PRODUCTION EVALUATION OF 718-ER® ALLOY

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Abstract

Allvac 718-ER® alloy, for "extended rupture life," is a slightly modified version of alloy 718 with increased phosphorous (P) and boron (B) content. A full-scale production trial was conducted to evaluate 718-ER in comparison with standard alloy 718. The processing characteristics of both alloys in melting/remelting, homogenization and hot working were evaluated. Microstructure and mechanical properties were also compared in detail with those of standard 718. Results showed that 718-ER could be manufactured in nearly the identical manner as standard 718. Consistent with earlier subscale results, tensile properties changed very little, but nearly a 100% improvement in stress rupture and creep properties was achieved in a full scale production heat of 718-ER.

Introduction

Previous studies performed at Allvac[1-4] have shown that increasing the P content of alloy 718 significantly improved the stress rupture/creep properties, although P has generally been regarded as a detrimental element in superalloys. In addition, it was found that there was a strong synergistic effect between P and B, i.e. the stress rupture/creep properties could be further improved by controlled additions of both P and B. In comparison with standard alloy 718, the increase in stress rupture life may reach 100-200% at the optimum combination of 0.022%P and 0.011%B. Other mechanical properties of 718-ER, such as strength, ductility and low cycle fatigue, are basically identical to those of standard 718.

Subsequent studies[5-8], performed in China, have demonstrated similar effects. Tensile properties were not noticeably affected, but significant improvement of up to 300% in stress rupture life and creep rate was observed. The optimum P level reported in these studies was quite close to that found in references 1-4.

Detailed studies on 718-ER have been conducted on small pilot plant heats, but to fully determine the commercial potential, a production scale evaluation was critical. Therefore, a project was initiated to make a full-size heat of 718-ER and to evaluate its processing characteristics, macro and microstructures, and various mechanical properties. To make a better comparison, one standard 718 heat was made by identical processing, side by side, and evaluated together with a 718-ER heat.

Experimental Procedures

Manufacture of Test Alloys

A 9080-kg vacuum induction melted, 508mm Rd vacuum arc remelted 718-ER heat, JG61 was made using standard 718 procedures. Three heats of standard alloy 718 were selected for comparison. The majority of this study was conducted on standard heat JG60 that was made immediately prior to JG61. In some cases, two other standard 718 heats (EU03 and EW02) were used, mainly due to material availability for that specific test.

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All ingots were homogenized at identical conditions and forged in the same manner to 203mm diameter billet. The billets were peeled, ground and immersion-sonic inspected to a number two flat bottom hole. Macro plates were cut at different ingot locations for inspection. Additional test material was taken from hot rolled 16mm Rd bar and coupons (pancakes) upset-forged from 51mm cubes.

Segregation Behavior and Hot Workability

Studies[9,10] have shown that P and B may increase the tendency of microsegregation of Nb and other elements in alloy 718, and that increased segregation could adversely influence hot workability. Therefore, a detailed study was conducted to characterize the segregation behavior and hot workability both in as-cast and wrought conditions.

Microsegregation in the as-cast condition was judged by volume fraction of Laves eutectic determined by quantitative metallography. In the homogenized condition, the Nb content in areas corresponding to the center of interdendritic and dendrite arms was measured by Energy Disperse Spectroscopy (EDS), and the ratio was used as an indicator of microsegregation severity.

The hot workability of as-cast and as-homogenized ingot materials was investigated by the rapid strain rate hot tensile (RSRHT) test and reduction in area and elongation used as an indicator of hot workability. Differential thermal analysis (DTA) was also performed on both alloys to determine incipient melting temperatures which could be used as an indirect measure of hot workability and provide important clues for explaining the results obtained by RSRHT.

Evaluation in the wrought condition was done on the 203mm Rd forged billets. The distribution of Nb across the lightly banded structure revealed by etching was determined by EDS, and the microsegregation characterized again by the Nb ratio between "dark" and "light" bands that correspond respectively to dendrite arms and interdendritic areas in the as-cast structure. Due to detectability limits of EDS, a progressive solution treating method of evaluating delta solvus temperature was also used to determine the degree of microsegregation. This procedure involved incrementally solution treating micro samples from pancakes. The grain growth behavior was examined and grain size was plotted as a function of solution temperature.

Mechanical Property Tests

The mechanical properties, including room and elevated temperature tensile, stress rupture and creep properties, were tested on various product forms, including forged billet, pancakes and rolled bar. Since all previous pilot plant heats had been evaluated on the same size rolled bars, this test may provide the best comparison of the effect of P-B modification in pilot plant and production heats. All samples were subject to standard heat treatment (954°C x 1 hr., AC + 718°C x 8 hrs., FC at 56°C/hr. to 621°C and held 8 hrs., AC).

Microstructure and Fractographic Study

Samples were studied by optical and scanning electron microscopy to define the effect of P and B on the microstructure. A fractographic study was also conducted on broken stress rupture samples to check for changes in failure mode with increased P and B levels.

Experimental Results

Chemistry and Segregation

The chemistries of all materials tested in this program are listed in Table 1. The P level of JG61 (718-ER) was at the optimum level for 718-ER, but B was lower and C higher than optimum, as defined from prior work with pilot plant heats[1-4].

As-cast microstructures are shown in Figure 1. Quantitative metallographic study on ingot samples indicated that as-cast 718-ER contained about 20% more Laves phase eutectic, suggesting that P and B promote Nb segregation. This is consistent with prior studies[9]. However, essentially all Laves phase particles were eliminated after a standard homogenization treatment of both alloys. Results of EDS for Nb segregation are shown in Table II. These data suggest that residual Nb interdendritic segregation in the ingot, following homogenization, is higher in 718-ER than in the standard alloy. There is, however, significant scatter in the data.

In the wrought condition, EDS results still show slight evidence of segregation, but there does not appear to be a significant difference between the two alloys. This conclusion is supported by results of the progressive solution treatment test of as-forged samples. Grain size, plotted in Figure 2 as a function of solution temperature, shows almost identical grain growth behavior between alloy 718 and 718-ER.

Hot Workability

Percent elongation and reduction in area of data from RSRHT testing are listed in Table III. The data for as-homogenized ingots is plotted in Figure 3. From these results, it is apparent that the reduction of area for these two alloys is very comparable except at the very highest test temperature. Fortunately, 1204°C is well above the standard forging temperature for 718. Percent elongation results were higher for 718-ER at all test temperatures except 1204°C. These data are consistent with the actual processing results in that no difficulties were encountered during the forging of heat JG61 and no sonic defects were found on U/T inspection.

RSRHT tests of billets resulted in a similar trend as for ingots (see Table III and Figure 4). Surprisingly the fall off in hot ductility occurred at an even lower temperature in 718-ER billet. In general, ductility for billet was higher than for ingot, especially at the lower test temperatures and for elongation. As for the case with ingot, the lower hot ductility displayed for 718-ER at the higher temperatures should not be a problem in normal production since standard forging temperatures are in the range of 1121°C or less.

Table I. Chemistries of 718-ER® and 718 Heats

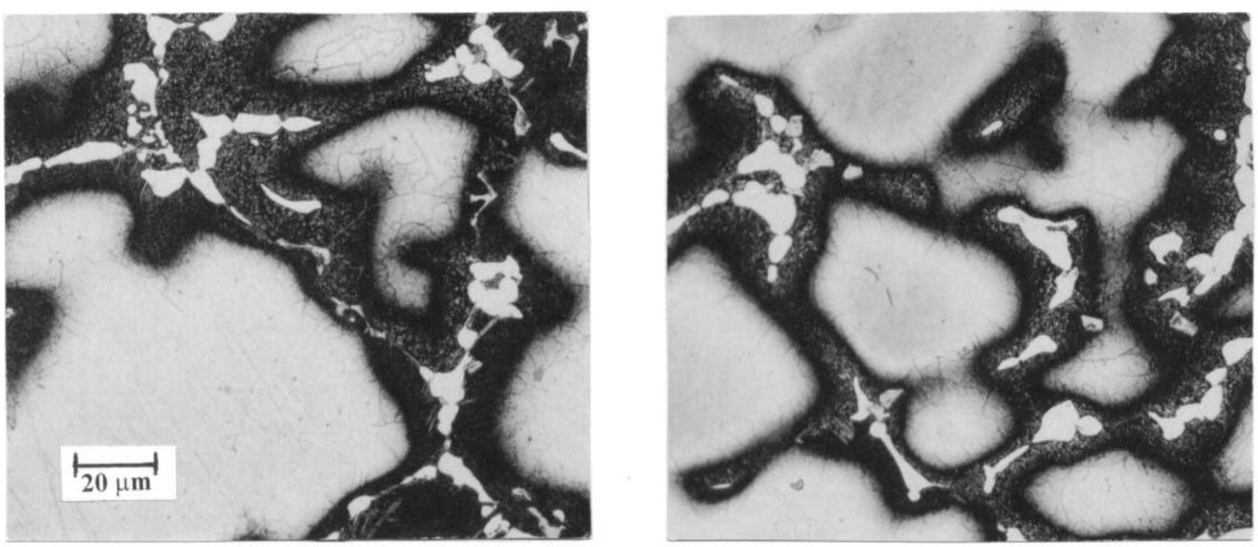
Element Wt.%	C	Mo	Cr	Fe	Mn	Si	Nb	Ti	Al	S*	P*	B*
JG61	0.023	2.92	17.9	17.5	0.06	0.08	5.39	0.99	0.57	4	220	77
JG60	0.022	2.90	18.0	17.4	0.08	0.09	5,36	0.96	0.57	4	60	40
EU03	0.026	2.93	18.1	17.1	0.06	0.10	5.44	0.97	0.49	4	80	37
EW02	0.023	2.90	18.1	17.2	0.08	0.11	5.37	0.94	0.49	5	50	41

* Contents of S, P and B are in ppm, others weight percent.

Table II. EDS Results of Microsegregation Analysis in Homogenized Ingot and Forged Billet

Alloy (Heat No.)	Nb Content in Homogenized Ingot			Nb Content in 203mm Rd Forged Billet		
	Interdendritic Area	Dendritic Arm	Nb Ratio	"Light" Bands	"Dark" Bands	Nb Ratio
718-ER (JG61)	5.77 +0.53/-0.32	4.18 +0.27/-0.19	1.380	4.77 +0.52/-0.59	4.51 +0.09/-0.11	1.058
718 (JG60)	–	–	–	4.98 +0.37/-0.86	4.62 +0.71/-0.71	1.078
718 (EU03)	5.22 +0.39/-0.46	4.39 +0.33/-0.41	1.189	–	–	–

Average of 12 independent measurements, weight percent.



(a) (b)

Figure 1. Cast Ingot Microstructure. (a) 718, EU03, (b) 718-ER®, JG61.

Table III. Results of Rapid Strain Rate Hot Tensile Tests of Ingot and Billet

	Hot Ductility (%)	Alloys	Test Temperature (°C)					
			927	1038	1093	1149	1177	1204
As-cast Ingot	EL	718 (EU03)	–	86.3	–	81.3	–	–
		718-ER (JG61)	–	70.7	–	6.5	–	–
	RA	718 (EU03)	–	95.9	–	80.3	–	–
		718-ER (JG61)	–	97.6	–	8.1	–	–
Homo-genized Ingot	EL	718 (EU03)	14.5	23.7	18.0	44.3	40.5	21.4
		718-ER (JG61)	28.8	37.8	67.9	67.5	54.8	1.4
	RA	718 (EU03)	44.6	72.1	88.2	93.7	84.1	82.0
		718-ER (JG61)	34.7	68.7	94.4	86.2	82.4	1.2
203mm Rd Billet	EL	718 (EU03)	36.9	50.7	47.3	52.0	53.7	12.3
		718-ER (JG61)	75.1	93.0	112.0	20.0	6.6	–
	RA	718 (EU03)	98.2	99.3	98.7	98.9	93.5	21
		718-ER (JG61)	98.0	98.9	98.9	20.0	0.8	–

Notes: 1. EL and RA are the elongation and reduction in area, respectively.
2. Each data is the average value of two independent measurements.

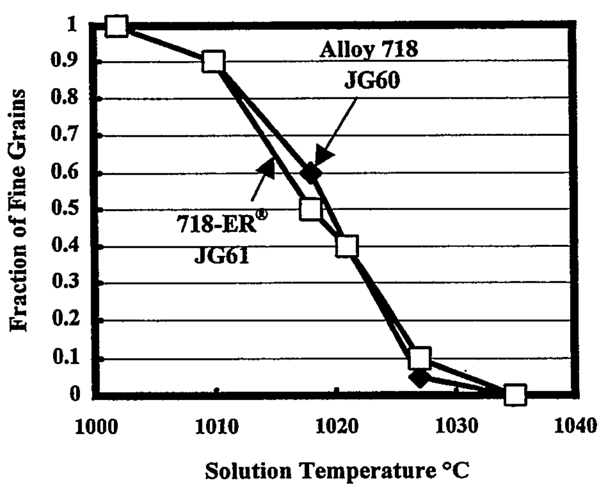


Fig. 2. Fraction of Fine Grains as Function of Solution Temperature in Progressive Solution Treatment.

Differential thermal analysis (DTA) showed that P and B in the range used had a minor effect on incipient melting (Laves eutectic) temperature of as-cast alloys. Only about a 6°C drop in temperature was seen in 718-ER (1143-1198°C to 1137-1188°C). There was almost no difference in incipient temperature of the wrought alloys (~1214°C). This seems somewhat inconsistent with the RSRHT test results.

Mechanical Properties

The mechanical properties of the various products tested are listed in Tables IV and V. Tensile properties within the three products tested were not significantly different for the two alloys. While ductilities were slightly lower at room temperature for 718-ER, they may be slightly higher at 649°C. The slightly higher strength for 718-ER billet most likely reflects a slight difference in structure.

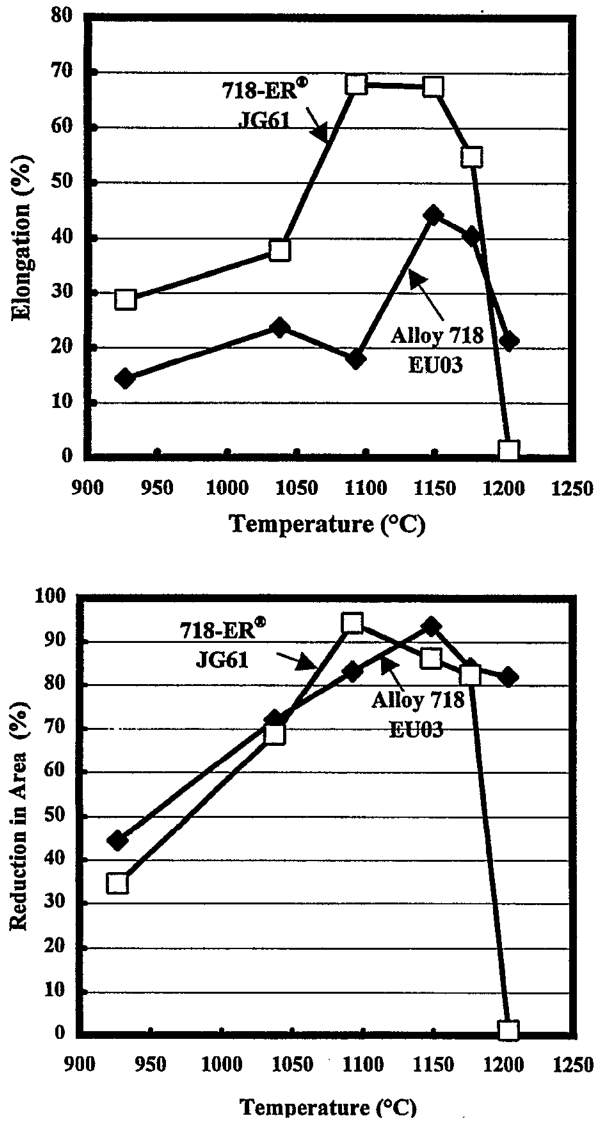


Fig. 3. Hot Ductility of Homogenized Ingots as Function of Test Temperature.

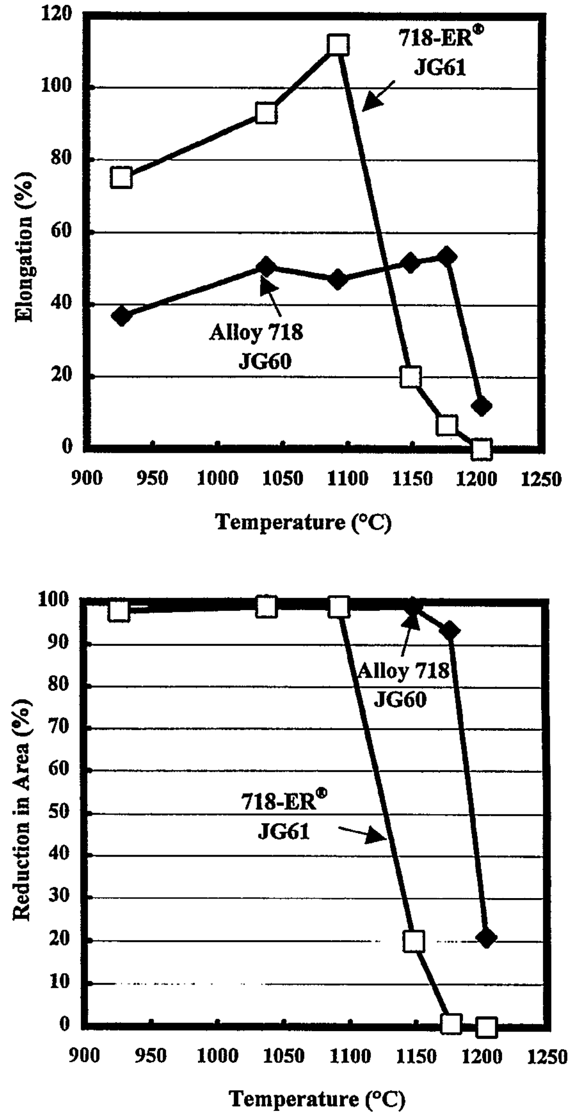


Fig. 4. Hot Ductility of 203mm Billets as a Function of Test Temperature.

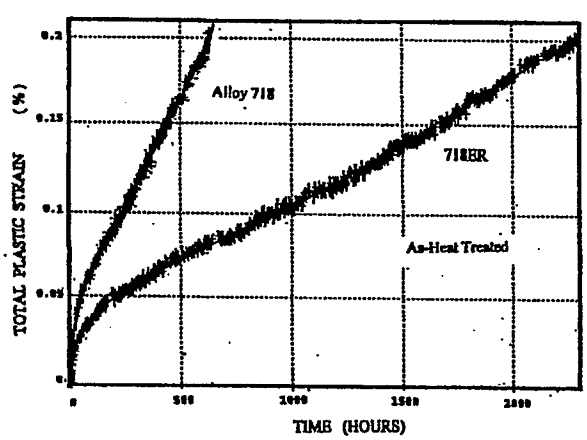


Fig. 5. Creep Curves of 718 (JG60) and 718-ER® (JG61) Pancake Samples, 621°C/621 MPa.

Table IV. Tensile Properties of Billets, Pancakes and Rolled Bars

Product Form	Alloy	Room Temperature Tensile				649°C Tensile			
		UTS MPa	YS MPa	EL %	RA %	UTS MPa	YS MPa	EL %	RA %
203mm Rd(1) Billet	718 (JG60)	1367	1134	20.8	40.2	1112	934	24.9	36.4
	718-ER (JG61)	1406	1237	17.7	38.0	1142	1038	23.8	43.0
Pancake(2)	718 (JG60)	1427	1108	18.8	28.0	1133	939	20.8	28.3
	718-ER (JG61)	1428	1096	16.5	19.7	1140	940	21.6	34.5
16mm Rd Bar	718 (EW02)	1459	1202	20.2	40.6	1174	1011	17.6	27.0
	718-ER (JG61)	1465	1216	19.6	38.5	1192	1004	23.9	57.9

All data points average of two tests:
(1) Mid-radius longitudinal orientation
(2) Transverse orientation

Table V. Stress Rupture and Creep Properties of Billet, Pancakes and Rolled Bar

Product Form	Alloy	Stress Rupture Test				Creep Test			
		649°C/759 MPa		649°C/690 MPa		621°C/621 MPa		649°C/621 MPa	
		Life (hrs)	EL (%)	Life (hrs)	EL (%)	Life to 0.2% (hrs)	Creep Rate (x 10^{-10})	Life to 0.2% (hrs)	Creep Rate (x 10^{-10})
203mm Rd(1) Billet	718 (JG60)	91	12.6	274	13.8	>2000	1.21	448	10.5
	718-ER (JG61)	166	11.2	528	17.2	>2000	0.67	824	5.93
Pancake(2)	718 (JG60)	54.8	22.5	158	22.5	866	5.51	57.5	73.6
	718-ER (JG61)	116.2	19.0	246	19.7	1889	2.50	169	28.4
16mm Rd Bar	718 (EW02)	96	19.0	233	18.5	–	–	–	–
	718-ER (JG61)	153	21.0	518	19.5	–	–	–	–

All data points average of two tests:
(1) Mid-radius longitudinal orientation
(2) Transverse orientation

As expected from previous work, there were substantial increases in stress rupture and creep performance for 718-ER compared to standard 718. Improvements ranged from 60% to 160%. All of these results agree very well with 718-ER alloys of similar P and B levels tested in previous studies[1-4]. Differences in rupture and creep properties for the different products tested (billet, pancake & bar) reflect differences in thermomechanical processing and structure (see microstructure and fractography section).

Figure 5 shows creep curves of standard 718 and 718-ER tested at 621°C/621 MPa. 718-ER was still in secondary creep well beyond 2000 hours, but 718 started tertiary creep at about 700 hours. The secondary creep rate of 718-ER was approximately 50% that of standard 718.

Microstructure and Fractography

The general features of billet microstructures of the two alloys were very similar, as shown by optical metallography and SEM studies, with two exceptions (Figure 6). The 718-ER billet had a slightly finer average grain size (JG61, ASTM 6 vs. JG60, ASTM 5), which is consistent with differences in tensile strength, and it appeared that the billet of JG61 had a more pronounced dark and light banding structure. The grain size in the light bands in JG61 was slightly finer and also contained more NbC particles. This indicates that JG61 had more residual microsegregation although EDS and the progressive solution treatment tests were unable to reveal it.

The grain size of pancakes was significantly refined in comparison to the billet grain size (ASTM 10-11 vs. 5-6). This finer grain size explains the lower stress rupture and creep life in pancake samples in comparison with billet samples.

The fracture surfaces of broken stress rupture samples of billet were analyzed, and their SEM photos are shown in Figures 7 (a) and (b). The fracture mode in 718-ER was completely dimple fracture, while some intergranular fracture facets can be seen in alloy 718. The intergranular failure in the standard alloy is clearly seen in the cross section of a broken rupture sample (Figure 7 (c)). This result is in agreement with previous work[4] and clearly illustrates that P and B additions increase grain boundary cohesion, and in turn the stress rupture resistance of 718-type alloys.

Discussion

These results clearly demonstrate the beneficial effect of P and B for stress rupture and creep properties of alloy 718 made on a full production scale. The improvements in stress rupture and creep properties seen in the 718-ER production heat were comparable with those reported on small-scale pilot plant alloys with similar P and B levels. On average, about 100% improvement in stress rupture life and creep resistance was achieved in production alloys of this study. As previously reported[4], pilot plant heats with similar P, B and C levels (0.022%P, 0.008%B and 0.025%C) showed similar increases in stress rupture life. Based on this work, it is reasonable to believe that further improvements in rupture and creep properties could be achieved in production scale heats by changing chemistry to the optimum levels for P, B and C (0.022%P, 0.011%B, <0.01%C).

Microstructural results suggest that P and B additions increase the amount of microsegregation, although the effect could not be measured by EDS or grain growth studies. This would suggest that an improved homogenization practice may be required for 718-ER.

Standard 718 processing conditions were used for all materials in this study and no difficulties were encountered with any of the resulting products. However, RSRHT testing clearly showed that P and B reduced the hot ductility of 718 at peak temperatures but may improve it at lower temperatures. The reduction in hot ductility was at temperatures (>1149°C) above the normal processing temperatures for 718. Nonetheless, this clearly points out the necessity of avoiding processing 718-ER at excessive temperatures. This effect most likely results from grain boundary segregation rather than liquation since the critical temperatures were much lower than the incipient melting temperature determined by DTA. Thus P and B segregation to grain boundaries may increase the grain boundary strength at lower temperature, but decrease it at higher temperature.

Conclusions

1. The beneficial effects of P and B additions on stress rupture and creep properties of 718, previously reported for pilot plant size heats, is fully scaleable to production size heats.

2. Stress rupture and creep properties observed in a production heat of 718-ER were on the order of 100% greater than for standard 718. Results from the production scale heat were in good agreement with data from small scale pilot plant heats of a comparable chemistry.

3. A full scale production heat of 718-ER was successfully processed to billet and bar using standard 718 thermomechanical processing conditions. Results show P and B have a detrimental effect on the hot ductility of 718, but only at very high temperatures, above those normally employed for hot working the alloy.

4. A higher degree of microsegregation was observed in 718-ER suggesting the need for improvement in homogenization practice.

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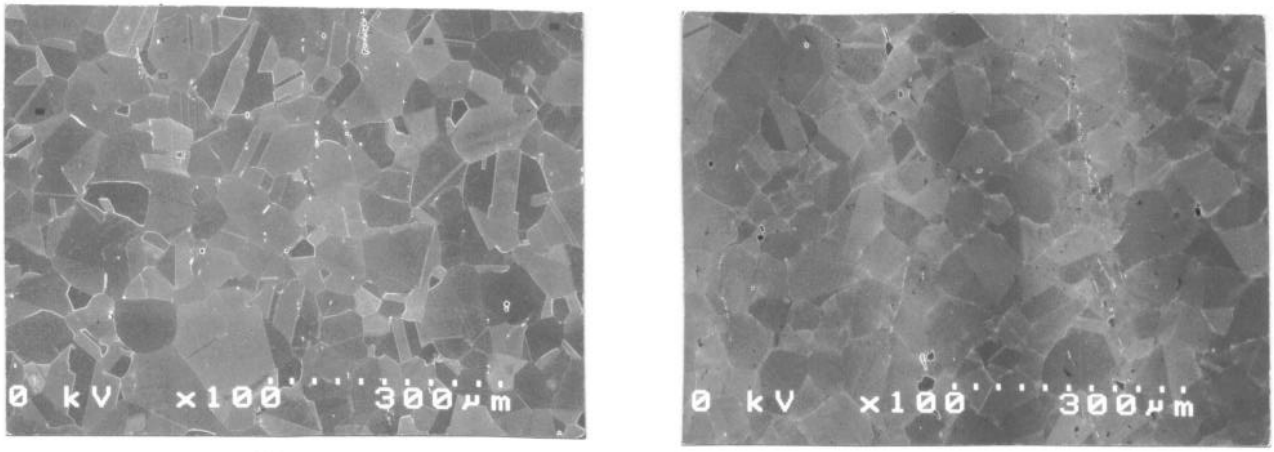
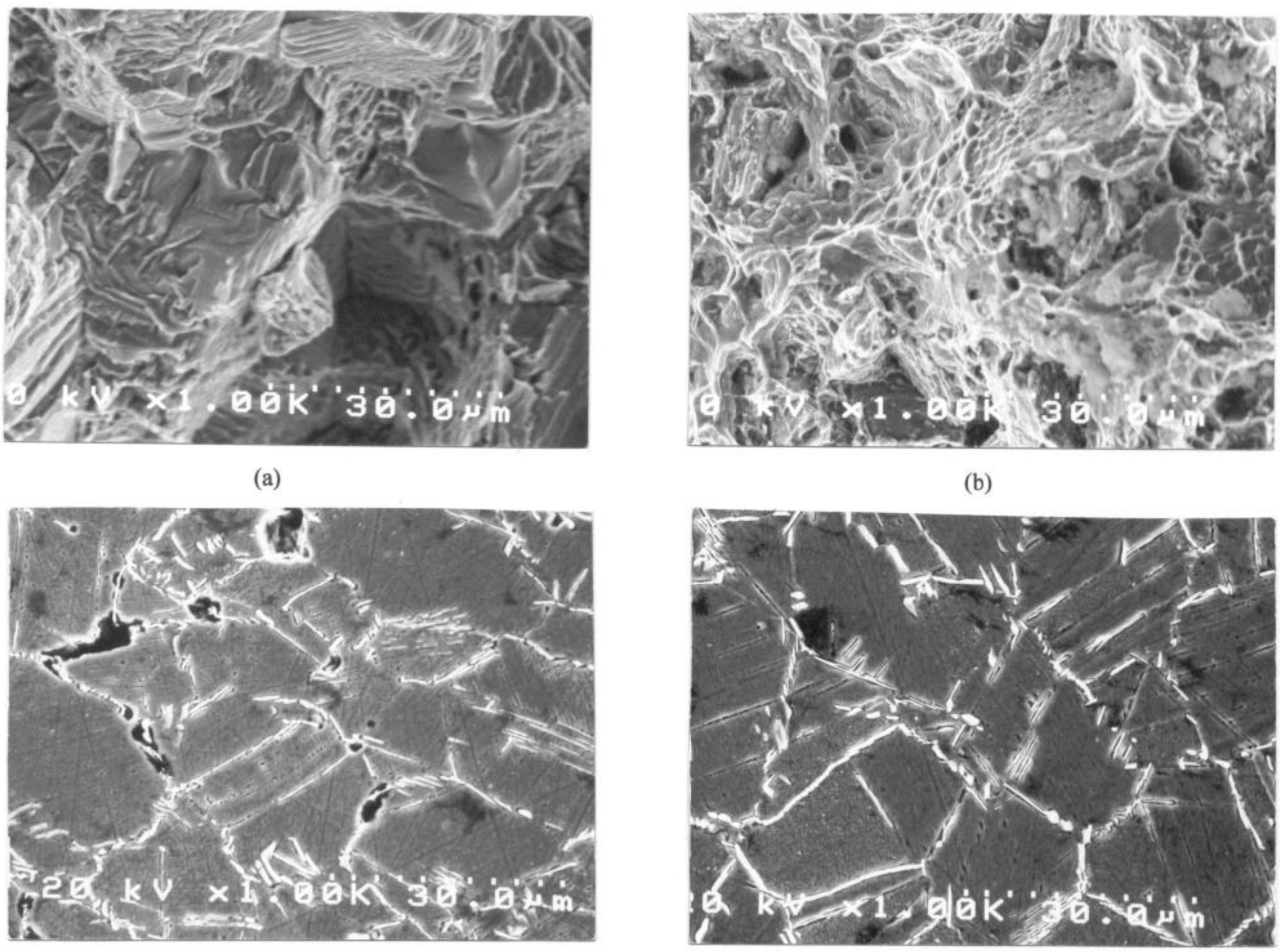


(a) (b)

Fig. 6. Microstructure of 203mm Rd Billets. (a) Alloy 718, JG60 and (b) 718-ER®, JG61.



(a) (b)

(c) (d)

Fig. 7. SEM Photos of Fracture Surface and Microstructure of broken Stress Rupture Samples. (a), (c) Alloy 718, JG60, (b), (d) 718-ER®, JG61.