Rene' 220C—The New, Weldable, Investment Cast Superalloy

Rene' 220C is tested against Alloy 718 and found to display much better weldability

BY T. J. KELLY

ABSTRACT. The major intermediate temperature investment cast superalloy in use today in the aerospace industry is Alloy 718. This alloy accounts for approximately 1800 tons of investment cast parts a year. It is an alloy originally designed to be used in the wrought condition and was adopted to casting with virtually no change in alloy composition. Alloy 718 contains relatively large amounts of Fe and Nb, and allows up to 0.35% Si, all of which contribute to Laves phase formation. The Laves phase, which has a low eutectic reaction temperature in Alloy 718, is a terminal solidification phase that forms at the interdendritic locations in castings and has frequently been cited as causing poor weldability.

Investment castings require weld repair in order to produce a product due to the inadequate state of development of today's casting process. Without it, few investment castings of any size could be produced in a cost-effective manner. Therefore, the weldability of an investment cast alloy is critical to its utilization, and Alloy 718 has provided sufficient weldability to function adequately for the entire aerospace industry to date. However, the industry is pushing to higher temperature and stress on components; therefore, the strength of Alloy 718, particularly in stress rupture and low-cycle fatigue, is being challenged beyond its capability.

With the alloy being pushed to its limit of strength and endurance, issues such as microcracking in weldments become more important. During welding, many of the grain boundaries in the heat-affected zone (HAZ) near the fusion zone of a weld rupture either during the thermal shock of heating or on solidification. Due to the composition of Alloy 718, the fusion zone material that backfills the open grain boundary cracks has the low melting Laves eutectic as its terminal solidification structure. The backfilled material is thus the last to freeze. This frequently results in the rupture of these same grain boundaries toward the end of the weld cycle, which then become microcracks.

A new alloy, Rene' 220C, has now been developed for use in investment castings in the aerospace industry. This alloy is capable of more than a 100°F (56°C) increase in operating temperature over Alloy 718, and in certain cast forms has better mechanical properties than wrought 718. Its castability is rated as equal or better than Alloy 718 and its weldability is much better than cast Alloy 718. The chemical composition of the new alloy was designed to provide improved high-temperature strength, good castability, and minimum susceptibility to fusion welding and postweld heat treatment flaws.

Weldability is improved both as measured by the Varestraint test and in field trials of the alloy in comparison to Alloy 718. The absence of Fe in this nickel-based superalloy reduces the amount of Laves phase that forms on solidification either during casting or welding. Since little Laves phase forms during the weld solidification cycle, no microcracks form. Moreover, this alloy forms a more stable delta phase due to the addition of Ta. This also improves the weldability of the alloy by remaining as a stable phase during welding, even into the fusion zone of the weld, as opposed to delta in Alloy 718, which liquates in the HAZ at only a slightly higher temperature than the Alloy 718 Laves eutectic.

KEY WORDS

Cast Rene' 220C Alloy
Cast Superalloy
Investment Castings
Hot Crack Resistance
S/Cr Chem. Effects
Rene' 220C Weldability
Ta vs. Nb Solubility
HIP Rene' 220C Temp.
Ni-Cr-Co-Nb System
Boron Effects
Ta Additional Effects

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Introduction

Rene' 220C is similar to the alloy identified by Chang (Ref. 1) to be used in structural castings at approximately 100°F (56°C) higher operating temperature than Alloy 718. The total change in alloy content from Alloy 718 to Rene' 220C was just in excess of 33%, as shown in the nominal alloy compositions below.

Alloy 718: bal. Ni, 18%Fe, 18%Cr, 5%Nb, 3%Mo, 1%Ti, 0.5%Al, 0.05%C and 0.003%B

Rene' 220C: bal. Ni, 12%Co, 18%Cr, 5%Nb, 3%Ta, 3%Mo, 1%Ti, 0.5%Al, 0.03%C and 0.003%B

Previous work by Baeslack (Refs. 2-4) and Kelly (Refs. 5, 6) have shown the three elements, Fe, Co and Ta, have a major effect on weldability as measured by the resistance of the alloy to avoid heat-affected zone (HAZ) liquation cracking. The most frequently cited cause of HAZ liquation cracking in Ni-Nb-containing alloys is the liquation of the Laves phase eutectic (Refs. 7-12). Laves phase is A_2B, generally Ni_2Nb, but can have Mo, Ta or Ti substituting for the Nb and Fe, Cr or Co substituting for Ni. This has the effect of changing the eutectic-reaction temperature. Further, the B levels in both alloys are identical. The B level has been identified by Kelly (Ref. 5, 6) as the most potent cause of HAZ microcracking in the Ni, Cr, Fe, Co, Nb alloy system.

The Fe in Alloy 718 is a Laves phase promoter and it is Laves phase eutectic liquation that is frequently cited as being the source of microcracking in the HAZ of cast Alloy 718 (Refs. 7-11). This is different than for wrought 718, in which Owczarski (Refs. 12-14) and Thompson (Refs. 15, 16) cited the constitutional liquation of NbC and Thompson (Ref. 17) and Shira (Ref. 18) cited S segregation to grain boundaries as the cause of HAZ microcracking.

The solubility of Ta in the Ni matrix in addition to Nb allows the cast alloy to develop higher mechanical properties without the formation of excess Laves phase, as would occur with a further increase in the amount of Nb (Refs. 19–22). Further, Ta additions can raise the Laves phase eutectic-reaction temperature by as much as 140°F (77°C) with a complete substitution for Nb, as shown in Fig. 1. This increased Laves phase reaction temperature reduces the distance into the HAZ that the Laves eutectic reaction can occur and thereby reduces the length of the microcracks that form. This is an oversimplification since there is an adequate amount of Nb in the alloy to form some Ni-Nb-type laves phase even in the absence of Fe. However, Wlodek (Ref. 23) found that Laves phase in the absence of Fe is less stable than it is in Alloy 718 with its 18%Fe. Therefore, it is a combination of less Laves phase forming, less stability in the Laves phase that does form, and a higher eutectic reaction temperature with the Ni matrix that improves this alloy's resistance to HAZ microcracking.

According to Sims (Ref. 24), cobalt is not a Laves phase promoter and thus can replace Fe and reduce the tendency of the alloy to form Laves phase. This lesser amount of Laves phase that is formed in Rene' 220C reduces the amount of low melting grain boundary phase that promotes microcracking.

Many of the structural castings of Alloy 718 and Rene' 220C are hot isostatically pressed (HIP) to ensure closure of any casting-related microshrinkage. This is done because microshrinkage is the primary cause of low-cycle fatigue crack initiation and failure in structural castings. There has long been controversy over what temperature is optimum to HIP Alloy 718. Kelly (Ref. 6) has shown that increasing the HIP temperature increases the amount of HAZ microcracking in cast Alloy 718. In general, it has been assumed that the effect on weldability due to HIP temperature was related to Laves phase eutectic liquation during HIP, resulting in gas absorption and grain boundary films of Laves phase (Ref. 25).

Wrought Alloy 718 and several other wrought superalloys such as Waspaloy are considered to be weldable with respect to microcracking in the HAZ if they have a grain size ASTM-6 or finer (Refs. 15, 26, 27). Therefore, fine grain castings are also expected to exhibit this increase in weldability with decreased grain size. However, even with decreased grain size in cast Alloy 718 or Rene' 220C, there is still the cast segregation to contend with (Refs. 19, 23, 28), a characteristic not present in the wrought material that can reduce the resistance to HAZ microcracking even in fine grain castings.

Weldability is actually defined by the American Welding Society as fitness for service, not the ability to avoid microcracking in the HAZ. In order to fully evaluate fitness for service, the mechanical properties of both repair and fabrication weldments were compared to the properties of the cast base metal.

Procedure

The results reported and discussed herein are based on several different programs and therefore embody a number of different procedures. In general, spot Varestraint weldability testing at 2% augmented strain was used to measure the elemental, heat treatment and grain size effects on susceptibility to HAZ liquation cracking. Metallographic sections were used to make a comparison of microcracking in cast Alloy 718 and Rene' 220C repair weldments. Mechanical properties of the weldments were evaluated using simulated weldments of identical section size and heat input.

The spot Varestraint test shown in Fig. 2 with the parameters was used to evaluate the effect of heat treatment, grain size and chemistry on the resistance to HAZ microcracking. This test uses a fixed gas tungsten arc for a preset constant time and a known radius of curvature die block to apply a constant strain, which causes HAZ cracking (a measure of weldability). All specimens are machined to matching dimensions, and identical size weld pools are created by the arc, which is switched off for an identical time period prior to impact by the die block on the reverse side of the specimen from the weld pool. The specimen is forced to conform to the die block, giving it a known radius of curvature and a known surface strain of E = Thickness/2R. Three measures are generally used to compare weldability by the Varestraint test: total number of cracks, total crack length (TCL) and average crack length (ACL). A fourth measure of weldability sometimes used with Varestraint testing is maximum crack length; however, this was not used in this investigation.

The spot Varestraint data were used in the analysis of statistically designed matrixes to evaluate the effects of composition, etc., on the weldability of cast alloy Rene' 220C. All of the statistical matrixes employed in this work were fractional factorial designs of the Taguchi type, L9, L16, etc. (Ref. 29), or Plackett-Burmann screening designs. These matrix experiments were analyzed using standard analysis of variance, linear regression and confidence limit techniques.

A comparison of cast Alloy 718 and Rene' 220C repair weldability was measured by having Precision Castparts Corp. make 23 identical simulated repair welds on identical sections of two identical components: one cast in standard Alloy 718 and welded with matching 718 filler metal; and one cast in Rene' 220C and welded

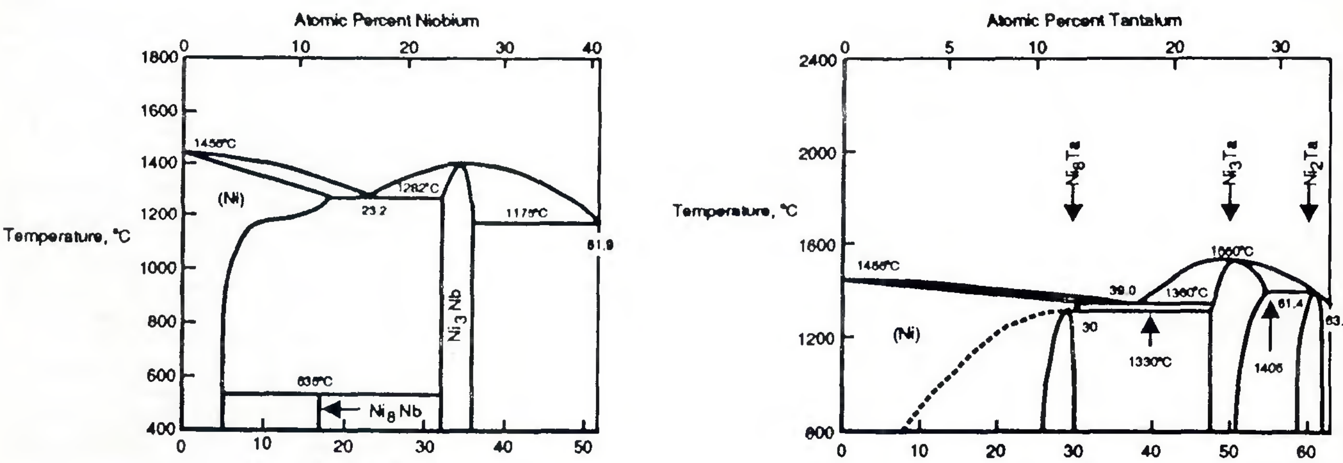
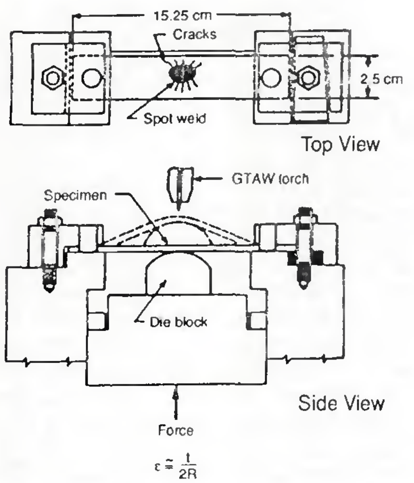


Fig 1 — The Ni-Cb and Ni-Ta phase diagrams showing the relative solubilities of Ta and Cb in the Ni system.

The Spot Varestraint Test



Test parameters

Welding current:	65 Amperes
Arc voltage:	15V, DCSP
Shielding gas:	Argon, 0.12 liters/sec.
Electrode type:	2% Thoriated Tungsten
Electrode size:	2.38 mm. diameter
Arc length:	6.3 mm.
Arc time:	15 sec.
Delay time:	50 msec.
Augmented strains:	0.29, 1.16, 2.9%

Fig. 2 — Schematic of spot Varestraint test apparatus and procedure.

with matching Rene' 220C filler metal. All of the weldments were then sectioned and examined metallographically to determine the extent of HAZ microcracking caused by the GTA repair welds. Figure 3 is a schematic of the repair weld locations on the component cross-section used for the evaluation. Normal repair weld procedures and matching filler metals were used for both trials. In order to make the repair welding evaluation as real as possible, the work was done by a casting vendor using its own people and proprietary parameters; therefore, the parameters cannot be reported, but the experiment could be redone using parameters acceptable to 718 welding with the same results expected.

Another measure of weldability is the ability of the welding filler metal and HAZ to attain the mechanical properties of the base metal. In order to determine the ability of Rene' 220C to maintain base metal mechanical properties across the weldment for both GTAW repairs and EB fabrication welds, simulated weldments were made using both processes. These weldments were made using the same material thickness and heat sink as actual parts would have, but using cast slabs to facilitate the machining of mechanical test specimens.

Due to the lack of thickness of the cast sections being welded, special test specimen configurations had to be developed for rupture testing. Since the data for the weldments were obtained from nonstandard test specimens, identical specimens had to be tested from the base metal for property comparison. The specimen configurations used for the mechanical property testing are shown in Fig. 4. The mechanical properties evaluated from the weldments included low-cycle fatigue, and smooth and notch rupture life. Low-cycle fatigue is a strain-controlled test that provides a pseudo stress measurement of fatigue life. Testing was done at the temperatures indicated in Table 2, using an alternating strain (with an "A" ratio of 1.0 alternating strain divided by mean strain) and 60 load reversals (cycles) per minute. Notch rupture specimens contained a notch with a $2.8K_t$ stress intensity factor.

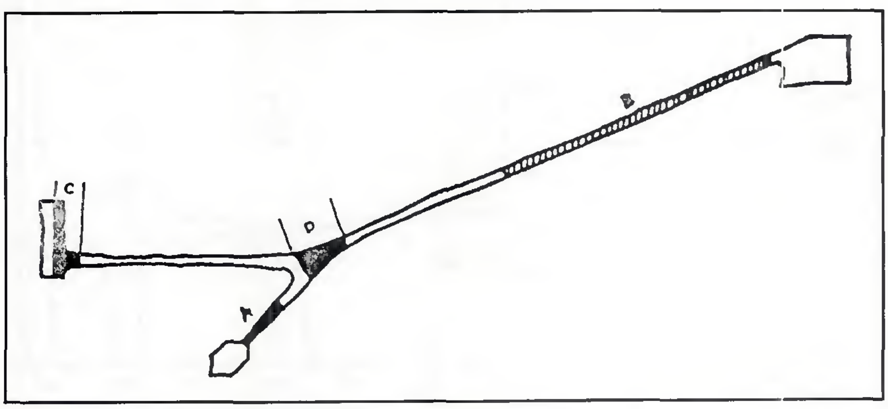


Fig. 3 — Schematic of simulated repair welds made on the actual component of Alloy 718 and Rene' 220C.

Both smooth and notched rupture tests consisted of placing a static load on the specimen at the temperature indicated and waiting for failure of the specimen or for some set time period before terminating the test, in this case a 200-h limit was used.

Results

This section will present the compilation of several programs which included measurements of Rene' 220C weldability from a material processing view and then two programs that are more practical in nature. The first section will review the development of weldability in the alloy along with the effects of thermal cycling, grain size and chemistry on weldability. The second section deals primarily with the practical aspects of weldability.

Development of Rene' 220C Weldability

Initially, the alloy known as CH22 was compared to cast Alloy 718 for weldability using the spot Varestraint test. The results of those tests appear in Fig. 5. Note that the original composition of CH22 was less weldable than cast Alloy 718.

A statistically designed experiment was used to determine the cause of poor weldability in this new composition. The design was a Plackett-Burmann 12-run matrix to evaluate the effects of B, Co, Ta, Si, Mn and Fe on the weldability of the basic Ni-20Cr-5Nb-3Mo-1Ti-0.5Al alloy composition. Figure 6 is a graphic illustration of the results, which show that the B content of the CH22 alloy was too high to permit welding. Moreover, the results show that the replacement of Co and Ta for Fe was beneficial for weldability. Manganese also appeared beneficial, but it is too difficult to control during vacuum induction melting, the process used for melting and casting nickel-based superalloys.

Figure 5 also shows that reducing the level of B from 100 ppm, which was the amount in the original CH22, to 30 ppm greatly improved the weldability of the alloy in comparison to cast Alloy 718. The reduced B version of CH22 was then renamed Rene' 220C. The composition of CH22 with reduced B is essentially the Rene' 220C baseline composition.

During the initial weldability evaluations there appeared to be an effect of thermal cycling on the weldability of Rene' 220C. Therefore, the effect of hot isostatic pressing (HIP) was evaluated with respect to weldability. The Varestraint data, both TCL and total crack count, shown in Fig. 7, demonstrate an inverse relationship of weldability with HIP temperature, with weldability decreasing linearly with increased HIP temperature. All data points in Fig. 7 are the average of three test results using conventional cast grain size of ASTM 0–1 for Rene' 220C with 30 ppm boron.

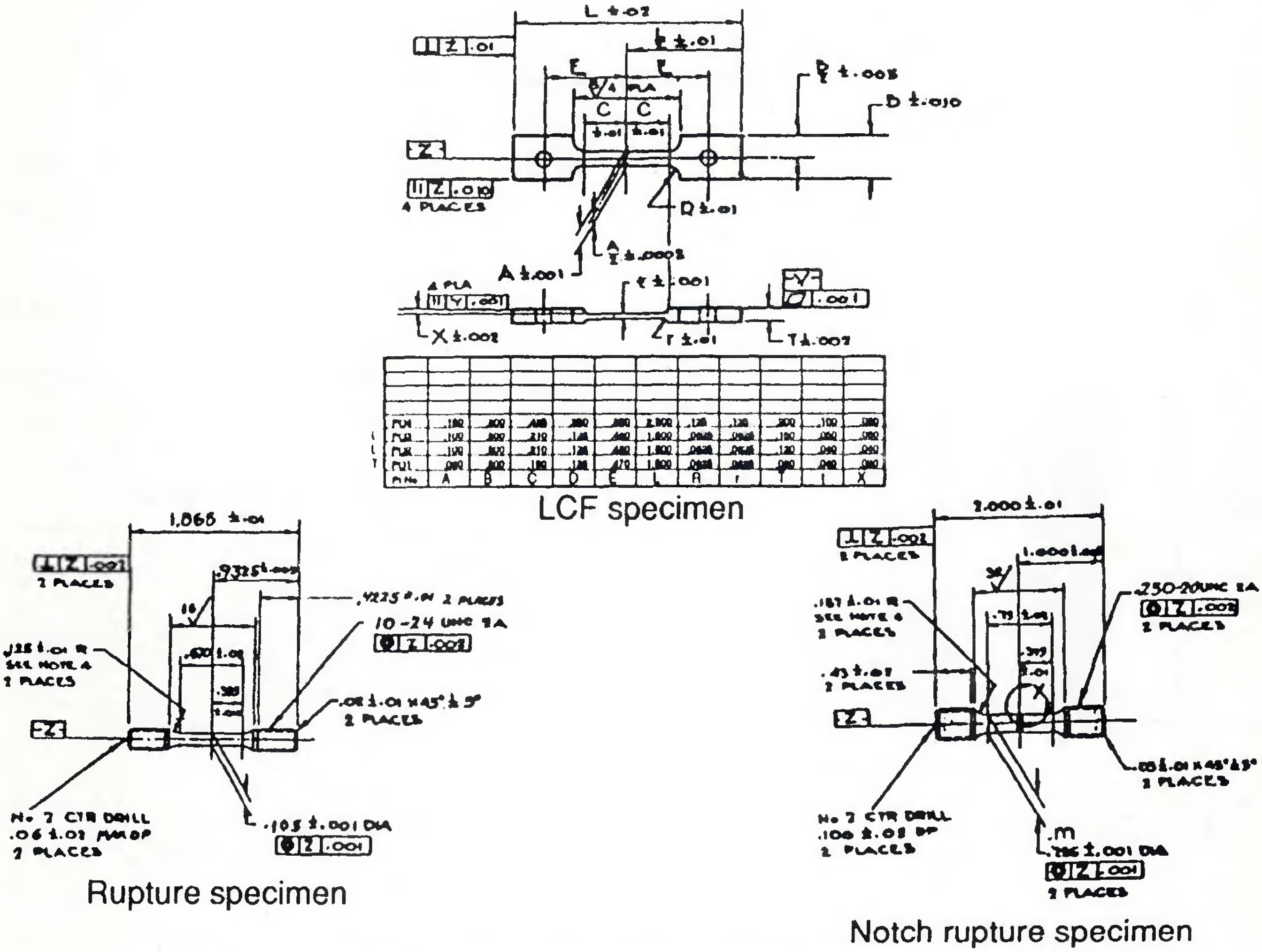


Fig. 4—Schematic of subsize mechanical test specimens used in the evaluation of the weldment mechanical properties.

Since the effect of B was so dramatic on the Rene' 220C weldability, B was examined over a wider range to determine if a lower limit existed below which it was no longer deleterious to weldability. This was particularly important since B is necessary for notch rupture ductility, as well as elevated temperature tensile ductility. Figure 8 shows that weldability, as measured by the Varestraint test using TCL, has an inverse linear relationship to the B content; as the B content increases, the weldability decreases linearly. All data points are the result of an average of at least three and as many as nine tests.

When grain size is taken into account, ASTM 4-6 vs. 0-1, the weldability tends to be the same above 60 ppm boron, but improves for the fine grain sizes ASTM 4-6 at the 30 ppm B level, as shown in Fig. 8. However, when the cast grain size of Alloy 718 or Rene' 220C drops into the ASTM 4-6 range, then the notch rupture behavior becomes erratic below the 30 ppm level. Therefore, any gain in weldability is offset by the loss of rupture ductility in the 1300°F (2372°F) range for Rene' 220C.

The evaluation of elemental effects on the weldability of Rene' 220C produced much the same results as the initial elemental screening to determine what was causing the poor weldability. Tantalum was found to be the only alloying element that was beneficial to weldability, while Nb, Ti and Al were found to be mildly detrimental, with B and Cr found to be very detrimental to the weldability of the alloy. These results appear in Table 1.

Measurement of Repair and Fabrication Weldability

The repair weldability was evaluated by comparing similar repair weldments of actual components cast from Alloy 718 and Rene' 220C at PCC. Each component had four areas which received simulated repair welds at GE's request. A schematic of areas receiving repair welds is shown in Fig. 3. A simulated repair weld is a GTAW made into a sound area of a casting that has been ground out to resemble a ground out defect location. Both components had six simulated repair welds made at each of the four shaded locations in Fig. 3. The weldments were then sectioned and examined metallographically for HAZ microcracks. Figure 9 shows that Rene' 220C was substantially better in repair weldability, as measured by the frequency and size of HAZ microcracks, than cast Alloy 718.

The defect areas that are identified after electron beam fabrication welds are

Table 1—The Effect of Major Alloying Elements on the Weldability of Rene' 220C

Weldability Measurement	Nb	C	B	Co	Ta	Mo	Ti	Al	Cr	G.S.
Total Crack Length	−−/4%		−−/26%		++/2%				−−/11%	−Sm/13%
Number of Cracks							−−/1%			−Sm/46%
Average Crack Length			−−/43%					−−/5%	−−/6%	

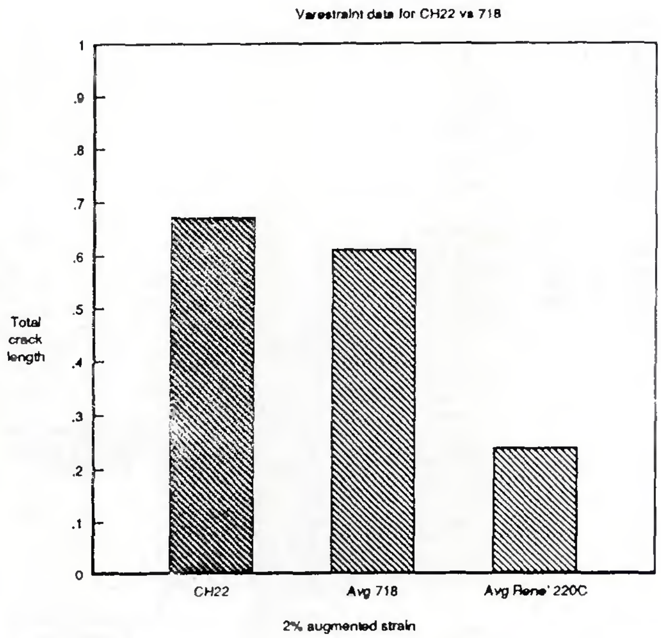


Fig. 5 — This graph compares the weldability of cast Alloy 718 to that of the Alloy CH22 with 100-ppm 8 and shows improvement in weldability caused by reducing the B to 30 ppm in René 220C.

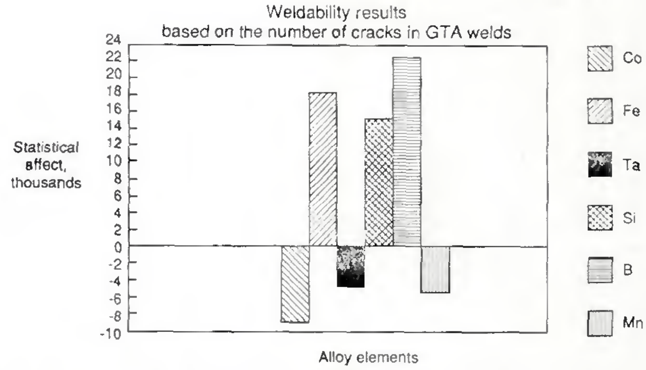


Fig. 6 — The results of a previous study on the effect of a major nickel-based superalloy alloying elements on the weldability of a generic nickel-based superalloy designed primarily around the Alloy 718 chemistry.

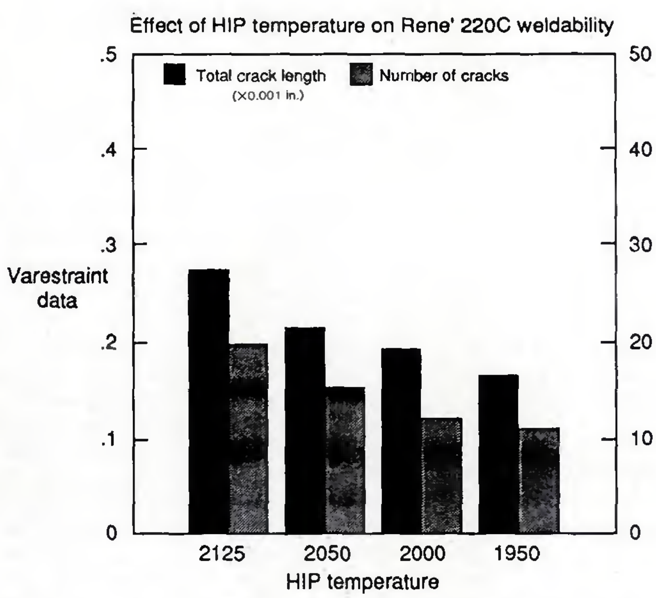


Fig. 7 — The effect of HIP temperature on the weldability of Rene' 220C as measured by Varestraint testing at 2% augmented strain using conventional cast grain size and 30-ppm B.

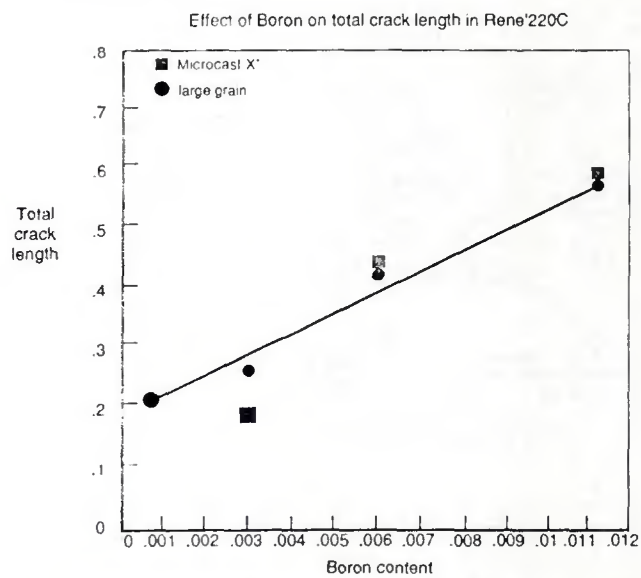


Fig. 8 — The effect of B content on the weldability of Rene' 220C as measured by the Varestraint test using 2% augmented strain for conventionally cast grain sizes of 0 to 6 for Rene' 220C.

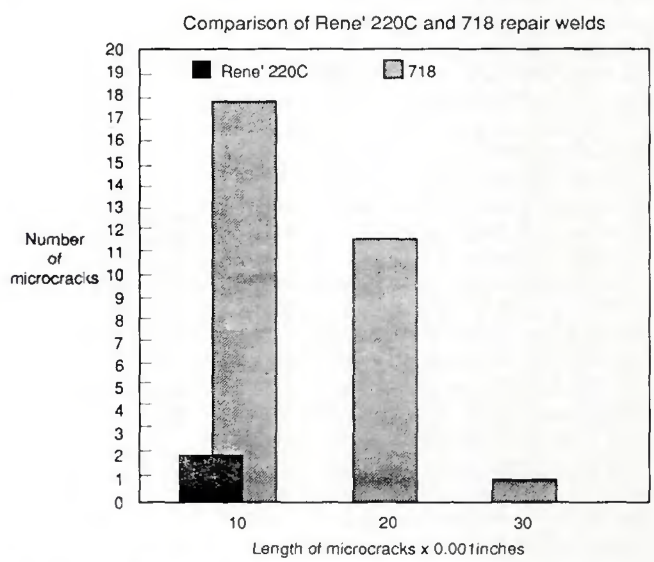


Fig. 9 — Display of the total number of microcracks counted and measured from the two components simulated repair weldment studies.

usually routed out and repaired using GTAW much the same as foundry repair procedures. In order to determine the fabrication weldability of Rene' 220C, the actual fabrication EBW parameters had to be established using actual hardware. Then properties were determined using these parameters to make weldments of cast slabs resembling the actual components in heat sink.

Using sections of the actual hardware, the HAZ microcracking tendency of Rene' 220C in production EBW was compared to cast Alloy 718. This was easily done by making weldments of cast Alloy 718 to cast Rene' 220C. An example of the HAZ microcracking found in these weldments is shown in Fig. 10. The cast Alloy 718 side of the weldment displays several microcracks, while the Rene' 220C has none. A similar weldment is made to wrought Alloy 718, and a representative microstructure shown in Fig. 11 contained no microcracks in either the wrought 718 or the cast Rene' 220C HAZ.

As part of the fitness-for-service portion of the weldability definition, the mechanical properties of the weldments had to be established. This was evaluated by cutting test specimens from cast slabs that had been welded together using the EBW parameters used for fabricating the actual component. Table 2 contains the results of the low-cycle fatigue, and notch and smooth rupture tests across the weldment. There is no difference evident in the average properties of the weldments compared to the base metal. All of the weldments either did not fail, or failed in the cast 718 or HAZ of the Rene' 220C when weldments included wrought 718.

Discussion

The compositional difference between the cast alloys 718 and Rene' 220C is that Alloy 718 is based on the Ni-Cr-Fe-Nb system, while Rene' 220C is based on the Ni-Cr-Co-Nb system with an addition of Ta. This provides a major difference when it comes to the weldability of the alloys. Carlson and Radavich (Refs. 19, 28) found that both alloys experience the same amount of segregation during solidification to form the investment cast microstructure.

Wlodek (Ref. 23) found that the terminal solidification phase in Rene' 220C is not a Laves phase eutectic as it is with Alloy 718 (Fig. 12), but rather an unstable globular eutectic delta phase, as shown in Fig. 13. The globular delta is unstable only in that it breaks down to form delta plates during heat treatment. The absence of Fe (which is a Laves phase promoter) (Ref. 24) from the alloy composition retards the development of Laves phase in the interdendritic area and at the grain boundaries. Further, as shown in Fig. 14, the delta plates in Rene' 220C are stable up to the

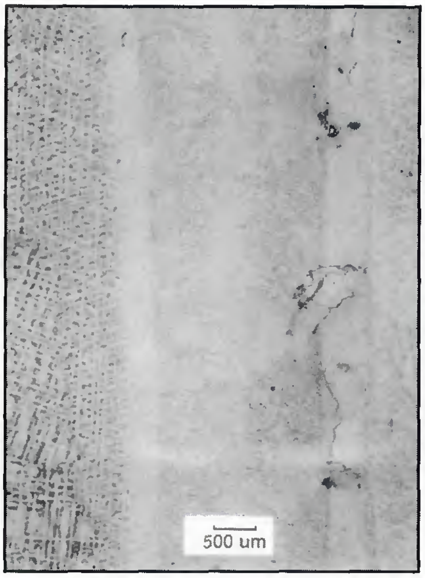


Fig. 10—Microstructure of a typical electron beam weldment of cast Alloy 718 to cast Rene' 220C showing the HAZ microcracking in the cast Alloy 718 compared to the crack-free HAZ on the Rene' 220C side of the weld.

Fig. 11—Microstructure of a typical electron beam weldment of wrought Alloy 718 to cast alloy Rene' 220C showing the microcrack-free HAZ.

Table 2—Results of Mechanical Property Tests from Rene' 220C Fabrication Weldments to Both Cast and Wrought Alloy 718.

	Low-Cycle Fatigue			
Weldment Type	Temp. (°F)	Stress (ksi)	Ns (kHz)	Location
Wrought 718/Cast Rene' 220C	1100	100	40	Cast Rene' 220C
Wrought 718/Cast Rene' 220C	1100	80	478	Rene' 220C HAZ
Wrought 718/Cast Rene' 220C	1100	60	511	Rene' 220C HAZ
Cast 718/Cast Rene' 220C	1100	100	4.5	Cast 718 HAZ
Cast 718/Cast Rene' 220C	1100	80	9.8	Cast 718 HAZ
Cast 718/Cast Rene' 220C	1100	60	503	Cast 718 HAZ

	Stress Rupture	
Weldment Type	Rupture Life	Notch Rupture Life
	1300°F/90 Ksi	1300°F/90 KSI
Wrought 718/Cast Rene' 220C	200+	200+
Cast 718/Cast Rene' 220C	200+	200+

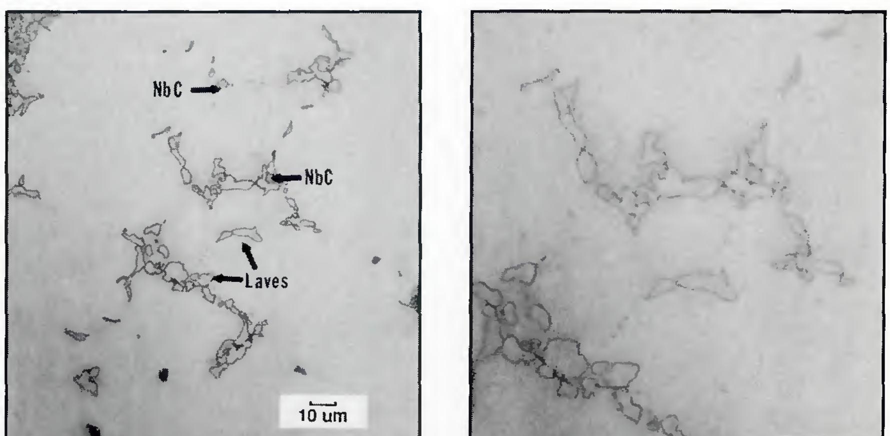


Fig. 12—The as-cast microstructure of Alloy 718.

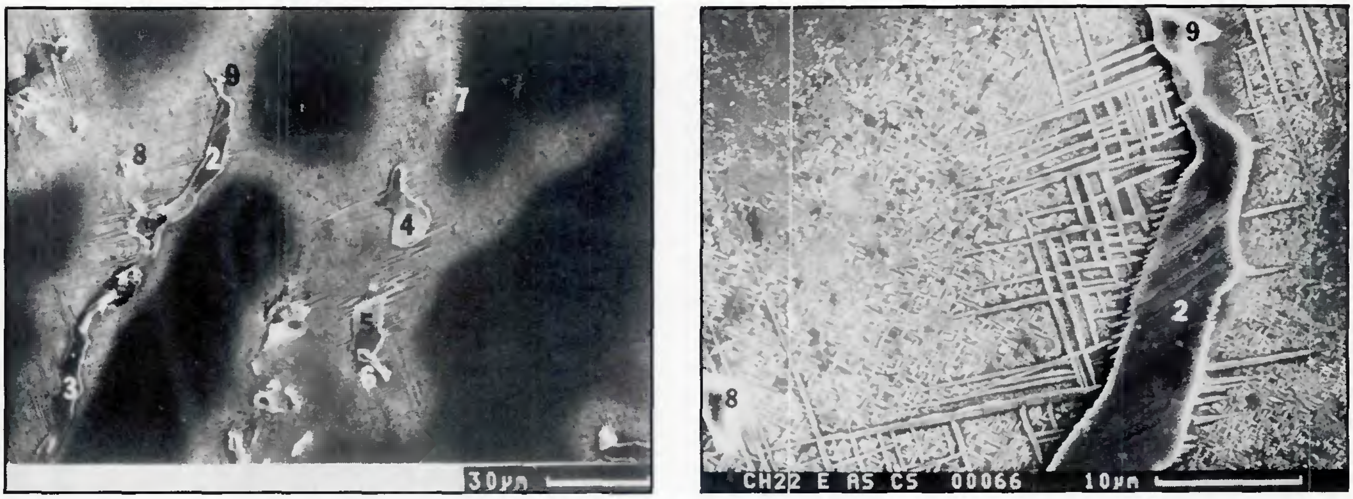


Fig. 13 — The as-cast microstructure of Rene' 220C.

fusion boundary of the EB weldment. It is believed that the increase in Ta in the delta phase has resulted in increased stability for this phase.

Previously, welding researchers have cited several Nb-related phases as responsible for HAZ microcracking in cast Alloy 718. Baeslack (Refs. 7, 9) cites both NbC constitutional liquation and the Laves eutectic reaction, respectively, as being responsible for HAZ microcracking. Thompson (Refs. 15,16) cites NbC constitutional liquation in wrought Alloy 718 and sulfur segregation in both wrought and cast 718 for HAZ microcracking. Kelly (Refs. 5, 6) demonstrated the B content of cast Alloy 718 was the most influential element in causing HAZ microcracking regardless of S, C or Nb content of the alloy — Fig. 15.

Earlier, Kelly (Ref. 30) determined the effect of the tramp elements, S, P, O and N, on the weldability of Rene' 220C. This study used a statistically designed experiment that varied the tramp elements to levels well above specification maximums, but obtained no discernible pattern for the effects of tramp elements on weldability within the compositional limits tested — Fig. 16. However, when boron, which was intended to be constant but varied over a range of 16 ppm, was added to the results, the statistical analysis became more complete with a large increase in the amount of data explained by the analysis. This again was due to boron's overwhelming effect on the weldability of cast nickel-based superalloys blocking out the effects of the tramp elements S, P, O and N, as it did in the previous study with cast Alloy 718 (Ref. 6). The lack of effect demonstrated by the maximum specification amounts of the tramp elements in these two studies points out the excellent work done over the years to establish the safe limits for tramp elements such as S, in order to avoid a HAZ microcracking problem in cast nickel-based superalloys.

Fig. 14 — The HAZ microstructure of an electron beam weldment of Rene' 220C showing an unmelted delta plate projecting into the fusion zone.

Baeslack (Refs. 2–4) has shown that the replacement of Nb with Ta in the Ni-Cr-Fe-Nb alloy system improves the resistance of the alloy system to HAZ microcracking due to two factors:

1) Ta tends to promote less Laves phase upon solidification.

2) The Laves phase that does form has a eutectic temperature approximately 140°F (77°C) higher than the Ni_2Nb formed with Nb.

Additionally, Kelly (Ref. 5) showed that statistically both Ta and Co additions to the basic Alloy 718 composition improve resistance to HAZ microcracking — Fig. 6. Therefore, it is not surprising that the replacement of Fe with Co in the Ni-Cr-Nb alloy system yields an alloy with greater HAZ microcracking resistance than cast Alloy 718. However, the initial weldability of CH22 with 100 ppm B was worse than that of cast 718 with 30 ppm B, as shown in Fig. 5, even with its known higher Laves phase content. However, Fig. 5 shows that for an equivalent B content Rene' 220C had a significantly better weldability than cast Alloy 718.

This wasn't surprising since B was shown in Fig. 6 to be the most potent source of HAZ microcracking in the Ni-Cr-Nb alloy system. What is surprising is the inverse linear relationship to weldability shown for B content in Rene' 220C. Pease (Ref. 31) had set an upper limit on B at 300 ppm

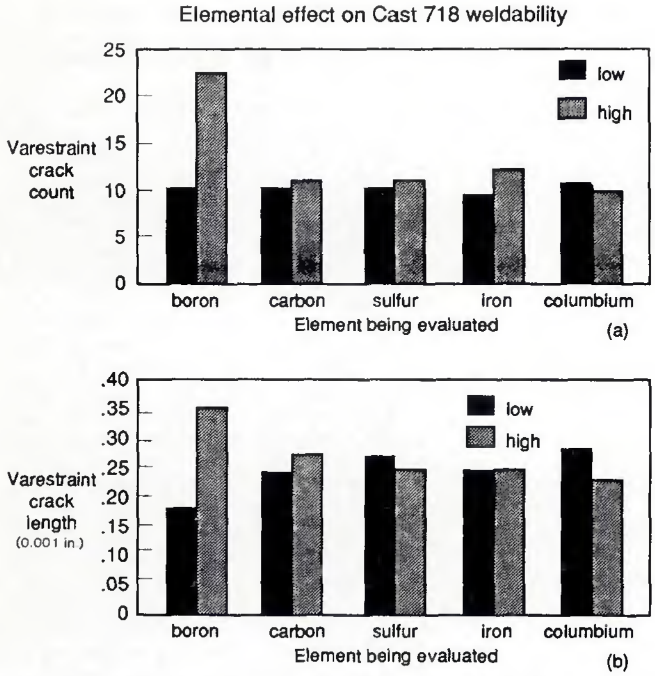


Fig. 15 — The effect of B on the weldability of cast Alloy 718 compared to the effects of the full specification range of the other elements typically cited as the cause of HAZ microcracking.

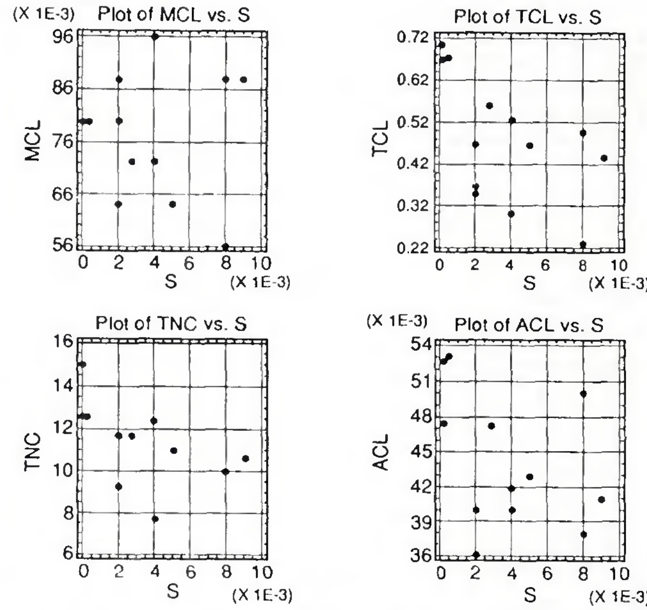


Fig. 16 — Raw data plots of the response to sulfur of the various spot Varestraint test results, showing no discernible pattern.

for the safe limit to avoid microcracking in Ni-based superalloys; however, Fig. 8 shows that the effect of B on weldability is linear down to approximately 10 ppm.

The results showing Cr to be detrimental to weldability in Rene' 220C were in general agreement with the teachings of Snyder and Brown (Ref. 32), who found that the weldability of cast 718 could be improved by lowering the Cr content to below 15%. In their patent, they show by quantitative metallography that lower Cr 718 contains less Laves phase and is more microcrack resistant during welding. Although no quantitative metallography was done in the Rene' 220C weldability study, it is likely that this same effect is being demonstrated by the spot Varestraint data of the cast Rene' 220C material.

Further, it has been shown in Fig. 7 that there is an inverse linear relationship of weldability with HIP temperature. As HIP temperature increases, the weldability of Rene' 220C decreases, which is similar to what was shown for cast Alloy 718 by Kelly (Ref. 6). This is probably due to a grain boundary reaction observed (Ref. 5) at approximately 2000°F (1093°C). This reaction was only seen in B-containing alloys and provided an easily wetted grain boundary surface for whatever phase was available to liquate in a bulk manner. Therefore, even the direct effect of HIP temperature on weldability likely relates back to the B content of the alloy.

From Fig. 8 it appears that the effect of B on Rene' 220C weldability is concentration- and grain-size dependent in that at high B levels the weldability of ASTM grain size 0–6 is the same, but at low B levels (30 ppm) the ASTM grain size 4–6 weldability improves with respect to the larger grain size 0–1. This may be due to the amount of B available to cover the grain boundary area. Since these are equiaxed cast grains, they can be assumed to approximate spheres, and therefore, the grain boundary area would be proportional to the square of the grain diameter. Consequently, the change in grain size from ASTM 1 to 5 would mean about a 25-fold increase in grain boundary surface. Thus, if the effect of B is limited to grain boundary reactions, then as the B level drops to 30 ppm, the effects would be expected to show up first as improved weldability on the fine grain microstructure.

In Fig. 8, the fine grain size, ASTM 6, is more weldable as measured by the Varestraint test than the coarse grain size ASTM 0–1 with the same 30 ppm B content, which is the first indication that the weldability is grain-boundary-concentration dependent. This indicates that there is a critical grain boundary B level required to cause a drop in the weldability. Unfortunately, the current analytical techniques are not capable of detecting low levels of boron, so the actual level required to reduce weldability can only be conjectured. However, the fact that the notch rupture behavior of the alloy becomes erratic in the ASTM grain size 4–6 material as the weldability increases with lower boron content is another indication of the effect being due to too little boron to cover the increased grain boundary area.

All of the preceding data were developed using Varestraint testing on laboratory-size specimens; however, it was not known how this related to the real world. In Fig. 9, the number of actual HAZ microcracks from 48 simulated identical repair welds of cast Alloy 718 and Rene' 220C are compared, and these data indicate that the difference shown in the spot Varestraint tests is conservative at best. Furthermore, metallographic evaluation of EBW fabrications (Fig. 10) also confirms the superior weldability of the new alloy over cast Alloy 718.

Summary

Rene' 220C is superior to Alloy 718 as a structural casting alloy both from weldability and mechanical property viewpoints. It has also been demonstrated that the alloy's weldability is inversely related to the HIP temperature. Additionally, it has been shown that the weldability of this alloy is directly affected by its B content, and at approximately 60 ppm, it becomes equivalent to Alloy 718 at 30 ppm boron.

Boron in bulk amounts lower than 20 ppm is difficult to accurately analyze for using available technology, and virtually impossible to isolate in grain boundaries until concentrations become high enough to form borides. Therefore, 30 years ago when Pease did his work, the 300-ppm level of boron may have been the limit of detectability.

Boron has now been identified as the primary cause of HAZ liquation cracking (microcracking) in two cast Ni-Cr-Nb superalloys and is probably the main contributor to liquation cracking in most of the other cast nickel-based superalloys containing boron, since it is usually added in amounts exceeding 50 ppm for intermediate-temperature grain boundary ductility. However, it is no easier to observe B now than it has been in the past, but if a means of counteracting its negative effects on weldability is to be found, an increased effort must be made to determine the mechanism. Once the mechanism is understood then it may be possible to make use of boron's beneficial effects on high-temperature properties without the detrimental effects on weldability.

Conclusions

1) The weldability of Rene' 220C is much better than that of cast Alloy 718.

2) Boron concentration has the largest detrimental effect on the HAZ microcracking in Rene' 220C. The microcracking tendency of Rene' 220C increases linearly with the boron content between 20 ppm and 100 ppm.

3) The weldability of Rene' 220C is inversely related to HIP temperature. As the HIP temperature increases from 1950°F to 2150°F (1065°C to 1177°C), the weldability related to HAZ microcracking decreases linearly.

4) Both GTA and EB weldments of Rene' 220C can attain similar mechanical properties to that of the matrix material.

5) There is no difference in the weldability of various grain sizes (ASTM 0 to 6) of cast alloy Rene' 220C as measured by the spot Varestraint test in the 60- to 110-ppm boron range.

6) The addition of Ta and the substitution of Co for Fe in Rene' 220C improve the HAZ microcracking resistance of Rene' 220C over that of cast Alloy 718 by reducing the amount of Laves phase present for the eutectic liquation reaction in the HAZ.

7) The tramp elements S, P, O and N have no more effect on the weldability of Rene' 220C than they do on cast Alloy 718.

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References

1. Chang, K.-M., and Nahm, A. H. 1989. Rene' 220: 100°F improvement over Alloy 718. *Superalloy 718 Metallurgy and Applications,* TMS, Edited by E. Loria.

2. Baeslack, W. A. III, West, S., and Kelly, T. J. 1988. Presentation to the AWS Annual Meeting, New Orleans, La.

3. Baeslack, W. A. III, Kelly, T. J., and West, S. L. 1988. Weld cracking in Ta-modified cast Inconel 718. *Scripta Metallurgica,* Vol. 22, pp. 729-734.

4. Baeslack, W. A. III, Kelly, T. J., and West, S. L. Morphology of weld heat-affected zone liquation cracking in Ta-modified cast Alloy 718. To be published in *Metallography*

5. Kelly, T. J. 1986. Investigation of elemental effects on the weldability of cast nickel-based superalloys. ASM, *Trends In Welding Research,* Gatlinburg, Tenn.

6. Kelly, T. J. 1989. Elemental effects on cast 718 weldability. *Welding Journal* 68(2):44-s.

7. Baeslack, W. A. III, and Tsay, Y. L. 1984. An investigation of heat-affected zone cracking in Alloy 718. Ohio State University, Columbus, Ohio.

8. Baeslack, W. A., Ernst, S., and Lippold, J. C. 1988. *Weldability of High-Strength Low-Expansion Superalloys.* MR8811, Edison Welding Institute.

9. Baeslack, W. A. III, and Nelson, D. E. Morphology of heat-affected zone liquation in cast Alloy 718. *Metallography* 19(3):371-379.

10. Kelly, T. J., Cremisio, W. H., and Simon, W. H. 1989. An evaluation of the effects of filler metal composition on cast Alloy 718 simulated repair welds. *Welding Journal* 68(1):14-s to 18-s.

11. Vicent, R. 1985. Precipitation around welds in the nickel-base superalloy, Inconel 718. *Acta Met.* 33(7):1205-1216.

12. Owczarski, W. A., Duvall, D. S., and Sullivan, C. P. 1966. A model for heat-affected cracking in nickel-base superalloys. *Welding Journal* 45(4):145-s to 155-s.

13. Owczarski, W. A., and Duvall, D. S. 1967. Further heat-affected zone studies in heat-resistant nickel alloys. *Welding Journal* 46(9):423-s to 432-s.

14. Owczarski, W. A. 1967. Some minor element effects on weldability of heat-resistant nickel-base superalloys. *Proceedings of the Symposium — Effects of Minor Elements on the Weldability of High-Nickel Alloys,* Welding Research Council, p. 6-24.

15. Thompson, R. G., and Genculu, S. 1983. Microstructural evolution in the HAZ of Inconel 718 and correlation with the hot ductility test. *Welding Journal* 62(12):337-s to 345-s.

16. Thompson, R. G. Relationship between microstructure and microfissuring in Alloy 718, to be published in *Welding Journal.*

17. Thompson, R. G., private communication to G. E.

18. Shira, C. S., Morrison, T. J., and Weisenberg, L. A. 1967. The influence of minor elements on Alloy 718 weld microfissuring. *Proceedings of the Symposium — Effects of Minor Elements on the Weldability of High-Nickel Alloys,* Welding Research Council, pp. 47-68.

19. Radavich, J. F., and Carlson, R. C. *Microstructural Characterization of Cast 718.* TM No. 85-512, General Electric, Evendale, Ohio.

20. Nakao, H., Oshige, H., Koga, S., Nishihara, H., and Sugitani. 1982. *Journal of Japan Welding Society* 51(12):989-995.

21. Cieslak, M. J., Headley, T. J., Kollie, T., and Romic, A. D., Jr. 1988. A melting and solidification study of Alloy 625. *Met. Trans. A,* Vol. 19A, pp. 2319-2331.

22. Knorovsky, G. A., Cieslak, M. J., Headley, T. J., Romic, A. D., Jr., and Hammetter, W. F. Inconel 718: A solidification diagram. To be published in *Met. Trans.*

23. Wlodek, S., and Field, R. D. The structure of Rene' 220C. R87AEB472, General Electric, Evendale, Ohio.

24. Sims, C. T., Stoloff, N. S., and Hagel, W. C. 1987. *Superalloys II,* John Wiley & Sons, New York, N. Y., pp. 233-234.

25. Wasielewski, G. E., and Lindblad, N. R. 1972. Elimination of casting defects using HIP. *Superalloys Processing,* MCIR, Columbus, Ohio, D1-D24.

26. Bologna, D. J. 1969. Metallurgical factors influencing the microfissuring of Alloy 718 weldments. *ASM Metals Engineering Quarterly,* pp. 37-43.

27. Adam, P. 1977. Welding of high-strength gas turbine alloys. MTU, Dachaueratr, 665, 8000 Munchen 50.

28. Radavich, J. F., and Carlson, R. C. Unpublished research on Rene' 220C.

29. Wu, Yuin. 1978. *Orthogonal Arrays and Linear Graphs.* American Supplier Institute, Inc.

30. Kelly, T. J. 1989. Elemental effects on the weldability of Rene' 220C. ASM, *Trends In Welding Research,* Gatlinburg, Tenn.

31. Pease, R. E. 1957. The practical welding metallurgy of nickel and high-nickel alloys. *Welding Journal*

32. Snyder, S. M., and Brown, E. E. 1988. U. S. Patent 4,750,944, Laves-Free Cast + HIP Nickel-Base Superalloy.