ADVANCES IN TRIPLE MELTING

SUPERALLOYS 718, 706, AND 720

J. M. Moyer, L. A. Jackman, C. B. Adasczik, R. M. Davis, and R. Forbes-Jones

Teledyne Allvac
P.O. Box 5030
2020 Ashcraft Avenue
Monroe, North Carolina 28110-5030

Abstract

Triple melting (TM) by VIM+ESR+VAR has been highly successful for Alloy 718, large diameter ingots of Alloy 706, and high hardener alloys such as Alloy 720. Frequencies of ultrasonic indications for TM 718 are significantly lower than for VIM+VAR melt 718 because fewer clusters of inclusions are present. The cleanliness associated with TM 718 was verified by microscopy and by electron beam melting of buttons after VIM, VIM+ESR, and TM. Furthermore, white spot frequencies were found to be reduced for TM 718. Ultrasonic defect frequencies of Alloy 706 and Alloy 720 are also low. A major advantage of triple melting Alloy 706 is that ingots up to 36 inches (914mm) in diameter can be melted without freckles or positive segregation problems.

Superalloys 718, 625, 706 and Various Derivatives
Edited by E.A. Loria
The Minerals, Metals & Materials Society, 1994

Introduction

The classic method for producing high temperature superalloys utilizes two consecutive melting steps. The first is normally Vacuum Induction Melting (VIM), whereby the raw materials are melted and cast into an electrode under a vacuum in an induction furnace. This step insures that the raw materials are homogeneously mixed together in the electrode, but it does not provide a solid product that is suitable for subsequent thermomechanical processing. The second step is either Vacuum Arc Remelting (VAR) or Electro-Slag Remelting (ESR).

The VAR process melts the electrode made in the VIM furnace into a water cooled copper crucible at a controlled melt rate. Although the VAR process reduces the levels of volatile tramp elements and can provide an ingot of the highest quality for forging, the VIM+VAR route has two drawbacks. First, the oxide cleanliness, particularly the maximum oxide inclusion size in VIM+VAR product, limits the Low Cycle Fatigue (LCF) life of rotating parts (1). Second, the VAR process tends to produce "white spots", or defects lean in solute elements compared to the matrix. These defects can reduce strength and LCF life (2).

The ESR process is somewhat similar to the VAR process, except that it melts an electrode through a molten slag that acts as a refining agent to remove oxide clusters. The resultant improvement in oxide cleanliness is a major benefit associated with the VIM+ESR route (3,4,5). A drawback of VIM+ESR material is its greater tendency, relative to VIM+VAR material, to contain regions of chemical segregation, especially along the center of large diameter ingots.

Since 1983, the benefits of VAR and ESR have been combined into a "triple melt" process, in which an ESR step is inserted between the VIM and VAR steps (VIM+ESR+VAR). The triple melt process mates the improved oxide cleanliness made possible by ESR with the superior macrostructure associated with VAR, one result being a 90% reduction in inclusion initiated LCF specimen failures compared to VIM+VAR material (1, also 3, 5, and 6). Additional benefits of triple melting are reported in this paper.

The objective of this work was to evaluate and compare triple melted (VIM+ESR+VAR) and double melted (VIM+VAR) material for:

- Top to bottom uniformity of chemical composition,
- Oxide cleanliness,
- Ultrasonic indications, and
- Macrostructure (white spots, freckles, ring pattern, and dendritic pattern).

Although most of the work involved Alloy 718, some results for three alloys of the following nominal compositions are included:

Table I. Compositions of the Alloys in Weight Percent

Alloy	C	Mo	W	Cr	Ni	Co	Fe	Nb	Ti	Al	B
706	0.01	-	-	16	41	-	38	3.0	1.75	0.25	.004
718	0.03	3	-	18	53	-	18	5.3	1.00	0.50	.004
720	0.01	3	1.25	16	56	15	-	-	5.00	2.50	.015

Chemistry Variations

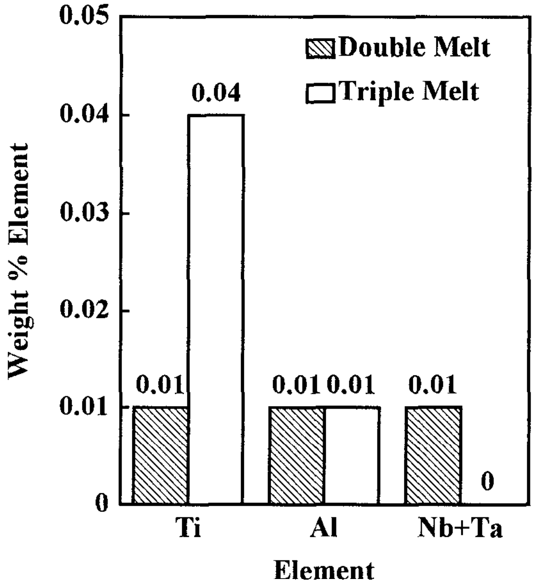

Figure 1. Average top to bottom differences in hardener content for double melt (VIM+VAR) and triple melt (VIM+ESR+VAR) ingots of Alloy 718.

The variation in chemical composition between the ingot top and bottom for double melt versus triple melt Alloy 718 was compared for one year's production and found to be very minor in both cases. This is shown in Figure 1 for the precipitation hardening elements in Alloy 718; titanium, aluminum, and niobium plus tantalum. The element having the greatest difference was titanium in triple melt material, the difference being due to the ESR step being inserted between VIM and VAR. The variation results from reactions with the slag during start up, when titanium in the electrode is initially oxidized until an equilibrium amount in the slag is attained. Titanium variation is minimized by making small additions of titania (TiO_2) to the slag at start up; the variation would have been greater than the 0.04 shown in Figure 1 had titania not been added. By adding titania, a corresponding pickup of aluminum at the bottom end of the ESR ingot is also avoided.

Oxide Cleanliness

One of the main advantages of triple melting superalloys is the dramatic improvement in cleanliness that can be realized. To demonstrate this improvement, the cleanliness of VIM, VIM+ESR, and VIM+ESR+VAR Alloy 718 was evaluated using the electron beam (EB) button melting test.

Following a nominal 2" (51mm) cutback, three 1.5" x 1.5" x 6.375" (38mm x 38mm x 162mm) blanks were cut from a 2" (51mm) thick full cross-section macro plate taken from the bottom end of a 14" (356mm) ø VIM electrode. A similar sampling procedure was employed for a 17" (432mm) ø VIM+ESR and 20" (508mm) ø VIM+ESR+VAR ingot to obtain six blanks from both top and bottom locations. The blanks were prepared and EB melted in a randomized sequence using practices established previously at Teledyne Allvac for Alloy 718, the details being very similar to those described previously (7). The nominal weight of the resulting EB buttons was 530 grams.

Following EB melting, the buttons were forwarded to Honeywell, Inc. (Clearwater, Florida) for semi-quantitative evaluation of the button rafts. Using an SEM/EDX system equipped with a light element detector and image analysis software, oxide particles larger than 0.5 mils^2 (3 x 10^{-4}mm^2) were counted and measured for surface area. In each individual button, the total oxide area was calculated and then divided by the button weight to determine the specific oxide area (mm^2/kg). Additionally, the qualitative composition of the five largest oxide particles observed in each button was determined. All EDX analyses were performed at an operating voltage of 10kV.

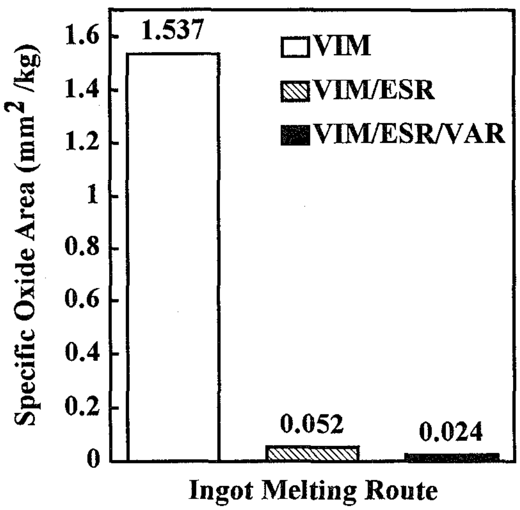

Figure 2. Comparison of electron beam button melt test results for Alloy 718 made using three different melt practices.

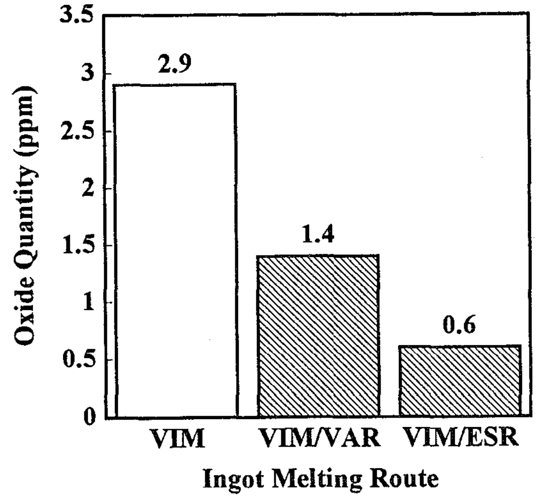

Figure 3. Comparison of Alloy 718 cleanliness made by Sutton (8).

Figure 2 presents a comparison of VIM, VIM+ESR and VIM+ESR+VAR 718 cleanliness. In each case, the values reported are averages of all the individual tests performed. As the data indicate, VIM+ESR+VAR was found to be cleaner than both VIM and VIM+ESR material. Furthermore, the results of this study showed that the cleanliness of triple melted material was much more consistent, as measured by the variation in individual button results and oxide frequency and size, than single or double melted material. While VIM+VAR 718 was not evaluated in this study, its cleanliness was expected to fall between those of VIM and VIM+ESR. As shown in Figure 3, this assumption was substantiated by Sutton (8) and was also reported by Maurer (4) in earlier studies. Cordy et al. (5) have also reported fewer and smaller oxide particles in triple melt 718 than in double melt (VIM+VAR). Table II presents the qualitative oxide compositions representative of VIM, VIM+ESR and VIM+ESR+VAR material. As expected, the major x-ray peaks were Al, Ca, Ti, Mg, and O (4).

Table II. Oxide Composition in Alloy 718 Qualitative X-Ray Analysis*

Ingot Melting Route	Major X-Ray Peaks***
VIM**	Al/Ca/O
VIM+ESR	Al/Ca/O Al/Mg/O Al/Mg/Ca/O Mg/Al/Ca/O
VIM+ESR+VAR	Al/O Al/Ti/O Al/Ca/O

* X-Ray Analyses Performed on EB Button Rafts
** Oxide Agglomerate
*** Major X-Ray Peaks Listed in Order of Decreasing Intensity

Ultrasonic Indications

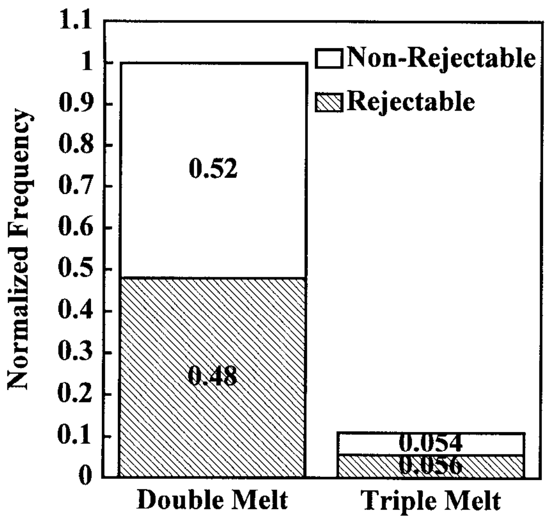

Figure 4. Relative numbers of ultrasonic indications in fine grained VIM+VAR and triple melted 718 billets.

The dramatic improvement in cleanliness of triple melt material when compared to double melt (VIM+VAR) is probably best exemplified by comparing results of ultrasonic inspection. Figure 4 shows the relative frequency of ultrasonic indications, both rejectable and nonrejectable, for a year's production of fine grained Alloy 718 billet immersion ultrasonic inspected to a No. 2 FBH standard.* Triple melt product has roughly an order of magnitude fewer ultrasonic indications than double melt. A reduction of 50% has been reported elsewhere (1).

Reductions in the frequency of ultrasonic indications for triple melt material can be attributed to VAR processing a cleaner, sounder electrode that results from the ESR process. The higher integrity electrode from ESR enables tighter process control in VAR as well as a cleaner product.

Macrostructure

Instabilities during the VAR process are reduced if the VIM electrode, which contains shrinkage cavities and porous regions along its length, is replaced by a much more solid ESR ingot (triple melting) (6). With its greater uniformity of melting conditions during the VAR step, triple melting can produce VAR ingots with fewer defects than its double melted (VIM+VAR) counterpart (3). Several types of these defects are discussed below.

Freckles

Freckles are regions of positive macro-segregation, which result from the flow of solute-rich interdendritic liquid in the mushy zone during solidification (3). Freckles in Alloy 718, for example, are enriched in niobium and titanium compared to the matrix. Their large potential size and poor mechanical properties make freckles undesirable (4). Examples of severe freckling in a 34" (864mm) diameter ingot of Alloy 706 appear in Figures 5 and 6.

Work at Teledyne Allvac has shown that freckles are less likely to occur in a triple melted ingot than in a double melted ingot of the same diameter. Table III shows that triple melting makes it possible to produce a larger ingot for a particular alloy than does double melting.

* No. 2 FBH = 2/64" (0.79mm) diameter flat bottom hole.

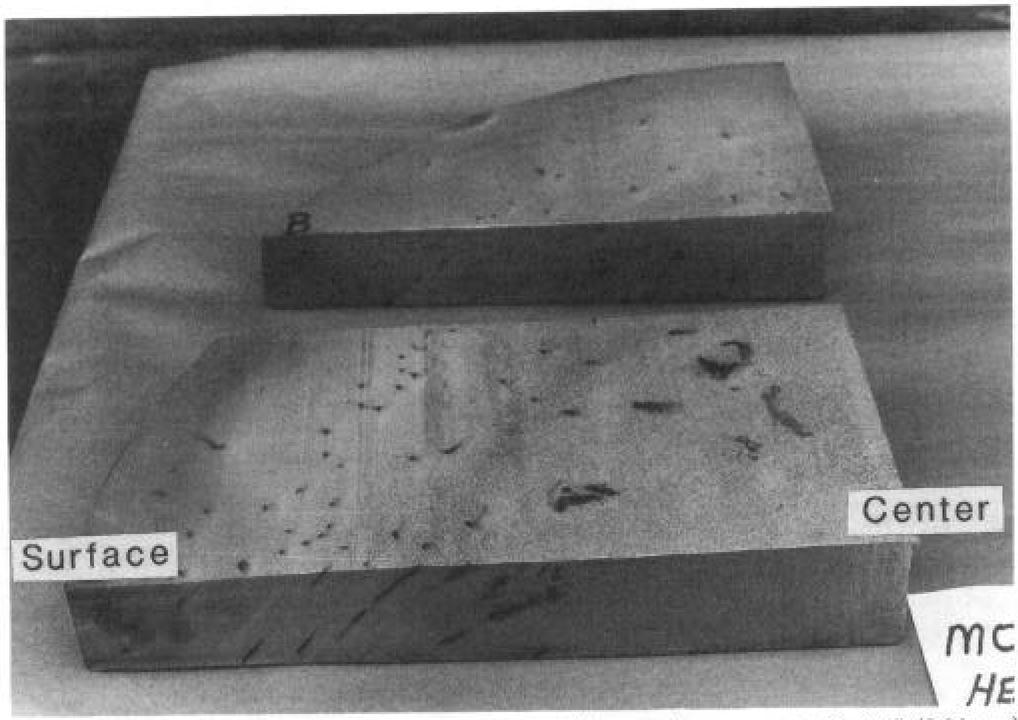

Figure 5. Large freckles outlining the pool profile near the top end of a 34" (864mm) diameter ingot of VIM+ESR Alloy 706. The topmost transverse face of the plate is on the ground.

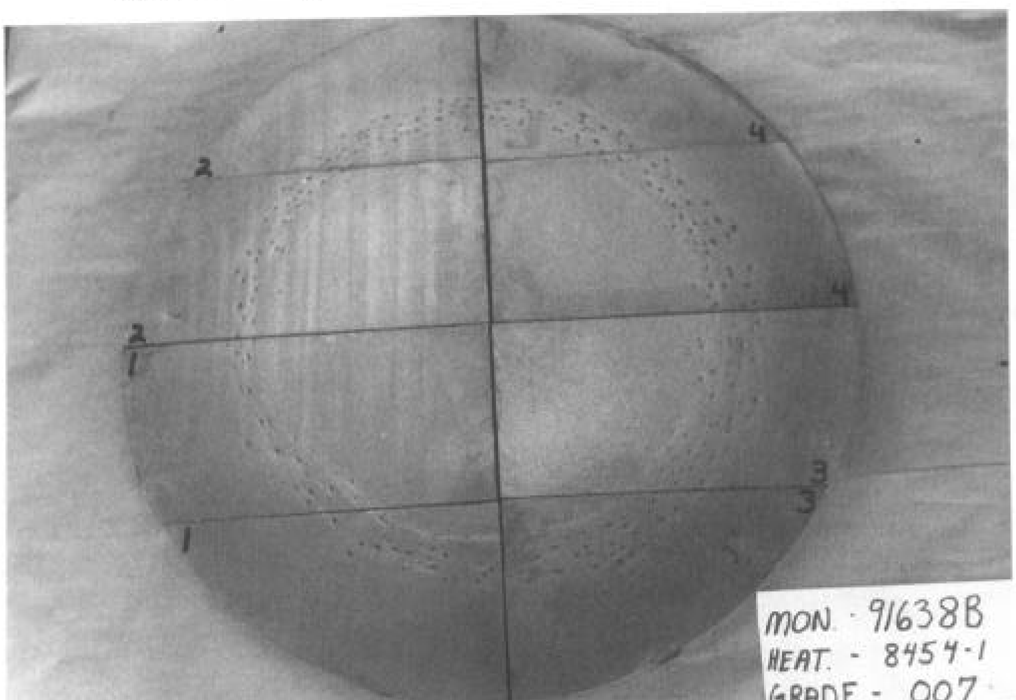

Figure 6. Pattern of freckles near the bottom end of the same 34" (864mm) diameter ingot of Alloy 706 pictured in Figure 5.

Table III. Maximum Diameters Presently Produced by Triple Melting

Alloy	Diameter	Double Melt Experiences for this Diameter
706	36 in 914 mm	Freckles in VIM+VAR and VIM+ESR.
720	20 in 508 mm	Maximum attempted = 17 in (432mm). Macrostructure was acceptable.

White Spots

The problems caused by white spots and their probable origins have recently been documented in great detail (2), an update of which is scheduled to appear later during this conference (9). Accordingly, only a brief summary will appear here.

Discrete White Spots. Figure 7 illustrates the VAR process using an electrode made in a VIM furnace. The low Nb-containing shelf, crown, and torus material may be detached, sink through the liquid, and become entrapped in the solidifying ingot. An example of the resulting discrete white spot can be found in Figure 8.

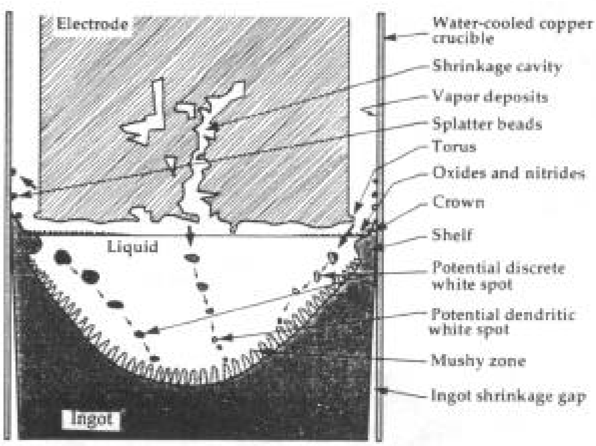

Figure 7. Schematic of the VAR process shows potential sources of discrete and dendritic white spots. (9)

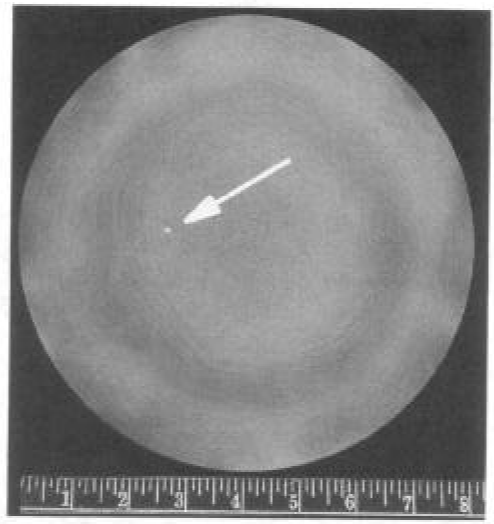

Figure 8. Discrete white spot in an Alloy 718 billet slice. Canada etch. Scale in inches (9).

If the shelf, crown, or torus material falls through a floating layer of oxide and nitride particles, the result may be a "dirty" discrete white spot that, upon subsequent forging of the VIM+VAR ingot, may crack and give rise to an ultrasonic indication. The reduction of oxides brought about by melting an ESR ingot instead of a VIM electrode in the VAR furnace may help explain why triple melt ingots contain fewer ultrasonic indications than VIM+VAR ingots (Figure 4).

As the shelf, crown, and torus are characteristics of the VAR process, one would not expect triple melting to reduce the frequency of discrete white spots. Indeed, Figure 9 demonstrates that there are about the same number of discrete white spots in triple melt as in VIM+VAR 718.

Dendritic White Spots. The solidification pipe (or shrinkage cavity) in the VIM electrode in Figure 7 results in a variable electrode cross-sectional area, a less stable arc, and erratic melting. Consequently, clusters of dendrites can fall into the pool, resulting in dendritic white spots near the center of the ingot's cross section. An example of dendritic white spots is found in Figure 10. If an ESR ingot is substituted for the VIM electrode pictured in Figure 7, as in the case of triple melting, there will be no shrinkage cavity, a very small chance (if any) for clusters of dendrites to fall into the liquid, and, one would expect, no dendritic white spots would be produced. Figure 9 shows that triple melting essentially eliminates dendritic white spots.

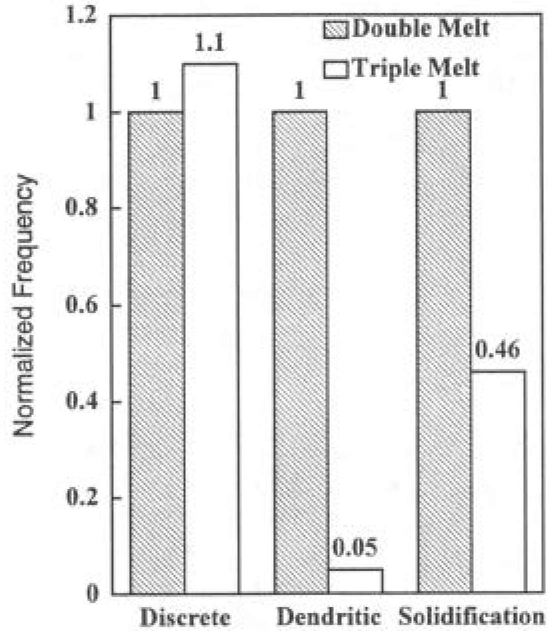

Figure 9. Normalized frequencies of the three types of white spots in Alloy 718. One year's worth of production data for VIM+VAR and VIM+ESR+VAR 718 are represented.

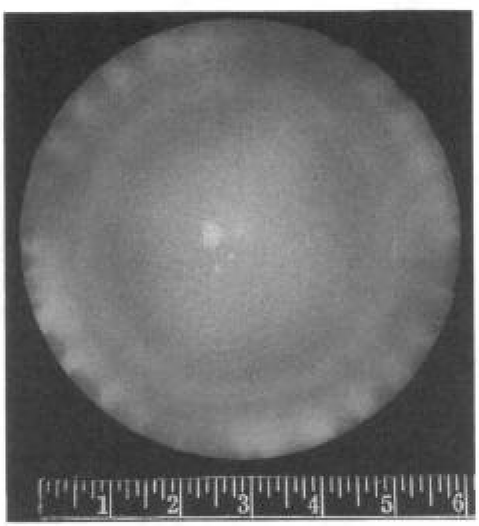

Figure 10. Dendritic white spots in the center of an Alloy 718 billet slice. Canada etch. Scale in inches (9).

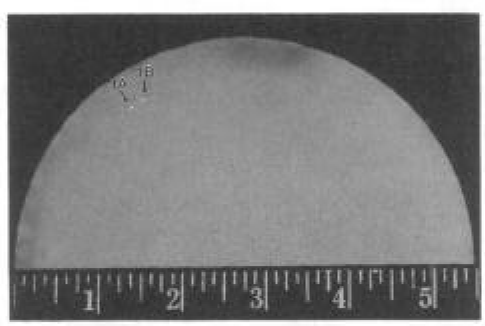

Figure 11. Solidification white spots in an Alloy 718 billet slice. Canada etch. Scale in inches (9).

Solidification White Spots. This type of white spot, in Figure 11, is thought to result from a localized decrease or arrest in the solidification rate of the VAR ingot. The slower rate allows coarsening of primary dendrite arms, which provides an opportunity for some interdendritic fluid to be swept away. What results is a region that is slightly leaner than the matrix in interdendritic solutes. As solidification white spots are caused by thermal perturbations, the more stable melting taking place during the VAR step of a triple melt process would be expected to produce fewer solidification white spots than the VAR step in a double melt process. Figure 9 demonstrates that triple melting cuts the frequencies of solidification white spots about in half.

Other Conditions

"Ring pattern", or "tree ring pattern" (3,4), consists of concentric rings visible in a macroetched billet slice. "Dendritic pattern", or "residual dendritism" has been defined in terms of micro segregation that may be observable macroscopically (3). If severe enough, either condition may be cause for rejection. As shown in Figure 12, the frequency of each condition is essentially unaffected by melting practice.

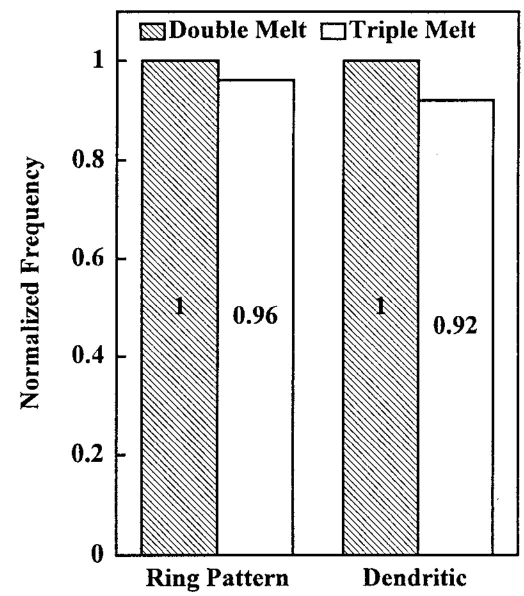

Figure 12. Normalized frequencies of ring pattern and dendritic conditions for VIM+VAR and VIM+ESR+VAR Alloy 718. One year's worth of data are represented.

Conclusions

There have been a number of advantages of triple melting (VIM+ESR+VAR) over double melting (VIM+VAR) documented. These include:

1. Ultrasonic indications are 90% fewer in triple melted material.

2. A larger diameter ingot can be made by triple melting.

3. There are significantly fewer white spot defects in triple melted material:

   a. Triple melting essentially eliminates dendritic white spots, and

   b. Triple melting results in 50% fewer solidification white spots.

4. Oxide cleanliness is improved, and there is greater consistency in the results for triple melted relative to double melted material.

The apparent disadvantage of the triple melt process is that it adds an additional melting step to a double melt process and, therefore, increases melting costs. However, the lower frequencies of defects found in triple melted billet results in improved overall yields (3). In addition, triple melted material's 90% reduction of inclusion initiated LCF specimen failures, 80% reduction of average inclusion size, and a previously reported 50% reduction in the number of rejectable ultrasonic indications in billet compared to VIM+VAR 718 has resulted in triple melted 718 being introduced into an ever increasing number of turbine and compressor disks, shafts, and seals (1).

References

1. R. D. Kissinger, "Trends and Near Term Requirements for GE Aircraft Engines -- Titanium and Nickel Base Disk Alloys" (Paper presented at Electron Beam Melting and Refining -- State of the Art 1991, Reno, Nevada, 13-15 November, 1991), 31-40.

2. L. A. Jackman, G. E. Maurer, and S. Widge, "New Knowledge about 'White Spots' in Superalloys," Advanced Materials and Processes, 143 (5) (1993), 18-25.

3. K. O. Yu and J. A. Dominque, "Control of Solidification Structure in VAR and ESR Processed Alloy 718 Ingots" (Paper presented at the International Symposium on the Metallurgy and Applications of Superalloy 718, Pittsburgh, Pennsylvania, 12-14 June, 1989), 33-48.

4. J. K. Tien, ed., Superalloys, Supercomposites, and Superceramics (Boston, Mass: Academic Press, Inc., 1989), 49-97.

5. J. T. Cordy, S. L. Kelley, and L. W. Lherbier, "Chemistry and Structure Control in Remelted Superalloy Ingots" (Paper presented at the 1984 Vacuum Metallurgy Conference on Specialty Metals Melting and Processing, Pittsburgh, Pennsylvania, 11-13 June, 1984), 69-74.

6. A. Mitchell, "The Present Status of Melting Technology for Alloy 718" (Paper presented at the International Symposium on the Metallurgy and Applications of Superalloy 718, Pittsburgh, Pennsylvania, 12-14 June, 1989), 1-15.

7. R. B. Blichmann, J. M. Moyer, and M. J. Oruska, "An EB Button Melting Test for Evaluating the Cleanliness of Rene' 95", (Paper presented at Electron Beam Melting and Refining -- State of the Art 1989, Reno, Nevada, 29-31 October, 1989), Part Two, 58-67.

8. C. M. Sutton, "Electron Beam Remelt; Substance, Scope and Future as a Quality Control Tool" (Paper presented at Electron Beam Melting and Refining -- State of the Art 1986, Reno, Nevada, 2-4 November, 1986), 297-317.

9. L. A. Jackman, G. L. Maurer, and S. Widge, "Understanding Solute-Lean Defects in Cast/Wrought Superalloys" (Paper to be presented at Superalloys 718, 625, 706 and Derivatives, Pittsburgh, Pennsylvania, 27-29 June, 1994).