

**Comparison of the Attributes of VIM + ESR
and VIM + VAR Alloy 718**

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Abstract

The flux present in electroslag refining has the innate abilities to control non-metallics and provide a stable heat source. These characteristics are not found in vacuum arc remelting. Consequently ESR material is demonstrably free of exotics.

The presence of a slag skin does adversely affect the heat flow from an ESR ingot. The use of sophisticated computer process control and cold flux starts enables optimisation and consistency of heat flow. Consequently the extent of segregation in ESR ingots can be almost comparable to VAR ingots size-for-size.

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Introduction

Alloy 718 contains almost 50% of alloying elements in a nickel base. Some of these elements are very reactive such as aluminium and titanium, and others form very low melting point eutectics such as niobium(1). Commerce wants high weight, thick section wrought product for processing into critical components. It is thus necessary to remelt alloy 718, like most nickel-base superalloys for two prime reasons.

- a) To improve the integrity of the alloy by reducing the content of reactive element products (inclusions), eliminating voids (pipe) and by control of exotics and,
- b) To minimise segregation of alloying constituents during solidification of large weight ingots.

There are only two established remelting methods; Electroslag Refining (ESR) and Vacuum Arc Remelting (VAR). The principles of both techniques have been described elsewhere(2).

ESR has been the dominant process in Europe whereas VAR has been the dominant process in USA. Accordingly process control technology for ESR is probably most advanced in Europe. Evidence of this can be seen at Inco Alloys Ltd (IAL) where the first and probably still the only fully computer controlled ESR furnace for the production of superalloys in the world operates. However, VAR process control technology is more universally widespread following the published works of Zanner et al(3).

IAL have been producing INCONEL alloy 718 both by VAR and fully computer controlled ESR for the most critical of aerospace applications and general engineering uses. IAL has thus built up data and experience to dispassionately compare the attributes of both remelt processes.

Essential Characteristic Differences of ESR and VAR

The essential differences between the remelt processes are:-

- a) In VAR, heat for remelting is generated by a DC vacuum between the electrode and the forming ingot. This arc is intrinsically unstable and provides no thermal buffer.

In ESR, remelting is by resistance or ohmic heating resulting from an AC current passing between the electrode and the forming ingot through a resistive slag. This heating method is stable and the slag has a large thermal capacity.

- b) In VAR, the atmosphere above the forming ingot is a low pressure of metal vapours and gases.

In ESR, the atmosphere is nominally air but the slag and its vapour act as significant barriers between the air and the ingot.

- c) In VAR, molten metal solidifies directly onto the water cooled crucible, resulting in a chill cast layer. This layer is depleted in the lower melting point constituents of niobium and titanium and often has entrained inclusions. This layer etches white and is referred to as white jacket in this paper.

In ESR, a slag skin is formed between the water cooled crucible and the solidifying metal. This avoids the chill cast white jacket and inclusions are alloyed or entrained in the flux.

- d) The annular shrinkage gap in VAR is under hard vacuum thus preventing heat transfer from the ingot to mould by conduction or convection. This effect can be greatly reduced by introducing a highly mobile gas such as helium into this cavity.

In ESR, the shrinkage gas contains air at atmospheric pressure. However, ESR ingots generally have a surface layer of low thermal conductivity slag.

- e) In VAR, the molten metal droplets rapidly transfer from the electrode to the ingot.

In ESR the droplets can react chemically and thermally with the molten flux.

- f) VAR is essentially a constant voltage and constant resistance process. Control of the electrode position relative to the forming ingot, that is arc gap, is almost universally by drip short detection for alloy 718. Heat input regulation is by current control alone.

In ESR the position of the electrode relative to the slag and the forming ingot affects the ohmic resistance. To allow independent control of electrode position and heat input, the most sophisticated systems regulate electrode position on resistance and heat input on power.

- g) In VAR, the length of the arc gap influences the stability of the arc and heat distribution. A long arc gap tends to cause more lateral arc strikes to the shelf and a concentration of heat in the centre of the ingot.

In ESR, the position of the electrode tip relative to the slag surface very markedly alters the heat distribution in the slag. An electrode immersed only a few millimetres into the slag results in intense heating in the centre but cold peripheral regions and hence thick slag skins.

Attributes of ESR and VAR

The effect of the differing attributes of ESR and VAR on some of the integrity and segregation features to be found in alloy 718 are summarised in Table 1. A more detailed subjective explanation is given below.

Table I The effect of the attributes of VAR and ESR on the integrity and segregation of alloy 718

Feature	Source		VAR attributes		ESR attributes															
	* VIM practice	* Electrode casting	* Deoxidation practice	* Electrode casting	* Electrode preparation	* VIM practice	* Deoxidation practice	* Electrode/remelt ingot solidification	* Contamination during electrode preparation and remelting	* Chill cast white jacket	* Dendrites in electrode	* Oxidised surface of electrode	* Long local solidification time	* Wide freezing range	* Steep melt pool profile	* Stirring of melt pool	* Rapidly varying solidification rate	* Furnace atmosphere		
Oxy-nitride agglomerations																				
Exogenous oxide inclusions																				
Fine oxy-nitride deoxidation products																				
Exogenous metallic inclusions																				
White spot																				
Interdendritic segregation																				
Freckle (channel) segregation																				
Tree rings																				
Chemistry control																				

Oxy-nitride agglomerations. Gross oxy-nitride inclusions occur when the melt deoxidation products of Al_2O_3 and MgO form agglomerates with insoluble nitrides of TiN. The extent of these agglomerates is influenced by primary vacuum induction melting and electrode casting practices and inevitably some oxy-nitrides are present in the electrode.

During VAR these oxy-nitrides are transferred directly from the electrode into the melt pool. Further agglomeration occurs on the melt pool surface, and migration to the edge of the melt pool concentrates these oxy-nitrides in the white chill cast jacket.

In contrast, during ESR any oxy-nitrides agglomerates are dissociated in the presence of the molten flux. The oxide component is fully alloyed with the flux. The free insoluble nitrides can then move towards the edge of the melt pool where they are entrained in the slag skin.

Exogenous oxide inclusions. Oxide inclusions can result from contamination from the environment in VIM or electrode preparation or remelting. Examples include furnace refractories, casting refractories and grinding wheel.

In VAR these inclusions remain largely unaltered and ultimately migrate to the white jacket.

In ESR these inclusions are totally fluxed. This attribute negates the hazard that ESR is an open process.

Fine oxy-nitride deoxidation products. During solidification of the electrode and remelt ingot fine deoxidation and denitridation products will precipitate.

In VAR the content of strong but trace deoxidants e.g. Mg, are low and the deoxidation products are present in a pure high activity form. Consequently the molten pool has a relatively high oxygen and nitrogen potential.

In ESR the flux can help retain trace deoxidants and deoxidation products are in solution in the flux. Due to the lower oxygen potential of the liquid metal pool and the absence of nuclei, secondary precipitates occur in a generally uniform and fine distribution and are largely independent of any nitrides. ESR therefore has the attribute of both reducing the total oxy-nitride content and giving a much finer distribution of inclusions without the inherent risk of re-entrapment of agglomerates.

Exogenous metallic inclusion. This refers to contamination from a source external to the alloy being remelted. Contamination can arise either in the electrode e.g. weld spatter in the electrode pipe or during the remelting process e.g. iron shot from mould cleaning.

In ESR contamination from the electrode is minimised by the molten slag layer assisting in melting in of foreign metal. However ESR is generally open to the environment and is therefore at risk of contamination during remelting. This risk can be minimised by rigid

security procedures. Although VAR is a closed environment, contamination entrained within the system e.g. in the electrode or on the mould, and indigenous sources e.g. spalling metallic condensate frill can readily be transferred without melting into the ingot.

White Spot. In alloy 718, areas depleted in the hardening elements niobium, titanium and aluminium tend to etch brightly compared to the surrounding matrix. The principal sources of localised bright etching areas or white spots include (4/5).

- dendrite skeletons falling from the electrode
- the frill of vapour deposited splats spalling or being eroded into the melt pool
- the chill cast white jacket of the remelt ingot being eroded into the melt pool.
- the surface layer of the electrode passing into melt without fully alloying.

In VAR, due to the intrinsically unstable nature of the vacuum arc, all the above mechanisms are feasible. The most commonly encountered mechanism is the erosion by the arc of the chill cast layer. As has been mentioned this chill cast layer or white jacket often has entrained dirt.

In ESR, there is no frill or white jacket and the heat source is stable and does not cause aggressive erosion of surface layers or dendrite spines. However in ESR, the surface of the electrode especially the wafer is heated to near melting point in air. This can result in oxidation of niobium, titanium and aluminium in the surface layers. In the hot-topping regime insufficient superheat may be available to fully melt and alloy this high melting point surface layer.

Interdendritic segregation. This term is used to describe micro segregation which occurs most markedly at the centre of an ingot. Micro examination of as-melted ingots of alloy 718 reveals dendritic spines depleted in niobium and interdendritic areas containing pseudo eutectic Laves Phase(1). Prolonged thermal diffusion treatments can largely eliminate these compositional differences. However examination of homogenised forged billet slices may still reveal the whiter etching dendrite spines and darker etching interdendritic areas. This phenomenon should not be confused with channel or freckle segregation.

Interdendritic segregation especially at the centre of the ingot arises from long local solidification times (LST) resulting from poor heat balances and wide melting ranges. Some effects are common to both remelt process. The larger the diameter of ingot, the longer the heat flow path to the cooled crucible. The greater the heat input especially in the centre line, the greater the LST. The higher the alloying content, especially niobium, the wider the freezing range.

In VAR about 50% of the heat input to the melt pool comes directly from the arc and the balance from the rain of molten droplets. Poor arc gap control can result in a concentration of both heat inputs to the centreline. Heat abstraction from the ingot to the mould across the shrinkage annulus is greatly enhanced by the presence of helium.

In ESR good electrode positional control is triply important on heat balance. With a satisfactory electrode position, less than 50% of the ingot heat input arises directly from conduction from the flux, the total heat input is uniform across the diameter and the slag skin has the least thickness. Conversely poor electrode positional control results in 50% of the heat arising from the slag and 50% from the metal rain mainly in the centre line and very thick slag skins to hinder heat abstraction.

Freckle (Channel) Segregation. Macro/micro examination of transverse billet slices may reveal dark etching spots that may be single or often in clusters, thus giving rise to the name freckle spots. In the longitudinal direction these features can have considerable length thus giving rise to the alternative name channel segregates. These are relatively massive streaks rich in low melting point constituents especially niobium and carbide. Because of their massive size, compared to interdendritic segregation, they are not readily eliminated by homogenisation. They occur where a steeply sloping liquidus profile exists, and the LST is relatively long and convective currents of liquid metal may occur.

In VAR, the heat input/melt rate and the arc gap can be accurately controlled to prevent freckle formation.

Likewise pool depths in ESR can be minimised by control of power input and accurate positioning of the electrode. However the presence of an insulating slag skin which can reduce heat extraction, and difficulty balancing this heat input to fuse and raise the temperature of the slag in the early stages, may cause deep melt pools and higher risk of freckle.

Tree Rings. Tree rings are often barely discernible on a microscale, but often can be quite apparent on a macroscale in the mid-radial to peripheral regions. They are caused by short term increases and decreases in the rate of growth of the liquidus profile. These changes can induce freckle type defects. Short term variations in the heat content of the melt pool causes these changes in solidification rate.

In VAR, because of the unstable nature of the arc and the lack of any thermal buffer, the heat content of the melt pool can vary. In ESR the converse is true.

Chemistry Control. Chemistry control is governed by the furnace 'atmosphere' defined as the medium to which the molten metal is exposed. In VAR, this is vacuum, whereas in ESR it is slag. The vacuum in VAR is inert to reactive elements such as niobium, aluminium and titanium and hence recoveries are consistent. However, critical volatile deoxidant additions (magnesium, calcium) are largely lost during remelting, whereas sulphur removal is not possible. A consequence of the latter effects may be reduced elevated temperature ductility and in the ultimate poor hot workability. The molten slag in ESR is essentially reactive. The slag composition must be selected carefully to be in balance with the reactive elements of titanium and aluminium in the alloy and without causing chemical contamination. Most ESR fluxes have a strong desulphurising capability and can be used to aid the recovery of deoxidants.

Summary of Attributes. Analysis of the above attributes indicates the capability of electroslag refining to produce a cleaner product than vacuum arc remelting. Also if conditions can be established and accurately controlled to optimise heat balance, good segregation structures and control of chemistry can be achieved.

Comparative Results

It is very difficult to obtain quantified rather than subjective assessments of material integrity and segregation on a commercial scale. This often arises because other physical phenomena have an overriding effect. For example the resolution of an ultrasonic test may be limited by the grain size and/or the bar diameter; 300 mm diameter bar with a grain size of ASTM 3 will only offer a resolution of about 1.2 mm FBH standard whereas 100 mm diameter bar with a grain size of ASTM 8 may be capable of testing to -18dB of 1.2 mm FBH. A further example can be seen in the influence thermomechanical processing can have on the appearance of segregation. Operations conducted at temperatures of ca 1000 C straddling the delta phase solvus does exaggerate the apparent niobium segregation. Different etches to reveal segregation give differing responses (6); generally grain etches do not make good segregation etches. Even the tried and long established cast release mechanical property test tends to measure the capability of the hot-working process for example roll-down or pancake forge, to generate a preferred wrought structure.

However at IAL thousands of tonnes of INCONEL alloy 718 have been produced both by ESR and VAR for all applications and all size ranges. With the exception of the differing remelt processes, all other aspects are identical. These aspects include equipment such as VIM and forge, techniques such as VIM and forge practices and test methods. IAL can therefore offer an unbiased side by side comparison of ESR and VAR. Below such a comparison is made of each feature listed in Table 1.

Oxy-nitride Agglomerations. There are two potential measures of the amount of agglomerations. The first method is to conduct a mass balance of nitrogen in the VIM melt prior to casting the electrode versus the remelt content. For VIM melts with nitrogen contents of 90 to 180 ppm, the nitrogen contents of ESR and VAR heats are similar at 80 to 90 ppm. When the VIM nitrogen content is less than 80 ppm, the remelt nitrogen content is similar or slightly lower even in ESR. No such readily measurable difference in oxygen content can be observed. High nitrogen VIM heats result in the formation of significant amounts of gross nitrides on remelting. The second test method is visual inspection of surfaces and ultrasonic inspection of the interiors. Examination of the skin of a VAR ingot will reveal entrapments of oxide-nitride agglomerations. Nitrides may be present in the skin of ESR ingots. However surface conditioning of the wrought bar removes these agglomerations. Ultrasonic testing has not revealed the presence of an agglomeration within an ESR product. That is not so for VAR but in the vast majority of instances the agglomerates were associated with white spot.

Exogenous oxide inclusions. There is no recorded incidence of a foreign oxide inclusion having been found in an ESR or VAR ingot of INCONEL alloy 718. However it should be noted the potential sources of such oxides are kept to a minimum for example electrode hot topping materials.

Fine oxy-nitride deoxidation products. There are three test methods that can give an indication of the oxy-nitride deoxidation product content; chemical, metallographic and electron beam button melts.

The oxygen content of ESR material is consistently less than or equal to 0.001%. VAR material likewise is generally less than 0.001%. However higher contents tends to occur at very low magnesium contents (< 5 ppm) and high magnesium contents (> 30 ppm).

It has already been mentioned that nitrogen contents are controlled initially by the nitrogen content of VIM melts, even in ESR although it be operated in air. In these conditions ESR provides slightly lower average nitrogen contents of 83 ppm compared to VAR with averages of 90 ppm.

Micro examination may reveal the presence of fine oxide or nitride particles but normally they are enveloped in the relatively large amounts of carbide in the alloy. No reliable assessment has been possible.

Electron beam button melt is not a routine commercial cleanness test. However the IAL button melts have confirmed the findings of other laboratories(7) that ESR alloy 718 is much cleaner than VAR. For example the alumina particle maximum size and number in ESR material is half that of VAR material, 100 μm vs 250 μm and 12 vs 20. IAL have also found that the raft of TiN particles is much less in ESR material than VAR.

Exogenous metallic inclusions. Only one occurrence of a foreign metallic inclusion in INCONEL alloy 718 is recorded. This happened in an ESR heat of general engineering grade and was observed in an end billet slice. From its composition it was identified as a droplet of another nickel-base alloy which became entrapped in the surface of the electrode during VIM casting.

White spot. Examination of ultrasonic indications in VAR product have almost invariably shown them to be associated with dirty white spot. The morphology of this white spot suggests that most originated from erosion of the shelf or white jacket. White spot has also been detected on routine assessment of billet slices taken from the extreme ends of forged bars. With strict control of process parameters such as close arc gap control, furnace pressure control, gas atmosphere control and electrode magnesium content, the occurrence of white spot is low.

In comparison white spot has never been detected in VIM + ESR INCONEL alloy 718 for critical aerospace applications. However small (2 mm dia) clean white spots have been found in billet slices from the head ends of remelt ingot for non-critical applications. These have been associated with the oxidation of the very hot electrode wafer and the very low slag and metal temperatures during hot-topping.

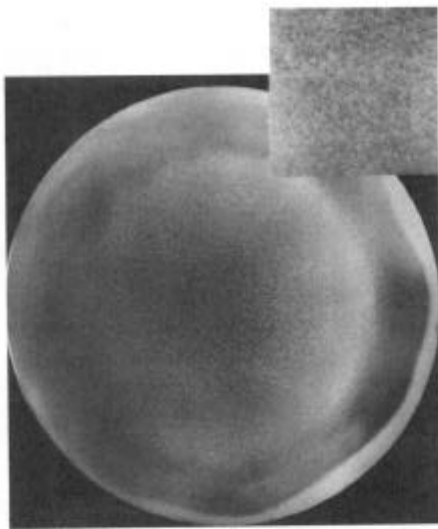


Figure 1 - Interdendritic segregation in forged bar from 380 mm VAR ingot

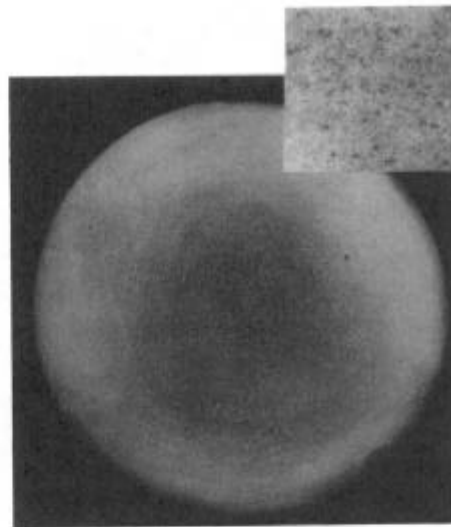


Figure 2 - Interdendritic segregation in forged bar from 460 mm ESR ingot

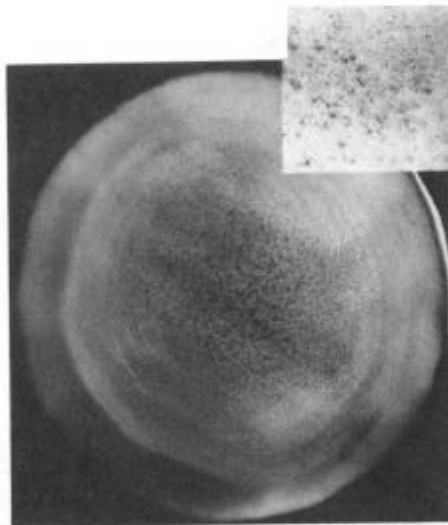


Figure 3 - Interdendritic segregation in forged bar from 540 mm ESR ingot

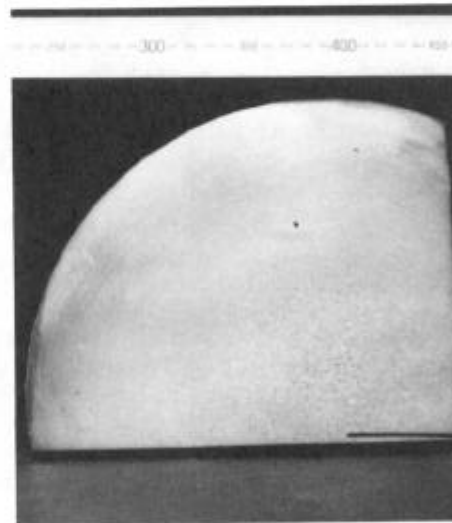


Figure 4 - Tree ringing and segregation in forged bar from VAR ingot

Interdendritic segregation. During development trials, ESR and VAR production scale ingots have been sectioned longitudinally to reveal the melt pool profile and give some indication of segregation. As has been shown by others(8) the pool shape in VAR is roughly hemispherical with fine columnar grains growing perpendicular to the pool. However contrary to other reports, with precision control of melt rate and electrode position, the pool profile of ESR ingots is saucer shaped rather than V shaped. The columnar grains are coarser than those in VAR probably due to the inherent stability of the process.

Transverse billet slices suitably etched reveal varying amounts of interdendritic segregation dependent on remelt method and remelt ingot diameter. Figures 1, 2 and 3 show a range from that observed in 380 mm diameter VAR ingot product through 510 mm diameter VAR or 460 mm diameter ESR to 540 mm diameter ESR product. Despite the apparent severity in the largest ESR product, micro analysis on SEM can barely resolve compositional differences even of niobium. In particular the averages and standard deviations of 100 analyses from the centre and peripheral regions were $\bar{x} = 5.23$ $\sigma = 0.226$ and $\bar{x} = 5.15$ and $\sigma = 0.197$ (For comparison a powder metallurgy sample gave $\bar{x} = 5.24$ and $\sigma = 0.133$).

Micro assessment of interdendritic segregation can be made by examining the carbide morphology. The centre to periphery variations are slightly greater in ESR product compared to VAR but these are negligible compared to the variations arising from comparing low carbon (0.025%) with high carbon (0.04%) material.

Freckle Segregation. Freckles have been observed in a small proportion of the bottom ends of ESR ingots. These conditions have been associated with the start-up conditions. In these early stages of the melt, conditions are varying widely; slag volumes and temperatures are changing and the power parameters are being profiled. As has been described before, the IAL furnace controls heat input on power and electrode position on resistance. These two parameters can be controlled independently of each other and computer recipe profiles are written for these even in the start phase. Modification of these profiles has reduced the incidence of freckles even in the largest diameter ingots to very low levels.

Freckles have not been observed in VAR ingots.

Tree Rings. Fig. 4 shows tree rings in VAR alloy 718. Despite its impact on macro assessment it is barely visible on micro assessment. Tree rings are barely apparent in ESR product except in the start phase material.

Chemistry Control. Comparison of the VIM electrode analysis with remelt ingot analyses shows the following:

- i) Base metals such as iron, nickel, chromium, molybdenum and also niobium are effectively unchanged by either remelting method.
- ii) The reactive element titanium is also unchanged by either remelting method. However in ESR it is necessary to have a carefully controlled slag chemistry that is in balance with the alloy.
- iii) The reactive element aluminium is unchanged in VAR. However, oxidation losses occur in ESR. These are typically 0.15% at the base of the ingot and 0.10% over the remaining ingot.
- iv) Carbon and silicon pick-up can occur at the base ends of ESR ingot from contamination from the slag. At IAL only cold prefused analysed slags are used and this pick-up can be maintained at less than 0.005% and 0.02% respectively.

- v) Recoveries of magnesium in VAR depends on many variables including electrode magnesium content, furnace pressure, arc gap, electrode to mould gap etc. All these have impacts on other characteristics e.g white spot, and hence compromise process conditions have to be set. These result in magnesium contents of typically 12 ppm.

Recoveries of magnesium in ESR depends on electrode magnesium content and slag chemistry. The process conditions at IAL result in typical values of 30 ppm.

- vi) Sulphur in VAR is inert and hence the sulphur content is that achieved in VIM. Untreated pure melts in Europe give typical sulphur values of 20 ppm.

ESR is very effective at reducing sulphur and single ppm values are the norm.

Mechanical properties. The mechanical properties that are achieved on cast release testing are greatly influenced by parameters totally unconnected with the remelting processes. For example the alloys hardener content especially niobium, the hot working method such as roll down or pancake forging, the grain size from ASTM 4 or ASTM 12, solution treatments and ageing treatments. IAL have found only one definite correlation and one tentative correlation between remelting methods. Ductility at room temperature and elevated temperature may be impaired slightly by the presence of the heaviest dendritic segregation in large diameter ESR ingots compared to the finest dendritic pattern in VAR ingots. However this pales into insignificance compared to the influence of magnesium sulphur ratio. If the magnesium content is less than the sulphur content, even with single ppm contents of sulphur, elevated temperature ductilities may be half of those with magnesium contents greater than the sulphur content. The Mg : S ratio in ESR is always greater than 1 : 1 whereas with VAR it may approach 1 : 1.

The impact of the high ductility and improved integrity of ESR material on crack growth rate dependent properties such as low cycle fatigue and fracture toughness have not been determined on routine cast release assessments.

Conclusions

- i) ESR produces material of the highest integrity which is demonstrably free of inclusions that are otherwise inherent in VAR.
- ii) ESR is not as effective as VAR in controlling segregation. However with sophisticated computer control of all important process parameters, ESR can consistently produce material that approaches the segregation standards of VAR.
- iii) Control of magnesium and sulphur in ESR ensures that higher ductility material is always produced. This degree of control is not possible in VAR.

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