EVALUATION OF COLD HEARTH REFINED

INCONEL* ALLOY 718

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Abstract

Several ingots of INCONEL alloy 718 have been melted by EBCHR and comprehensively assessed for macro and micro structure, cleanliness in terms of chemistry and inclusion number and size, hot workability and mechanical properties, especially with regard to low cycle fatigue life and crack propagation data. Results of this evaluation are presented here.

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Superalloys 718, 625 and Various Derivatives
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Introduction

The increasingly greater demands made by aero-engine manufacturers on alloy producers to improve the performance of their materials at higher temperatures and stresses has precipitated, in the past few years, a considerable amount of work on cold hearth refining of superalloys. This has been identified as possibly the best way of significantly improving the cleanness of high strength nickel base superalloys used for critical turbine disc applications. This initial body of work has been concentrated on alloys such as INCONEL alloy 718 on which there is an enormous amount of data freely available. This work has given an insight into the capabilities of the process and the possibilities of using it for refining the ultra high strength alloys such as PM Udimet 720. It is really these alloys, made presently by powder atomisation, which will ultimately derive the greatest benefit from hearth melting. However, the work on Alloy 718 has been invaluable in defining and optimising process parameters and conditions.

All the melts mentioned in this work were conducted on a pilot EBCHR plant at Leybold AG in Hanau, Germany. The details of this furnace have been described elsewhere [1,2]. The ingot sizes were all 250mm diameter weighing up to 400 kg each.

Trials conducted so far on INCONEL alloy 718

Initial trials were conducted on VIM+ESR as feedstock [1] and were essentially just sighting shot melts to establish the basic viability of the process. The results obtained on this VIM +ESR +EBCHR material were nevertheless good with reduced oxygen and nitrogen levels obtained with a consequential improvement in LCF life compared to the VIM+ESR feedstock[1]. A more comprehensive programme involving several melts using VIM feedstock was then undertaken. A thorough evaluation of this material involving chemical and microstructural, as well as cleanliness and mechanical properties, is being undertaken. Optimisation of the EBCHR process has also been a major objective of this work and beam power distributions, solidification control, barrier effectiveness and the effects of feedstock quality have been studied. Figures 1 and 2 show the difference between VIM and VIM+ESR feedstock of the demands made on the EBCHR process.

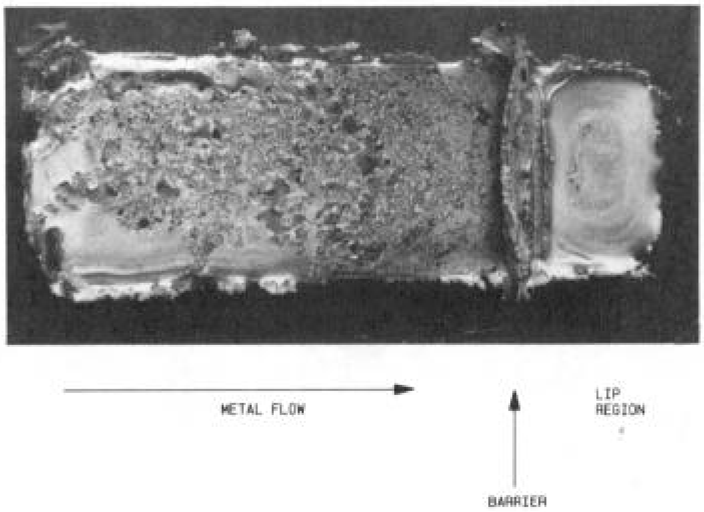


Figure 1 - Skull of VIM feedstock

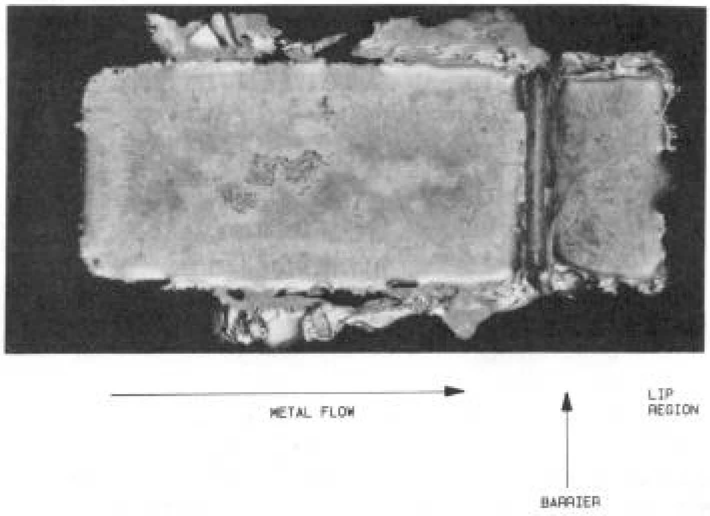


Figure 2 - Skull of VIM + ESR feedstock

Macro and microstructural evaluation

Structures of the as-cast ingots (figure 3) show that there is no adverse macro-segregation. On a micro level, detailed analysis was made of features such as dendrite arm spacings and local solidification times (LST). Table 1 gives secondary dendrite arm spacings from an ingot melted under close to optimum conditions at 180 kg/h. The spacings towards the bottom of the ingot (50 mm from bottom) are the shortest, corresponding to an LST of approximately 200 seconds (from [3]). The figures for the middle of the ingot (500 mm from bottom) indicate a slight increase in secondary dendrite arm spacings and hence local solidification time. This can be explained by examining the melt protocol which indicates that at the halfway stage of the melt the power input on to the ingot surface was increased due to the ingot edge solidifying too rapidly and therefore "sticking" to the crucible during withdrawal. This extra heat on the ingot edge clearly caused the secondary dendrite arm spacings to increase to 75um in the ingot middle. The higher values of arm spacings on the ingot top (50 mm from top) are due to the hot topping stage at the end of the melt.

Position in transverse direction	Secondary Dendrite Arm spacings		
	50mm from ingot bottom	Ingot middle	50mm from ingot top
Edge	69	75	87.0
Mid Radius	69	73	88.0
Centre	66	70	85.0

In each case the values are averages of the distances between as many adjacent secondary dendrite arms as possible per primary dendrite.

Table 1 - Secondary dendrite arm spacings for VIM + EBCHR ingot

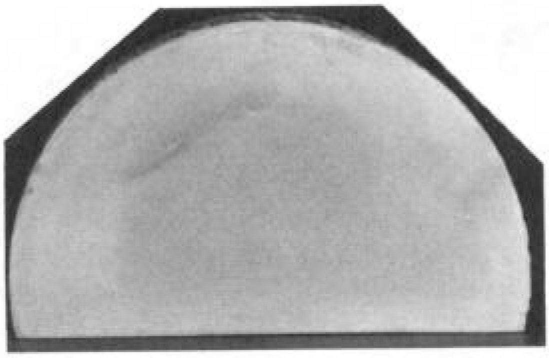
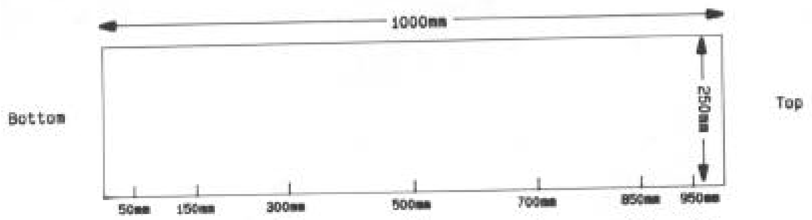


Figure 3 - As cast macrostructure of EB refined ingot

It is interesting to note the consistency of the secondary dendrite arm spacings across the ingot surface, indicating good heat extraction as well as a well controlled melting process. Comparing these results with those of Mitchell and Balantyne on VIM + ESR and VIM + VAR [3,4] it is clear, even taking into account the smaller diameter ingot in this study, that solidification can be controlled to a great extent in EBCHR and indeed that segregation may even be reduced in EBCHR due to this enhanced ability to refine the microstructure.

Cleanliness evaluation along ingot length

The chemistry and cleanliness (by EB button melting) of an ingot was ascertained along its length to establish whether the consistency in microstructure and solidification was matched by chemistry and cleanliness. The ingot was sectioned approximately every 150 mm along its length and full chemical analysis as well as button samples were taken. Figure 4 shows that except that at the very bottom, where higher loss of chromium, nitrogen, oxygen and magnesium occurs due to the greater exposure of the molten metal during start-up, the chemistry of the ingot is remarkably consistent. This is reflected in the EB buttons which show that, certainly compared to VIM + VAR and even VIM + ESR, VIM + EBCHR INCONEL alloy 718 contains fewer and smaller oxides (figures 5 and 6).



	50mm	150mm	300mm	500mm	700mm	850mm	950mm
Nitrogen (ppm)	40	50	52	48	51	50	50
Oxygen (ppm)	3	4	4	4	5	4	4
Chromium (%)	17.04	18.36	18.34	18.21	18.37	18.34	18.40
Magnesium (ppm)	7	27	20	20	20	23	22

Feedstock (VIM INCONEL alloy 718) analysis was;	N	O	Cr	Mg
	100ppm	10ppm	19.08%	83ppm

Figure 4 - Chemical analysis along ingot length

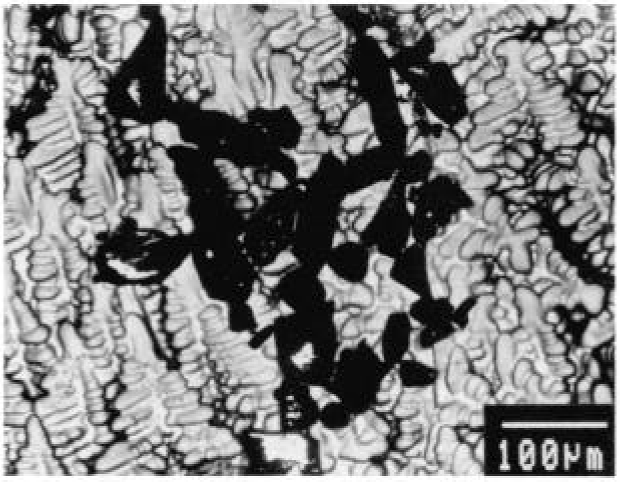


Figure 5 - Raft of inclusions on VIM + VAR button showing several oxides which are larger than 150 um in diameter

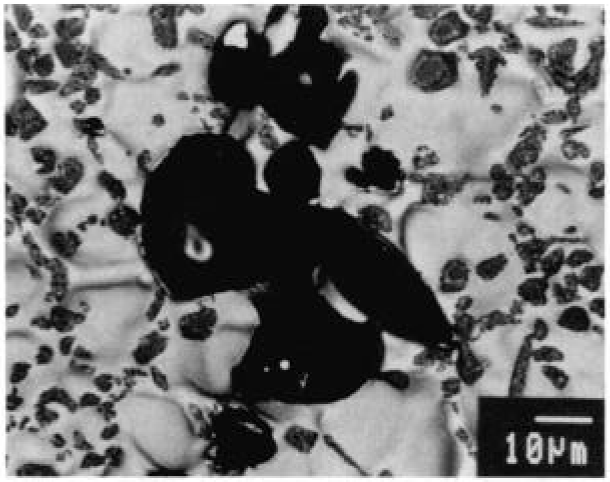


Figure 6 - Raft of VIM + EBCHR button showing fewer oxides with the largest particle being no more than 40 um in diameter

Further processing of VIM + EBCHR INCONEL alloy 718

The 250 mm diameter as-cast ingots were homogenised and forged to 125 mm square. The forgeability of the alloy was very good and fine grain ingot was obtained (figure 7). Samples 80 mm x 80 mm x 60 mm were taken from various positions along the ingot length and slab forged to give a 3:1 reduction in thickness. The grain size was therefore reduced and one of ASTM 8-8.5 was recorded in the slab forged material. The mechanical testing was performed on this twice forged material.

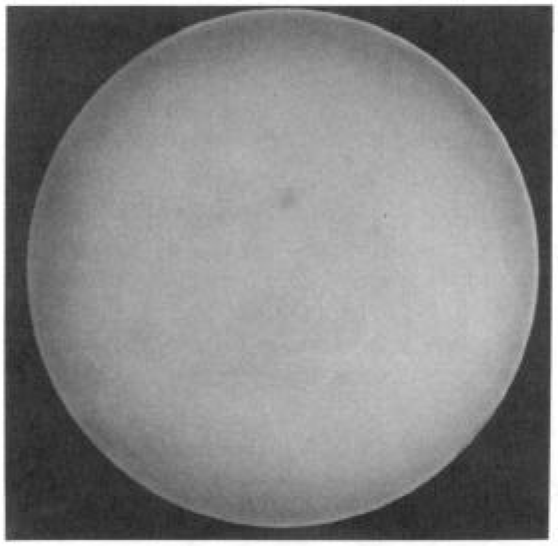


Figure 7 - As forged macrostructure showing no segregation

Mechanical testing of EB refined material

A thorough mechanical test programme was organised to assess the properties of the VIM + EBCHR material. Tensile test results (table 2) at room temperature and 550°C show good strength and ductility even at higher temperatures.

The most important property in the superclean material would be that of low cycle fatigue life. It is evident from previous studies [5] that LCF life is indeed increased in EB refined material, compared to VIM + ESR material.

However, previously a statistical evaluation had not been made and therefore this time one set condition has been picked at which fifteen samples will be tested to ascertain the scatter in the results. A low scatter giving consistent results will obviously mean that the material is more homogeneously cleaner than conventionally melted INCONEL alloy 718. Unfortunately at the time of writing this paper, all the LCF testing has not been completed.

Fatigue crack propagation results can be seen in figures 8 and 9 in the form of da/dN vsΔK graphs at room temperature and 550°C. The load ratio, R was 0.1 and the frequency used was 0.25 Hz in trapezoidal waveform. It can be seen that at room temperature the ΔK_o or ΔK_{th} value is approximately 17 MPa/m and at 550°C this value decreases to about 15 MPa/m (both values extrapolated from da/dN vs ΔK curves). It has to be emphasised that the grain size of the material used in these tests was ASTM 8-8.5 (19 um). King [6] quotes ΔKo values of 8 MPa/m at room temperature and 7 MPa/m at 538°C (both at R = 0.1 and for material of grain size 22 um) for conventionally melted Alloy 718. The specific processing history of the latter material is not known and therefore it is perhaps somewhat difficult to compare the two sets of results. It is, however, evident that VIM + EBCHR material demonstrates at least similar, if not better, crack propagation resistance to conventional Alloy 718.

Test Temperature Degrees Celsius	0.2% P.S. N/mm2	Tensile Strength N/mm2	Elongation %	Reduction of Area %
Room Temperature	1249	1425	15.6	26.2
	1231	1446	15.6	23.3
550C	1073	1240	17.9	34.5
	1079	1287	17.0	29.3
The material was given the following heat treatment: 1h/980C/OQ + 8h/720C/FC AT 55C/h to 620C Hold 8h/AC				

Table 2 - Tensile test results for VIM + EBCHR material

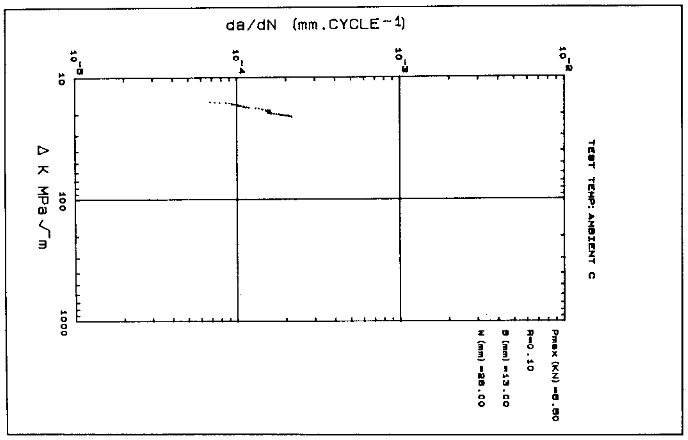


Figure 8 - da/dN vsΔK curve at room temperature

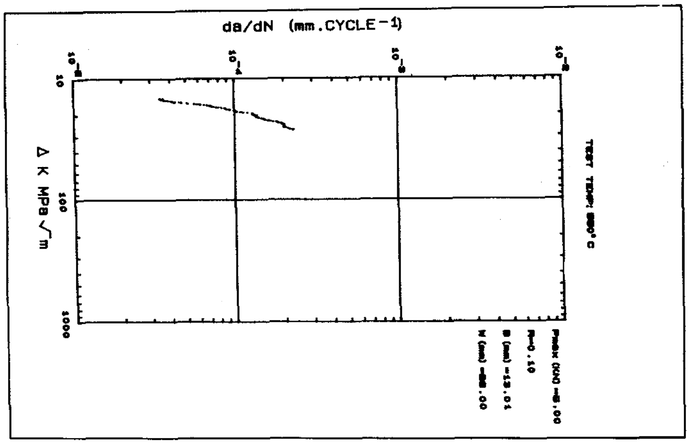


Figure 9 - da/dN vs ΔK curve at 550°C

Conclusions

1. Macro segregation - free INCONEL alloy 718 has been successfully melted by EBCHR from VIM feedstock.

2. The cleanliness of the VIM + EBCHR material is demonstrated to be better than VIM + VAR and VIM + ESR material by EBBM and chemical analysis.

3. The alloy in the EB refined state has good forgeability.

4. Mechanical tests show good tensile strength and ductility at high temperature and also good crack propagation resistance in fine grain VIM + EBCHR material.

References

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