ELECTRON BEAM COLD HEARTH REFINEMENT PROCESSING OF

INCONEL* ALLOY 718 AND NIMONIC* ALLOY PK50

S. Patel+, I.C. Elliott+, H. Ranke++, H. Stumpp++

\+ Inco Alloys Limited, Holmer Road, Hereford, U.K.
++ Leybold AG, Wilhelm-Rohn-Strasse 25, 6450 Hanau 1, West Germany

Abstract

The use of Electron Beam Cold Hearth Refining (EBCHR) to produce very clean nickel based superalloys has been the subject of a number of investigations in the past, aimed at providing material with enhanced properties for components such as aero-engine gas turbine discs. In these, the useful working life is largely limited by the presence of certain defects which would ultimately initiate fracture. Such undesirable features can include nitrides, carbonitrides and oxides, the quantity and morphology of which is generally referred to as the cleanness of an alloy. This paper describes the EB refining of two established disc alloys melted in a 250 kw Leybold EB furnace equipped with two KSR 250 guns, INCONEL alloy 718 and NIMONIC alloy PK50 (similar composition to Waspaloy**) and describes the EB melting process performance and resulting metallurgical structures, chemistry, forgeability, cleanness levels and mechanical behaviour .

* Trademark of the Inco family of Companies.
** Trademark of the United Technology Corporation.

Superalloys 1988
Edited by S. Reichman, D.N. Duhl, G. Maurer, S. Antolovich and C. Lund
The Metallurgical Society, 1988

Introduction

There is an increasing demand nowadays from manufacturers of aero-engine gas turbines to be supplied with nickel based superalloys which will perform satisfactorily at higher stresses and temperatures. It is therefore necessary to investigate methods of achieving extremely high cleanness levels in these alloys by reducing the size and quantity of non metallic low density inclusions (LDI's) which are primarily responsible for initiating fatigue cracks in critical components such as turbine discs (1).

Electron Beam Cold Hearth Refining (EBCHR) is proposed as a production means for superalloy refining especially relating to LDI reduction (2). It is a sensitive process during which optimum melting conditions need to be achieved in order to obtain the highest quality material. Any deviation from these optimum conditions can lead to problems with the most critical parameters, and may result in some of the undesirable features ending up in the material.

In order therefore to evaluate and optimise the process, ingots of VIM + ESR INCONEL alloy 718 and VIM + ESR NIMONIC alloy PK50 were melted in an EBCHR furnace and the resulting material processed and assessed against material produced using conventional methods.

Electron Beam Furnace Design

Several investigations have been performed in the past to try and achieve refined superalloys with superior material qualities especially with regard to an improvement of behaviour under higher stresses. It is well known that stress related behaviour closely correlates with the size and quantity of low density inclusions and high levels of the latter can lead to a significant reduction in gas turbine component lifetimes.

Electron Beam Cold Hearth Refining is known to be a production means for superalloy refining especially in relation to LDI reduction (3).

In order to evaluate this process, pre-refined ingots of VIM + ESR INCONEL alloy 718 and VIM + ESR NIMONIC alloy PK50, supplied by Inco Alloys Limited were melted in a horizontally fed EB furnace installed in the laboratory area at Leybold in Hanau.

The arrangement of the EB guns, trough and crucible in an EBCHR process is shown schematically in Figure 1. The refining effect is based on LDI flotation. Oxide particles, which float to the surface of the trough pool, are restricted by means of a water cooled mechanical skimmer from entering the crucible.

A medium sized sate of the art, EB furnace manufactured at Leybold in which EBCHR processes can be performed on a pilot scale is shown in Figure 2. Because of its modular design, different set up modifications are possible which allow the performance of other EB processes such as horizontal and vertical dripmelting for the refining of refractory metals. Bar shaped feedstock can be fed via a horizontal or vertical feeding system whereas granules can be fed by means of a flanged vibration feeding system.

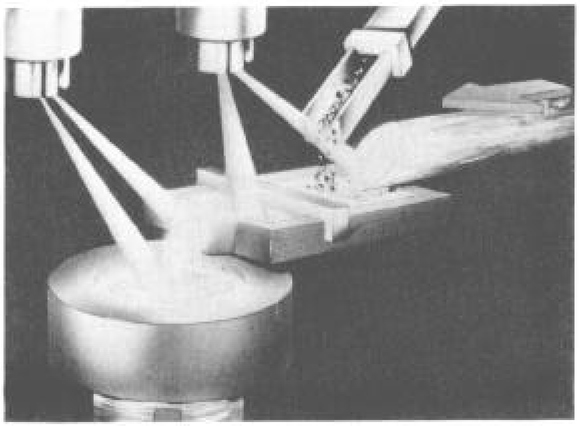


Figure 1 - Schematic showing the arrangement of EB guns, trough and crucible in EBCHR process.

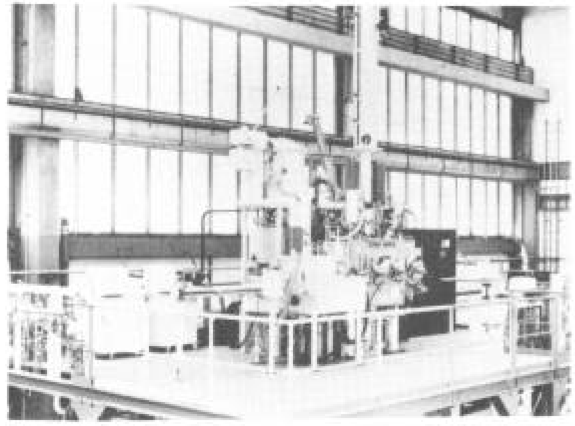


Figure 2 - A medium sized state of the art EB furnace manufactured at Leybold.

The furnace is equipped with two EB guns, type KSR 250/35 with a maximum power of 250 kw at 35 kv. The installed EB power amounts to 300 kw. The furnace evacuation is done by means of a baffled oil diffusion pump having a nominal pumping capacity of 30,000 l/s.

To guarantee continuous melting operation without intermediate venting, the horizontal bar feeding chamber can be separately vented and recharged during melting. The capacity of the bar feeding chamber is three bars with a maximum length of 800 mm and a maximum diameter of 120 mm each.

In order to control the homogeneity with respect to the chemistry and structure of the final ingot, a reproducible beam pattern control is absolutely necessary. This is achieved using computer system BD 564. It contains a flexible u-computer system which allows simultaneous control of up to five EB guns. Fifty different programmes, each consisting of up to 64 different preprogrammed patterns such as circles, various areas and inclined lines can be stored. Beside pattern frequency, the position and dwell time can also be programmed. The application of the computerised deflection control leads to well defined process parameters which allow melting performances of a high quality.

For improved quality control, the furnace is additionally equipped with a residual gas analyser, a pyrometer for temperature indication of the melt surface and a sample taking mechanism by means of which samples can be extracted from the melt pool for chemistry evaluation purposes.

In these tests the dimensions of the installed trough were as follows: 450 mm length x 150 mm width x 50 mm depth. The crucible diameter was 200 mm, resulting in EB melted ingots weighing approximately 250 kg. The influence of the melting speed on the ingot structure was studied by varying the melt rate in the range between 40 kg/hr and 130 kg/hr. The melt rates of the INCONEL alloy 718 and NIMONIC alloy PK50 ingots which were forged and subsequently evaluated and whose results are outlined below were 110 kg/hr and 125 kg/hr respectively.

Forgeability of EBCHR alloys

The EB melted material was processed through a conventional route which included forging of the material from 200 mm dia. to 100 mm dia., slab forging the 100 mm dia. material to achieve a reduction in width of 3 to 1 and then carrying out all the mechanical tests on the resultant material. The main aspects of interest were the "metallurgical" structure achieved to assess whether there was any segregation, the forgeability of the alloys, the change in chemistry, the cleanness levels as shown by Electron Beam Button Samples and the mechanical properties obtained.

The surfaces of the as-cast EBCHR ingots were reasonable and comparable to those of ingots melted by conventional methods (Figure 3). Top and bottom slices from the as-cast ingots were

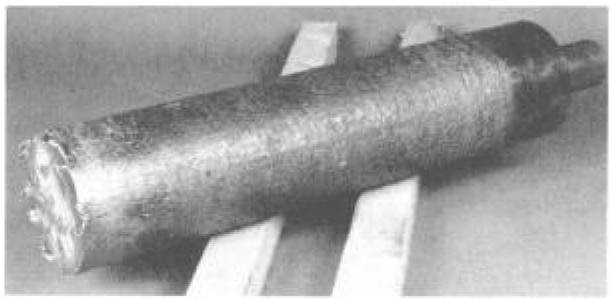
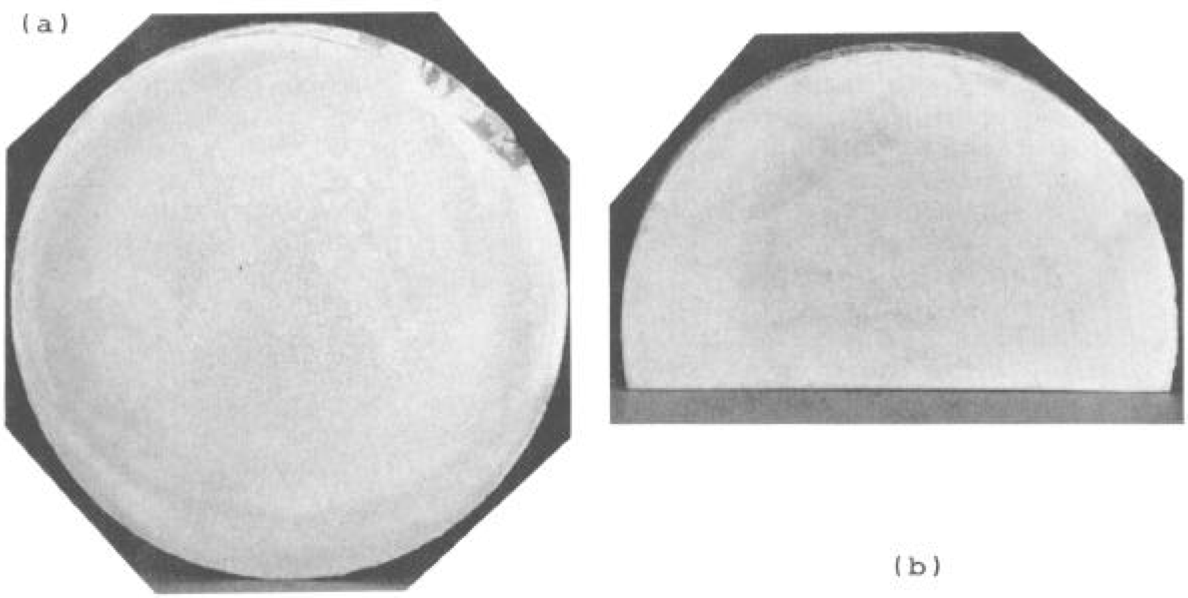


Figure 3 - 200 mm dia., as-cast EBCHR ingot of NIMONIC alloy PK50

taken and macroetched to ascertain the structure. It can be seen from Figure 4 that good structures were obtained with no evidence of serious macro segregation or undesirable features.

(a)



(b)

Figure 4 - 200 mm dia. macro-slices of (a) INCONEL alloy 718 and (b) NIMONIC alloy Pk50 showing no serious macrosegregation.

The chemistries of the two alloys after EB melting were analysed and are shown in tables 1 and 2. As expected, there is

Start Stock		EB Melted
0.036%	C	0.033%
18.57%	Cr	17.63%
17.60%	Fe	18.00%
53.50%	Ni	53.84%
0.55%	Al	0.59%
3.05%	Mo	3.13%
5.06%	Nb	5.40%
1.10%	Ti	1.03%
5ppm	S	5ppm
70ppm	N	40ppm
7ppm	O	5ppm
37ppm	Mg	-

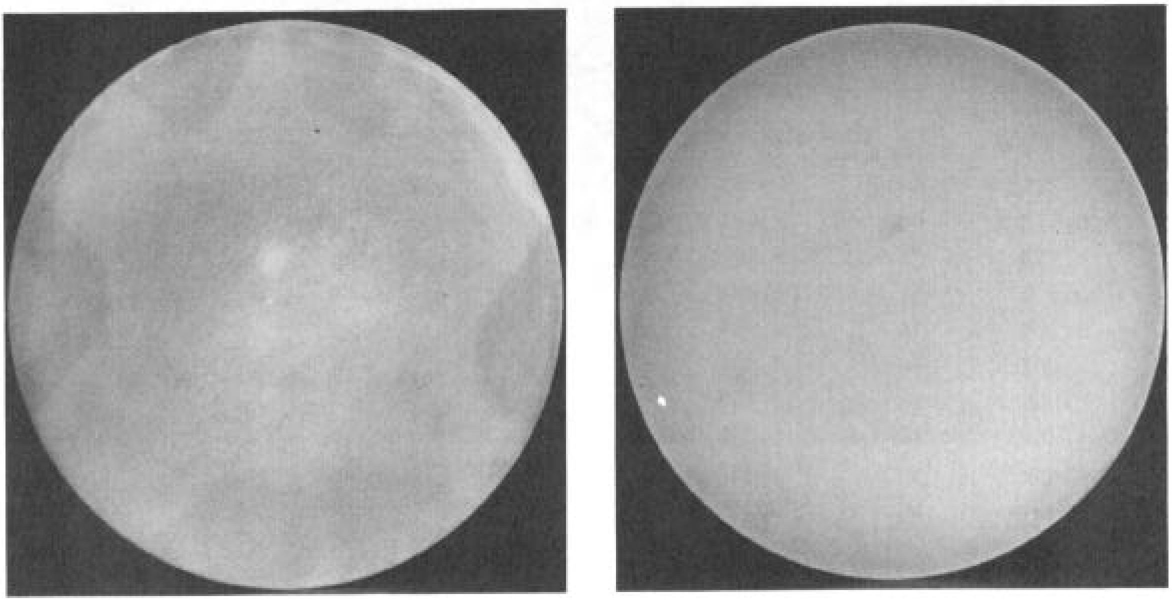
Table 1 - Chemical analysis of INCONEL alloy 718 before and after EB melting.

Start Stock		EB Melted
0.02%	C	0.010%
19.30%	Cr	18.72%
Bal	Ni	Bal
1.29%	Al	1.30%
13.50%	Co	13.50%
4.20%	Mo	4.38%
3.16%	Ti	3.24%
4ppm	S	4ppm
20ppm	N	20ppm
7ppm	O	4ppm
40ppm	Mg	-

Table 2 Chemical analysis of NIMONIC alloy PK50 before and after EB melting.

a loss of chromium in both alloys. It is greater in INCONEL alloy 718 (0.94%) than in NIMONIC alloy PK50 (0.58%). This could have been due to the greater rate at which the INCONEL alloy 718 was melted. Magnesium was reduced in both cases from around 40 ppm to virtually zero. The achievable nitrogen level in nickel based alloys depends amongst other things on the titanium content. NIMONIC alloy PK50 is a high titanium (~ 3.16%) and consequently low nitrogen (20 ppm) containing alloy. There was no detectable change in its nitrogen level after remelting. In the case of INCONEL alloy 718 which has a lower titanium content (~ 1.10%) and therefore higher nitrogen (70 ppm), there was indeed a significant reduction in nitrogen content from 70 ppm to 40 ppm. This is an important result as the lower nitrogen level means fewer titanium nitrides and carbonitrides contributing to a "cleaner" alloy. The oxygen level of the INCONEL alloy 718 showed a reduction from 7 ppm to 5 ppm whereas the NIMONIC alloy PK50 showed a reduction from 7 ppm to 4 ppm. The trace elements such as Sb, Zu, Pb and Sn were also favourably reduced.

The forgeability of the alloys depends very much on the chemistry and it was therefore both interesting and encouraging to note that both forged well. The magnesium and sulphur contents are especially important. It is considered crucial to obtain a Mg:S ratio of greater than 1 to achieve the optimum elevated temperature ductility in these alloys and especially so in the case of INCONEL alloy 718. In both cases however virtually all the magnesium was lost upon EB remelting and therefore forgeability problems might have been expected. This has, in the past, been considered to be one of the drawbacks of the EBCHR process. Nevertheless, none of the anticipated problems were encountered and both alloys forged without any difficulties. Macroslices from the forged bars (Figure 5) once again show very good structures with no adverse macro segregation.



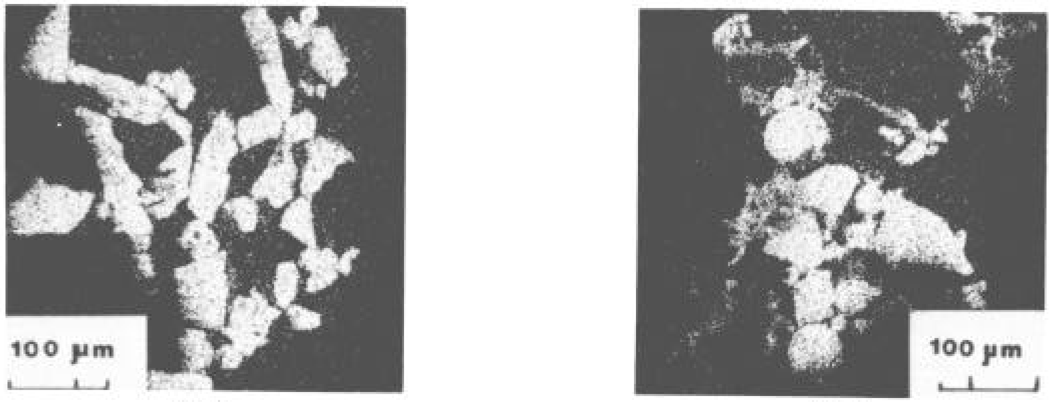
(a) (b)

Figure 5 - Macroslices from 100 mm dia. forged bars of (a) INCONEL alloy 718 and (b) NIMONIC alloy PK50.

Cleanness and Mechanical Properties

Electron Beam Button melting is a means of assessing the cleanness of an alloy with regards to LDI content (4). A 2 lb sample is melted under vacuum by an electron beam into a water cooled copper crucible. The LDI's float to the surface of the button and form a cap, the evaluation of which gives an indication of the relative cleanness of the alloy.

Electron Beam Buttons were melted from the EB melted material as well as material used as starting stock. In the case of INCONEL alloy 718 (Figure 6) the aluminium X-ray maps of the button from the VIM + ESR starting stock material and the button from the VIM + ESR + EBCHR material show that there is an agglomeration of Al-rich particles on both buttons but that the one on the latter is very much smaller. This result corresponds well with reduction in oxygen level shown by the chemical analysis (Table 1). There is no single solid cap of nitride particles on either the button from the starting stock material or that from the EB melted material. Instead there are some very small (mainly <5 um) Ti-rich particles scattered on dendrite arms in the central region of the buttons and once again their number appears to have reduced after EB melting more or less in direct proportion to the reduction in nitrogen content as indicated by chemical analysis (70 to 40 ppm).



(a) (b)

Figure 6 - Al X-ray maps of EB button rafts of (a) start stock and (b) EBCHR INCONEL alloy 718 showing a reduction in oxides after EB remelting.

NIMONIC alloy PK50 also shows an indication of reduction in oxides after EB melting. The button from the VIM + ESR + EBCHR material contained a very small agglomeration of purely Al-rich oxide particles (Figure 7) and absolutely no trace of any other particles anywhere on the button surface. The button from the starting stock material, however, showed several purely Al-rich as well as Al + Mg spinels scattered around the central region of the button. An estimation based on a detailed analysis of both buttons showed that there was at least a four fold decrease in the volume fraction of oxides after EB melting. This is a greater reduction than was anticipated on the basis of the chemical analysis (Table 2).

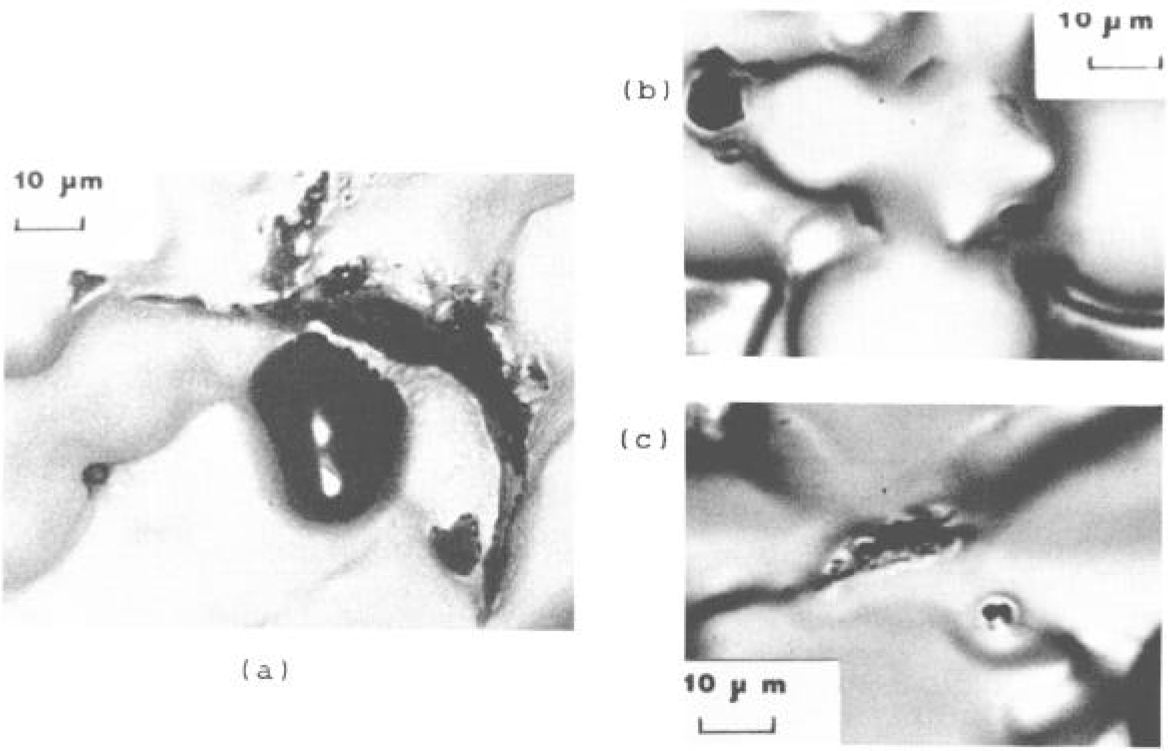


Figure 7 - SEM backscattered micrographs of EB button rafts showing (a) the only oxide particles found on EBCHR NIMONIC alloy PK50 and (b) and (c) two typical regions from start stock NIMONIC alloy PK50 button showing several oxide particles.

The mechanical properties of interest are tensile, stress rupture, creep and low cycle fatigue (LCF). Good tensile results were obtained despite the complete loss of magnesium upon EB melting and the expected detrimental effect of this on the ductility of the alloys. It can be seen from Tables 3 and 4 however that the results obtained are very good and especially so in the case of INCONEL alloy 718 where the R of A figure of 62.7% at 650°C was deemed excellent. The stress rupture and creep results for both alloys are also well within specification requirements.

All samples were given the following heat treatment;
1hr 980°C OQ + 8hrs 720°C FC 50/60°C/hr to 620°C. Hold 8hrs AC.

Tensile Test results

Test Temp. (°C)	0.2% PS (N/mm2)	TS (N/mm2)	Elong (%)	R of A (%)
20	1213	1410	22.6	45.8
650	1017	1166	27.7	62.7

Stress Rupture Results

Test Temp. (°C)	Stress (N/mm2)	Life to Rupture (hrs)	Elong. (%)
650	760	74	28

Table 3 - Mechanical Properties of EB melted INCONEL alloy 718

All samples were given the following heat treatment;
4hrs 1020°C OQ + 4hrs 850°C AC + 16hrs 760°C AC

Tensile Test results

Test Temp. (°C)	0.2% PS (N/mm2)	TS (N/mm2)	Elong (%)	R of A (%)
535	781	1083	24	26.1

Stress Rupture Results

Test Temp. (°C)	Stress (N/mm2)	Life to Rupture (hrs)	Elong. (%)
730	550	35	31

Creep Results

Test Temp. (°C)	Stress (N/mm2)	TPS at 100hrs
670	510	0.04
670	555	0.05

Table 4 - Mechanical Properties of EB melted NIMONIC alloy PK50

In the case of INCONEL alloy 718, the LCF tests, which have been carried out under strain control at 538°C and have been compared with premium quality INCONEL alloy 718 obtained from a 9" production ingot, show that for the same strain levels, the EB melted INCONEL alloy 718 performed consistently better (Table 5). Both materials had gone through a similar processing route which involved slab forging on a laboratory scale.

Due to a lack of suitable material being available at the time, samples from a cut-up of a forged disc were used as a reference for the EB melted NIMONIC alloy PK50.

The results show that whereas at the highest strain levels the EB material performed better, at lower strain levels the material from the forged disc gave longer lives (Table 6). These results for the NIMONIC alloy PK50 should perhaps be viewed with the fact in mind that the two materials had not gone through a similar processing route and that the material from the forged disc would have received more controlled work compared to the EB melted material which had been slab forged on a laboratory scale. More work is being carried out in this area to provide comparable data.

Strain %	Cycles to Failure	
	Reference	EB Melted
0.55	21070	42160*
0.75	12350	32250
0.85	5196	13680
0.95	5923	8225
1.02	2004	2173
1.10	1526	3025
* Sample unbroken		

Table 5 - LCF results for reference and EB melted INCONEL alloy 718.

Strain %	Cycles to Failure	
	Reference	EB Melted
0.60	123100*	122900*
0.75	9167	5897
0.85	6175	3697
0.95	7420	4275
1.02	2347	2642
1.10	1195	2106
* Sample unbroken		

Figure 6 - LCF results for reference and EB melted NIMONIC alloy PK50.

Despite the experimental nature of the EB melts, it has been demonstrated that with these two alloys forgeable ingot may be obtained with good structures. Moreover, electron beam control and patterning has been developed such that the controlled solidification of the ingot avoids the deleterious segregation observed in many previous exercises. Chemical and mechanical properties of the EBCHR forged material indicate that the process control in the hearth region may not have been optimum. However, further to the encouraging structure and forging properties observed, reductions in nitrogen and oxygen appear to be reflected in preliminary LCF results. Further work is being carried out to establish the optimum hearth refining conditions to maximise this effect and to apply the processing information thus developed to more defect sensitive alloys, as these are the alloys where EBCHR can be most effective in producing high quality material for rotating components in gas turbine engines.

Conclusions

1. The EBCHR process is a sensitive one, which, under optimum process parameters can be used to produce excellent quality, "clean", Ni-base superalloys.

2. The structures obtained for both INCONEL alloy 718 and NIMONIC alloy Pk50 were very good with no unacceptable macrosegregation.

3. The forgeability of both alloys was remarkably good considering the complete loss of magnesium upon EB melting.

4. There was a reduction in oxygen levels for both alloys. A similar reduction in nitrogen levels was observed for INCONEL alloy 718.

5. These chemical analysis results were reflected in the comparison between EB raft test buttons from starting stock material and the EB melted material.

6. The changes in chemistry had no detrimental effect on the mechanical properties. LCF properties of EB melted INCONEL alloy 718 were better than those of premium quality production material of the alloy.

8. The work reported in this paper was done on a purely experimental basis. The results however are clearly encouraging and form a base for future work.

References

1. J.K. Tien and E.A. Schwarzkopf
"Assessing the Needs for EB Refining of Superalloys". Electron Beam Melting and Refining, State of the Art, 1983.

2. E.E. Brown, et al.
"The Influence of VIM Crucible Composition, Vacuum Arc Remelting and Electroslag Remelting on the Non metallic Inclusion Content of MERL 76". Fourth International Symposium on Superalloys, 1980.

3. C. d'A Hunt, et al.
"Electron Beam, Cold-Hearth Refining Furnace for the Production of Nickel and Cobalt Base Superalloys." Electron Beam Melting and Refining, State of the Art, 1983.

4. C.E. Shamblen, S.L. Culp and R.W. Lober.
"Superalloy Cleanliness Evaluation Using the EB Button Melt Test." Electron Beam Melting and Refining, State of the Art, 1983.