VIM + ESR ALLOY 718 - AN ASSESSMENT OF CHEMISTRY CONTROL, ALLOY CLEANLINESS AND MECHANICAL PROPERTIES

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Summary

Factors which affect the control of chemistry during melting of the superalloys via VIM + ESR are discussed with particular reference to Alloy 718. Cleanliness of the route is assessed by the EB button melt technique and it is confirmed that VIM + ESR material is"superclean". Tensile and LCF properties are presented together with comment on the effect of oxide inclusion levels.

Introduction

Electroslag Remelting(ESR) has for a long time been regarded as an alternative process to Vacuum Arc Remelting(VAR) in the production of non-critical superalloy gas turbine components. It has gained considerable ground in this direction, initially for economic reasons because of higher yields(1,2), but subsequently because of very favourable comparisons with VAR regarding hot workability(1,3,4), carbonitride rating(5) and oxide inclusion levels(1,3,6,7). For instance, Brown et al(7) found in a comparative study of VAR and ESR that the oxide content of VAR material was not reduced from that at the VIM stage, and was typically 2 ppm, but the oxide content in ESR material showed significantly lower figures of 0.3-0.6 ppm. However cognizance of the detail of the particular ESR process is essential if this benefit is to be realised, for there are instances where no advantage has been found(2,4).

For historical reasons the double vacuum melting route(VIM + VAR) is regarded as the most important melting process for the production of superalloys for rotating parts in aero-engines and other critical applications, particularly in the U.S.A. This position is defended at least in part by arguing that double vacuum melting offers the best method of producing low trace metalloid and gas levels. In reality these trace elements are effectively controlled at the VIM stage, and therefore VIM + ESR is equally capable of producing superalloy with the same low trace element levels. An added bonus of ESR is the total freedom from metal fume condensate which occurs in VAR above the melt line, and which can be re-introduced into VAR ingot as spots of extraneous segregate. Furthermore the metal pool profile is shallower in ESR for equivalent melt rates and ingot sizes (3,4,6) and hence normal and inverse segregation is reduced.

It is the purpose of this paper to describe the development of a manufacturing route for disc quality Alloy 718 via the VIM + ESR route, which offers:-

1) consistent reactive element control
2) good ingot surface quality
3) homogeneity of ingot and billet structure
4) a low level of oxide inclusions, and
5) consistent mechanical property response.

Alloy 718 has been produced at GSL via this route since 1971, and ever since that time it has been used in HP turbine discs.

ESR Operation at GSL

Plant. The GSL ESR plant has been described in detail elsewhere(8). The furnace operates in single-phase a.c. mode at 50 Hz. A molten slag start is used which provides the dual benefit of refining the slag of certain trace metalloids(notably lead) and reducing the bottom end discard(8). Ingot withdrawal practice is used with falling baseplate and a static collar mould. This technique produces a very thin slag skin when operated correctly, since the ingot grows up against newly formed slag skin which is continuously generated at the metal/slag/mould interface. The ensuing ingot surface quality is very high, requiring only minor preparation for forging.

Slag Chemistries. To cater for the wide range of alloys produced at GSL, various slag compositions are used based upon CaF_2 with additions of CaO, MgO, Al_2O_3 and TiO_2. The physical and chemical properties of slags and the effects of the various components on melt rate and alloy chemistry have been extensively reviewed by Duckworth and Hoyle(1,9). The compositions of the slags used at GSL all lie within an extensive mono-liquid field which exists over a range of operating temperatures(10) and whose liquidus temperatures are within the range 1350-1500°C (2460-2730°F).

Alloy Chemistry Control Via ESR

The control of alloy chemistry throughout secondary melting is obviously of prime importance and the lack of it has been cited as a potential disadvantage of the ESR process. Some loss of the reactive elements, aluminium and titanium, is of course inevitable during the process; but these losses can most certainly be made reproducible and therefore controllable by using slags which are tailored to the alloy chemistry - the balanced slag philosophy. These losses are usually offset by adjusting the chemistry of the electrode.

From a study of many ESR melted nickel-base superalloys it has been found that the losses of the reactive elements at the bottom of an ingot (δAl and δTi)are dependent upon the relative activities(concentrations) of these elements in the alloy:

$$\text{i.e.} \quad \frac{1}{\delta Al} = a. \frac{Ti}{Al^{4/3}} \qquad (1)$$

$$\text{and} \quad \delta Ti = b. \frac{Ti}{Al^{4/3}} \qquad (2)$$

This behaviour, shown in Figures 1 and 2, is expected from the oxidation reaction constants for these two elements:

$$K_1 = \frac{C^{2/3}(Al_2O_3)}{C^{4/3}[Al] \times C^2(O)} \quad \text{and} \quad K_2 = \frac{C(TiO_2)}{C[Ti] \times C^2(O)} \qquad (3)$$

Following these initial and predictable losses, the variations of aluminium and titanium along an ingot length(ΔAl and ΔTi) obey slightly modified dependencies. ΔAl remains inversely proportional to $Ti/Al^{1.33}$, but it can be either positive or negative, Figure 3. ΔTi is nearly always positive(i.e. titanium increases towards the top of an ingot), but is independent of $Ti/Al^{1.33}$. Instead, the fractional increase in titanium ($\Delta Ti/Ti$)along an ingot length becomes dependent upon the total activities of aluminium and titanium in an alloy, Figure 4. Thus the use of a balanced slag is seen to reverse the initial titanium oxidation reaction at a rate which is inversely proportional to the reactive element content of an alloy. It is also seen to reverse the aluminium oxidation reaction for low values of $Ti/Al^{1.33}$.

With slag compositions that are employed at Glossop it has been found that melt rate has little or no effect on ingot chemistry, at least within the normal melt rate control range of ± 5% Figure 5. This is not universally true as GaO et al (11) have demonstrated.

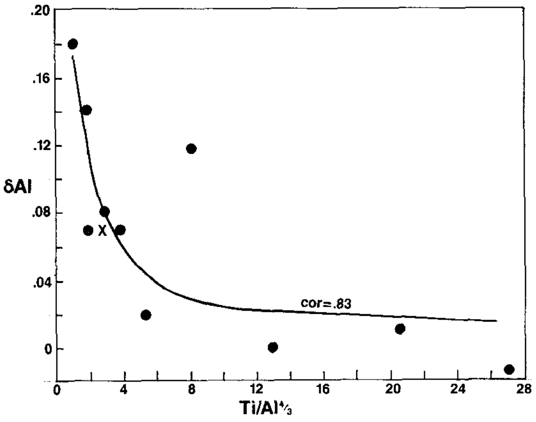

Figure 1 - The dependence of aluminium loss at the bottom end of ESR ingot(δAl) upon the relative activities of aluminium and titanium. Each point represents averaged data(minimum 14 casts) for one alloy. Alloy 718 is marked by an X.

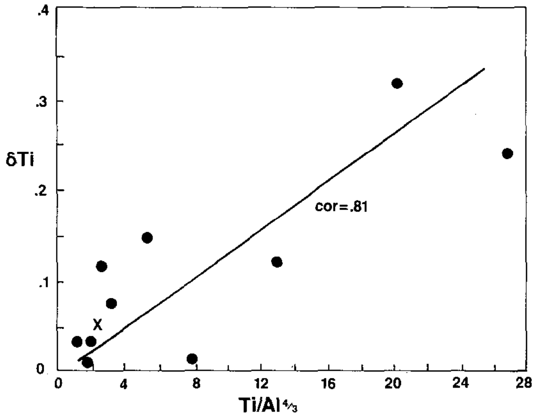

Figure 2 - As for Figure 1, but showing the dependence of titanium loss(δTi) on the relative activities of aluminium and titanium.

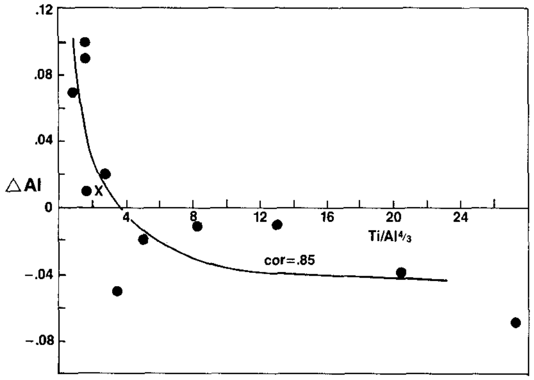

Figure 3 - Variation of ingot chemistry top-bottom for aluminium, expressed as a function of the relative activities of aluminium and titanium in an alloy. The position of Alloy 718 is marked by an X.

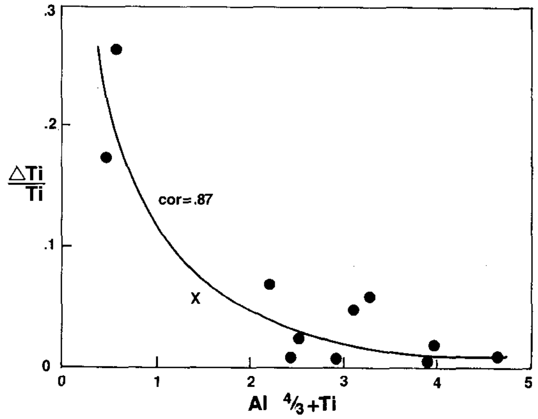

Figure 4 - Fractional variation in titanium along an ingot length expressed as a function of the total activities of aluminium and titanium in an alloy. The position of Alloy 718 is marked by an X.

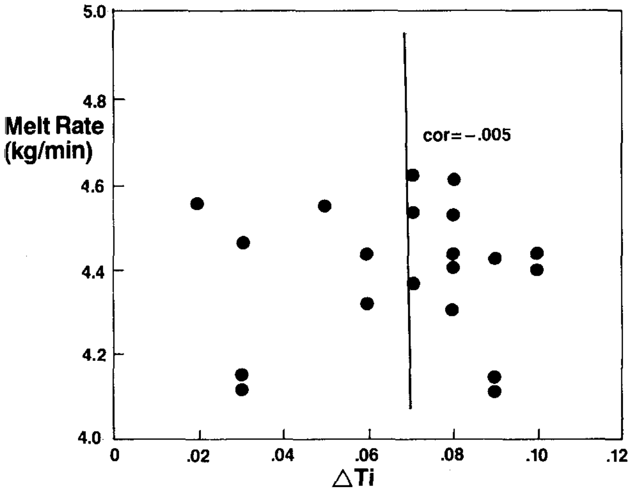

Figure 5 - Graphical plot showing the independence of titanium variation along an ingot length upon melt rate. The data shown is for Alloy 718.
Accuracy of Ti analysis = ± .03%

The chemistry control achieved for Alloy 718 is shown in Table I. Points to note are:

1) a reduction in sulphur after ESR
2) top and bottom analyses for aluminium and niobium indicate good control of both elements
3) the variation in titanium bottom-to-top is on average only.0 6 wt%
4) no increase in nitrogen

Table I. Typical VIM and ESR Analyses* for Alloy 718

	C	B	S	Mo	Nb	Ni	Co	Fe	Cr	Ti	Al	Si	Mg$^+$	N$^+$
VIM	.028	.005	.0020	3.0	5.34	52.1	.17	18.1	17.9	1.03	0.59	.11	53	82
ESR top	.028	.005	.0008	3.0	5.28	52.1	.17	18.1	18.0	1.04	0.53	.09	25	77
btm	.028	.005	.0009	3.0	5.27	52.1	.17	18.1	18.0	0.98	0.52	.10	34	74

* averaged data over 25 casts
\+ ppm, all others wt%

Typical trace element levels found in VIM + ESR Alloy 718 are shown in Table II. These levels are comparable with VAR product.

Table II. Typical Trace Analysis* for VIM + ESR Alloy 718

Ag	Zn	Cd	Ga	In	Tl	Sn	Pb	As	Sb	Bi	Se	Te
.1	1	<.1	28	<.1	<.2	20	.3	9	3	<.1	<1	<.5

* all figures in ppm, determined by hollow cathode.

Cleanliness

The oxide content of VIM and VIM + ESR Alloy 718 has been measured by a technique originally developed by Brown et al(7) which involves the EB button melting of sample material. The great advantage of this technique is that it appears to offer an absolute indication of metal cleanliness and because of this it has been adopted, with some modification, by the alloy producer and engine manufacturer alike.

VIM + ESR samples for EB cleanliness assessment were cut as diametric slices from billet material, from positions relating to the top and bottom of eight parent ingots. A VIM sample was similarly cut from an electrode to provide an indicator against which the ESR alloy could be judged. Prior to EB melting the slices were acid cleaned to remove cutting debris and discolouration.

The melting and assessment were kindly performed by Special Metals Corporation. The samples were drip melted into a hemispherical water cooled copper crucible and the surface of each button was swept by the electron beam so that the oxide was gathered into a central raft for area analysis. The underside of each button was checked to ensure that no oxide had been drawn away from the top surface by the peripheral effect of surface tension.

The results, which are at this stage preliminary only, are shown in Table III. A full quantitative and chemical analysis is still being done.

Table III. EB Cleanliness Assessment

Sample Identity		Button Weight (kg)	Rating (specific oxide area, cm^2/kg)
VIM		.578	.3 - .4
VIM + ESR	A top	.536	<.005
"	B bot	.555	<.005
"	C bot	.426	<.005
"	C bot	.586	<.005
"	D bot	.614	<.005
"	D bot	.605	<.005
"	E top	.554	<.005
"	E bot	.377	<.005
"	F top	.527	<.005
"	G top	.537	<.005
"	H top	.555	<.005

Individual ESR casts are labelled A-H

The cleanliness of the samples has been classified on a scale ranging from 0 upwards and a figure of .1 and greater indicates "dirty" material. The quantity of oxide produced from the VIM + ESR samples was, in all cases insufficient to permit any area measurement. In the opinion of the personnel doing the assessment, all the VIM + ESR samples were rated as "superclean" and given a figure of <.005 on the scale. That the ESR process is actually cleaning-up the alloy is evident from the rating of .3-.4 given to the VIM electrode, though it is believed that this latter figure is artificially high since some of the oxide appeared to be of exogeneous nature. Even so the ESR ratings remain significantly lower than

VIM and below that of VAR alloy where ratings of <.01 are more typical. The reproducibility of VIM + ESR is evident from the results in Table III.

The ESR facility at GSL has been assessed by Viking Metallurgical Inc., who have supplied EB Alloy 718 electrode for remelting. The billet cleanliness results that have been so far obtained are equal to those in Table III.

Mechanical Properties

The point seems to have been reached in disc design such that oxide inclusions of 50μm and less(12) are determining cyclic life. This has led to a "superclean" technology approach to high strength disc manufacture in order that material properties can be more effectively realised. It has also caused a re-examination of the more convential disc alloys such as Alloy 718. This alloy, because of its high resistance to crack initiation is a good candidate for superclean technology, and ESR is even now being used as a cleaning-up stage in a triple melting process(VIM + ESR + VAR). This is an expensive solution to a problem when it can be shown that the properties of VIM + ESR ingot are at least equivalent to VAR product.

Transverse tensile data generated from 150-250mm diameter billet produced from 430mm diameter ingot, together with longitudinal data from 20mm diameter bar are shown in Table IV. The difference in strength between these two sets of data, 3-8%, can be explained by the difference in hot working reduction and grain size(ASTM 4-6 for the billet data and ASTM 7-9 for the bar data).

Direct aged data is shown in Table V.

Table IV. Tensile Data for VIM + ESR Alloy 718

		RT				650°C(1200°F)			
		0.2%PS MPa	TS MPa	Elong %	RA %	0.2%PS MPa	TS MPa	Elong %	RA %
transverse billet*	$\bar{x}$	1152	1364	20	35	972	1122	20	43
	min	1037	1292	12	24	896	1056	15	25
	max	1260	1444	25	47	1020	1183	25	52
	$\bar{\sigma}$	64.7	48.5	3.5	6.3	44.6	46.3	3.2	7.2
small diameter bar^{+}	$\bar{x}$	1244	1490	20	41	1010	1178	27	61
	min	1180	1428	18	35	937	1158	21	53
	max	1296	1530	23	47	1049	1231	31	66
	$\bar{\sigma}$	39.6	39.6	1.3	5.0	38.7	40.9	3.1	4.0

* 12 casts, 16 results
\+ 9 castsm 9 results.

Table V. Direct Aged Data(Single Result)

	RT				650°C(1200°F)			
	0.2%PS MPa	TS MPa	Elong %	RA %	0.2%PS MPa	TS MPa	Elong %	RA %
small diameter bar	1482	1599	14	23	1235	1353	16	40

Cut-up tensile data(13) from VIM + ESR Alloy 718 manufactured HP turbine discs compares very favourably with data shown by Meetham(14) for other disc alloys, Figure 6.

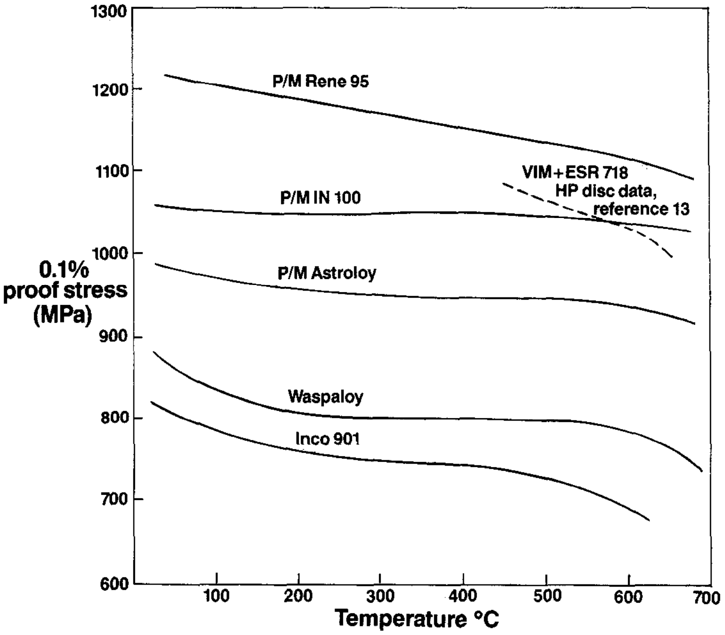

Figure 6 - 0.1% proof stress data obtained by Rolls-Royce Ltd.(13) on HP discs manufactured from VIM + ESR Alloy 718, compared against proof stress data compiled by Meetham(14) for other disc alloys.

LCF must provide the most sensitive measure of metal cleanliness. Davidson and Aubin(15) quoting work of Track and Betz (16) point out that stress-controlled LCF testing exhibits the greatest sensitivity to inclusions, and the effect becomes most pronounced when $R = \sigma \min/\sigma \max = 0$. Stress controlled LCF data(13) generated at 600°C and 625°C by Rolls Royce Limited on VIM + ESR manufactured HP discs is shown in Figure 7. The grain size of the material was generally ASTM 8 and finer. This data compares very favourably with that for other Alloy 718 data(17) and indeed a high strength powder alloy (18).

A close examination of the 600°C and 625°C LCF data for VIM + ESR Alloy 718 in Figure 7 reveals that the total time spent at maximum stress before failure(i.e.LCF life(h) ÷ 2.5)is in excess of the stress-rupture life for the alloy at that same maximum stress. At lower test temperatures(i.e. 550°C and below)the LCF life is, as intuitively expected, considerably less than the stress-rupture life at the equivalent(maximum)stress. The extension of LCF life beyond the stress-rupture life at 600°C and 625°C strongly suggests some change in the way in which fatigue and creep damage is accumulated at these temperatures. A thin foil study is required to elucidate the true mechanism, but in the meantime two explanations are offered; The rate of accumulation of damage has been decreased by slip dispersal and strain hardening. Alternatively, planar slip is simply being annealed out during the off-load part of the cycle.

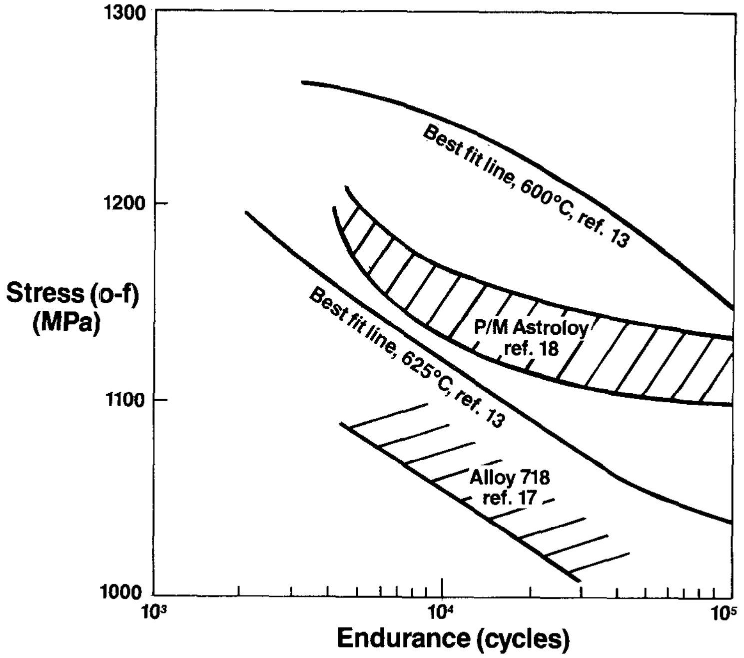

Figure 7 - VIM + ESR Alloy 718 HP disc LCF data obtained by Rolls-Royce Ltd.(13)at 600°C and 625°C, 0.25Hz, square wave, compared against other data at 600°C for Alloy 718(17) and Astroloy(18).

A fractographic examination of the test pieces by Rolls-Royce Limited produced a further and very remarkable observation that no origin of failure was attributable to oxide inclusions. The same observation on GSL Alloy 718 has been made by General Electric who carried out LCF tests at 400°C(750°F) and 538°C(1000°F). Fracture of all test-pieces(eighteen)was found to have initiated at grain boundary features and not at oxides or carbonitrides. It can be inferred therefore that VIM + ESR Alloy 718 is as clean as it needs to be for the improvement of LCF strength.

Conclusions

1. Loss of aluminium and titanium at the bottom of ESR ingot is related to the activities of these elements in the alloy. The variation in aluminium and titanium along the length of an ingot is controlled by slag composition as well as by the activities of these elements.
2. Tight control of the reactive elements along an ingot length has been demonstrated for ESR Alloy 718.
3. The VIM + ESR route has been shown to produce "superclean" Alloy 718.
4. Very high 600°C and 625°C LCF strengths have been demonstrated for VIM + ESR Alloy 718.
5. The origin of cracking in the LCF tests was attributable to grain boundary sources rather than oxide inclusions.

Acknowledgements

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