated in this experiment. Therefore, it appears that it would be economically unsound to pursue further removal of P from Alloy 718 for improvements in weldability.

The results for C are interesting in light of the theories regarding the constitutional liquation of carbides reducing weldability in wrought Alloy 718. If these theories were correct for cast Alloy 718, a large negative effect should have been produced by the 0.1% C evaluated in this experiment, but the results were somewhat variable, tending toward a minimum C required to improve weldability. In fact, in Fig. 3, the results for C show no difference in weldability between the less than 10 ppm and 0.1% C heats. If carbide liquation were the effective mechanism, then the high C should show a major increase, which it does not.

The conflict between theory and results may be explained by looking at Fig. 7. Note that in this area of the HAZ of cast Alloy 718 there are large pools of liquid that formed with solid carbides between. This demonstrates the difference between wrought and cast Alloy 718 weldability. In the cast alloy, there are many areas/phases (interdendritic areas rich in Cb-containing Laves or Delta phase) that will liquate before the constitutional liquation temperature of CbC is reached. In a good wrought 718 structure, no such low-melting phases or areas should exist other than CbC. Further, if C is removed from the cast alloy it will release additional Cb to form more low-melting Laves-phase eutectic or Cb-segregated areas, which would be expected to further reduce weldability.

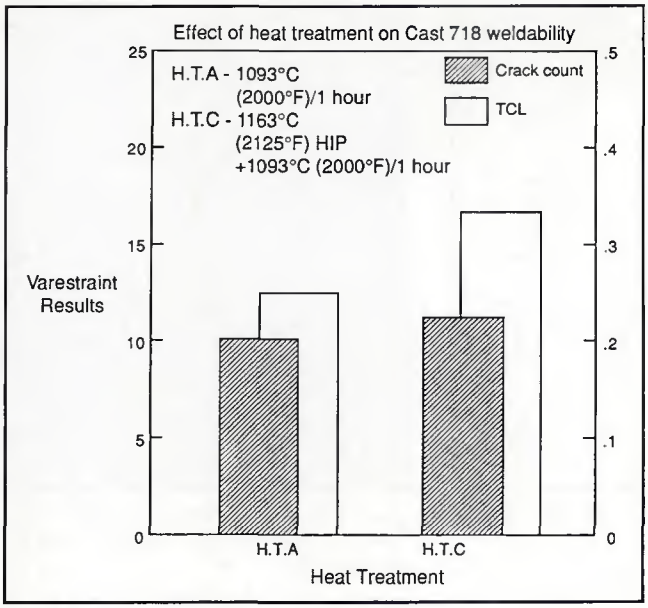

Fig. 8 — The effects of heat treatment on the number of cracks and total crack length recorded in the Spot Varestraint test

The response for Hf and Zr was variable, but in general, it indicated that there was no need to add either element to Alloy 718 for weldability.

Molybdenum gave an unexpectedly strong but variable response to weldability. It is a known Laves phase and carbide former, but is present to a far less degree then Cb, and if it is similar to Cb, why doesn't it respond similarly? Actually, it does after exposure to low-temperature thermal cycles (heat treatments A and B), but it reacts opposite to Cb after exposure to temperatures above 1163°C (2125°F). Since the indication is that low amounts of Mo reduce weldability after high-temperature exposure as opposed to Cb, which reduces weldability if present in high amounts after similar exposure. This is due to the thermal stability that an increased amount of Mo would give to the Laves-phase eutectic in cast Alloy 718. As the Mo content of the alloy increases, the Mo content of the Laves phase will increase due to partitioning of Mo to the Laves phase, and this would raise the Laves-phase eutectic temperature.

A look at the binary phase diagrams for NiCb and NiMo (Ref. 14) supports this in that the liquidus temperature increases for the A_2B composition in the NiMo diagram over the NiCb diagram, and this means that as Mo substitutes for Cb in the Laves phase, the liquation temperature should increase. This would indicate that the Laves phase that forms will have a higher eutectic reaction temperature with more Mo, which will mean the liquid grain boundary film that does form will not extend as far out from the fusion zone as with high Cb content, therefore, weldability would be improved.

Heat treatment is another approach often used to try to improve the weldability of cast Alloy 718. In this study, four different heat treatments were evaluated separately for their effects on the weldability of the alloy. Only two heat treatments, A and C, were tested through the entire chemistry matrix; the results are shown in Fig. 8, which shows the average number of cracks and the total crack length per Varestraint specimen (graph uses the average of 60 specimens per bar) regardless of chemistry for each heat treatment tested. The actual average data from the 20 runs are shown in Table 6. It is clear that the lower temperature heat treatments are better for weldability, but none of these treatments provides weldments with a crack-free HAZ.

Alloying elements are added to most alloys in order to achieve mechanical properties not weldability. Therefore, with boron being detrimental to the weldability for cast Alloy 718, the mechanical properties of the alloy should be evaluated for elemental effects to determine if elements detrimental to weldability are required. In Table 7, the effects of the elements in this study on the 649°C (1200°F) tensile and stress-rupture properties are shown. Note that boron is essential to both stress-rupture life and hot ductility. Moreover, these results provide a better justification for maintaining low S and Si contents in the alloy than did the weldability results. Further, the reason for high Cb is clear and the ineffectiveness of adding Hf to cast Alloy 718 is again demonstrated.

Table 7—Effects of the Elements on the Mechanical Properties of Cast Alloy 718

	C	Si	S	P	Cb	B	Fe	Mo	Hf	Zr
Long age										
649°C (1200°F) 0.2% yield					+3[e]	−−[a]	++[b]		−−	
649°C ultimate			−−		+3	−−	++		−−	
649°C % elongation		−1	−−	++	−3	+2[d]	++	−−	−−	++
649°C/13 MPa (90 ksi) stress rupture		−−	−1		++	+2				
Short age										
649°C 0.2% yield				+1	+3	−−			−−	
649°C ultimate			−−	−−	+2	−−			−−	
649°C % elongation	−−	−2	−−	++	−3	+1			−2	

(a) −− Low level of variable increased property.
(b) ++ High level of variable increased property.
(c) 1 = 90% confidence level.
(d) 2 = 95% confidence level.
(e) 3 = 99% confidence level.

Summary

Though the statistical approach taken here is that of a screening experiment, it is therefore not absolute in its results because it cannot easily identify synergistic effects. It does demonstrate that, through the extremes of the specification limits for the elements evaluated, only the actual alloying elements Cb, Fe, Mo and B have a major impact on weldability. Boron had the major detrimental influence on weldability, far greater than S, Si, P, Hf, Zr and C.

Since the evaluation of mechanical properties shows B to be required, and it is the major element reducing weldability, then it would follow that improved weldability becomes a matter, albeit an expensive one, of lowering the other elements further. Further complicating the task of improving weldability is the fact that only a small effect by heat treatment has been shown in this study and none of the treatments provided weldments with a crack-free HAZ.

Conclusions

1) Boron is the most detrimental element to weldability of cast Alloy 718.

2) The specification limits for elements such as S, P, Si and C are already satisfactory to prevent weldability problems from these elements.

3) Columbium and boron are the major contributors to the 649°C (1200°F) tensile and stress rupture properties of Alloy 718 from the elements evaluated in

this program.

4) The weldability of cast Alloy 718 is unlikely to be effectively influenced by heat treatment or minor element variations within the Alloy 718 specification.

Acknowledgments

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