

CAUSES AND EFFECTS OF CENTER SEGREGATION IN ELECTRO-SLAG REMELTED

ALLOY 718 FOR CRITICAL ROTATING PART APPLICATIONS

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ABSTRACT

This paper discusses some of the possible causes and effects of center segregation in electro-slag (ESR) remelted alloy 718. This "defect" was investigated as part of a program to develop processing parameters that would result in consistently segregation free ESR 718 ingots suitable for gas turbine rotating part applications. Various remelt parameters; including melt rate, slag chemistry and volume, and electrodes immersion depth were evaluated. These remelt trials were also monitored by special equipment. In addition, ingot chemistry (Cb analysis) and billet conversion practices were investigated. Material from the processing trials was evaluated, or characterized, by means of macrostructure, microstructure, and mechanical properties. Results of the program to date reinforce the premise that electro-slag remelted 718 ingot product has a higher susceptibility to macro-segregation than the same product that is vacuum arc remelted. However, there is also substantial evidence to suggest that the center segregation can be affected positively by controlled remelt and conversion practices.

## Introduction

Electro-slag remelting of superalloys has been an established process for several applications and alloys for many years, both in the US and abroad. In recent years, the ESR process has made strides towards acceptance in more critical applications and for the more segregation prone precipitation hardening superalloys. The quest to develop successful ESR practices is being motivated by the potential benefits of the ESR material relative to the vacuum arc remelted (VAR) material. Principle among these benefits are a significant improvement in cleanliness, especially as it relates to inclusion sizes; and the reduction, or possible elimination of "white spots." Reduction in size and number of inclusions or "defects" in the material has been shown in several testing programs to improve low cycle fatigue (LCF) life.

Alloy 718 is the largest volume precipitation hardening superalloy currently being pressed into service for critical rotating disc applications in gas turbine engines for the aerospace industry. While the ESR 718 material has demonstrated improved "cleanliness" relative to VAR 718, it has not been without other potentially serious problems. Alloy 718 has always shown the greatest tendency for macro- and micro-segregation of any of the high volume, wrought superalloys due to its large temperature differential between liquidus and solidus. The ESR process only adds to the potential problems relative to VAR because it is more complex and has more process variables which have an affect on the solidification of the ingot. (Figure 1.)

The driving force towards cleaner material and longer life for some highly stressed rotating discs has led one major engine company to somewhat of a compromise. So-called "Triple Melt" 718 has been in use for some years now with excellent results. This VIM + ESR + VAR process has given some of the virtues of each of the remelting practices to the quality of the final material. The ESR step has done a commendable job of cleaning up the VIM electrode, while the final VAR remelt assures a relatively consistent, segregation free ingot. However it is still a compromise since the VAR step may re-agglomerate some of the fine, widely dispersed inclusions resulting from the ESR step into larger "clusters." In addition, even though the "electrode" for the final VAR is relatively sound and homogenous, the probability of some "white spot" formation during the vacuum arc remelting exists. Of just as much concern, however, is the high cost of the "triple melt" material as a result of the extra process steps and very significant yield losses incurred.

## Remelting and Processing Trials

All of the material involved in this program was melted, remelted and converted to billet at Cytemp Specialty Steel Division. The 718 electrodes were melted and cast in a 30 ton VIM facility in Titusville, Pennsylvania. The electro-slag remelting was accomplished in a newly refurbished ESR facility in Cytemp's Bridgeville, Pennsylvania plant. Billet conversion, ultrasonic testing, macro-etch inspection, mechanical property testing, and much of the microstructural evaluation was done in Titusville.

The ESR furnace used for this development program had just gone through an extensive upgrade, which was in fact an integral part of the overall program. Previous experience with ESR 718 made in this shop showed very inconsistent ingot quality with respect to segregation; some ingots were good, and others very poor. The worst problems were linked to poor

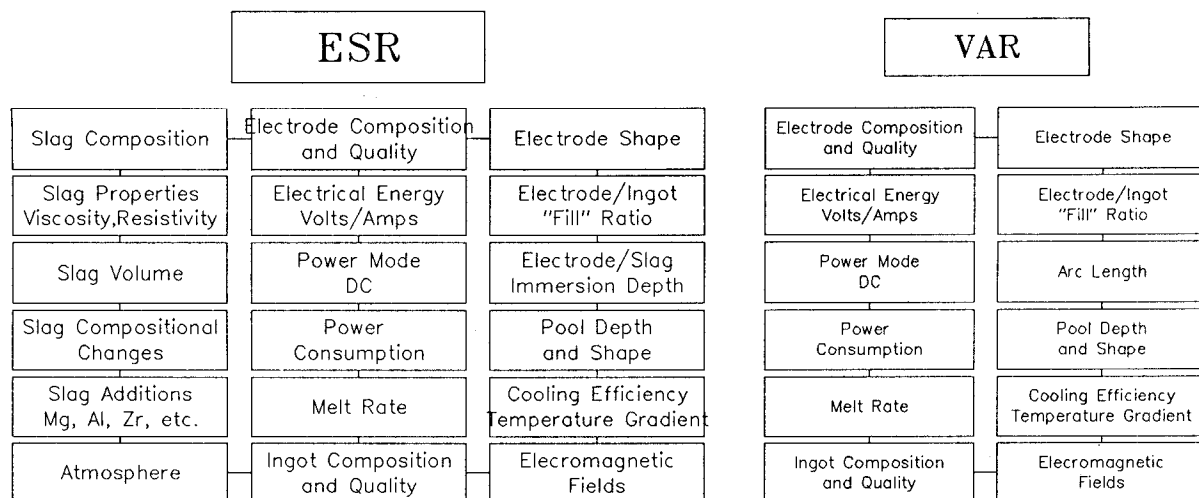


Figure 1. — Process Characteristics of ESR and VAR (1)

electrode/slag immersion depth control resulting from an inadequate ram drive system and outdated voltage or "swing" control. In general the upgrade consisted of a new electro-mechanical ram drive system with solid state drive controls, a new load cell weighing system, and Consarc Corporation's Automatic Melt Control (AMC) system which included melt rate control and automatic voltage control.

Nine high columbium (~5.35%) ingots, 17" in diameter were remelted and evaluated in this specific program. Several other ingots of low columbium (~5.10%) in the same ingot size were melted before, and since, in order to test the newly refurbished furnaces, evaluate the effect of lower columbium on segregation, and on a production basis for other applications. Previous work to develop ESR 718 for critical applications<sup>(2)</sup> had established many of the remelt variables to relatively narrow ranges. For example, it has been shown through production experience and through determining local solidification times for ESR and VAR ingots that the melt rates required for relatively segregation free Alloy 718 are essentially the same. The slag composition has considerable effect on slag melting temperature and fluidity; and while some latitude exists for choosing the exact composition, the nominal slag composition used in these trials was held constant at the 60% CaF<sub>2</sub>, 20% CaO, 20% Al<sub>2</sub>O<sub>3</sub>, with 5% TiO<sub>2</sub> arrived at in the earlier work. Another maxim that was arrived at earlier and adhered to in this program was that there would be no additions of the bulk slag composition during the remelt because of problems with any of the available slag addition systems. It would also be another process variable requiring close control and monitoring in a process already loaded with such variables. Also established in the earlier programs was the requirement for a very shallow electrode/slag immersion depth and carefully controlled and consistent start-up practices to assure thin slag "skins" and an adequate slag "cap" at the end of the remelt.

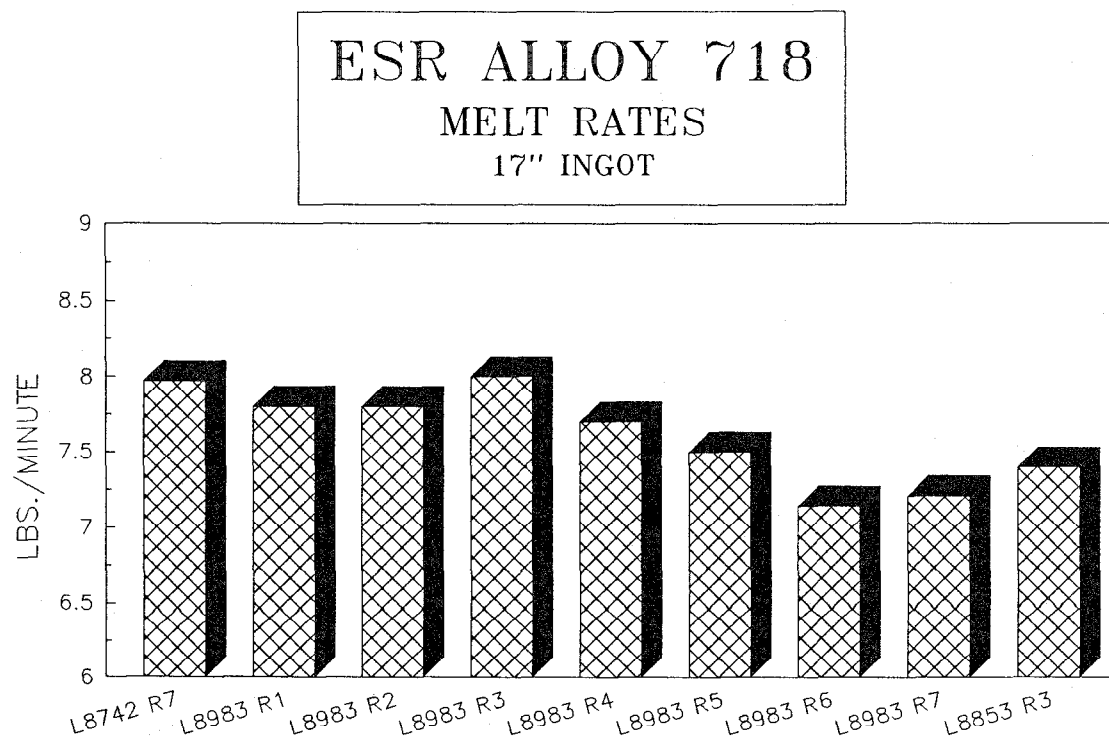
The remelting trials for the nine ingots are summarized in Figure 2. The first two ingots were remelted using the same parameters that were used to remelt two segregation free ingots prior to the furnace upgrades.<sup>(2)</sup> (The results of these two ingots were not reproducible, and for that reason the furnace upgrade was done.) The next two ingots were remelted using the same parameters except that a slag "conditioner" was added to lower the melting temperature of the slag and increase its fluidity. While the limits for melt rate had already been established to some extent, melt rate was varied within this range to determine the effect, if any, on the center

# ELECTRO-SLAG REMELT TRIALS

## Alloy 718

Heat Number	Practice	Ingot Surface	Slag "Cap" Height	Melt Rate Aim
L8742 R7	Standard	Top "necked"	4"	Standard
L8983 R1	Standard	Top "necked"	4"	Standard
L8983 R2	Add "Conditioner"	OK	4.5"	Standard
L8983 R3	Add "Conditioner"	OK	5.5"	Standard
L8983 R4	Standard	Bottom good	2.5"	Reduce 7%
L8983 R5	Add "Conditioner"	Good	6"	Reduce 7%
L8983 R6	Add "Conditioner"	Good	6"	Reduce 14%
L8983 R7	20% added Slag	Hvy "skin" btm 18"	6.5"	Reduce 14%
L8853 R3	High "fill ratio"	Top "necked"	3"	Reduce 14%

Figure 2. -- Summary of remelting trials.



Melt rate defined by power-on to power-off.

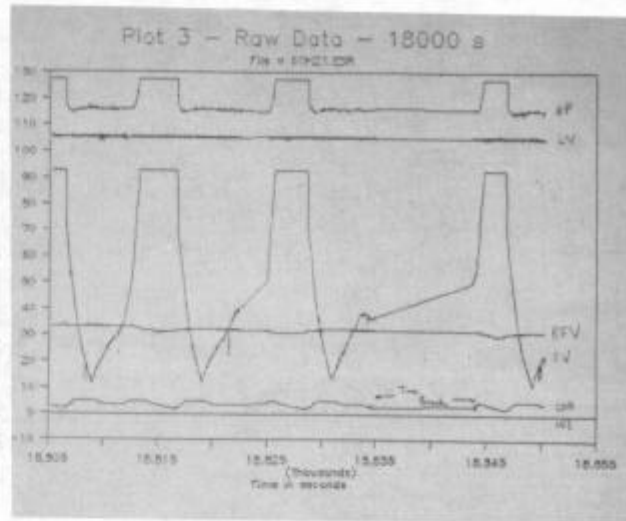
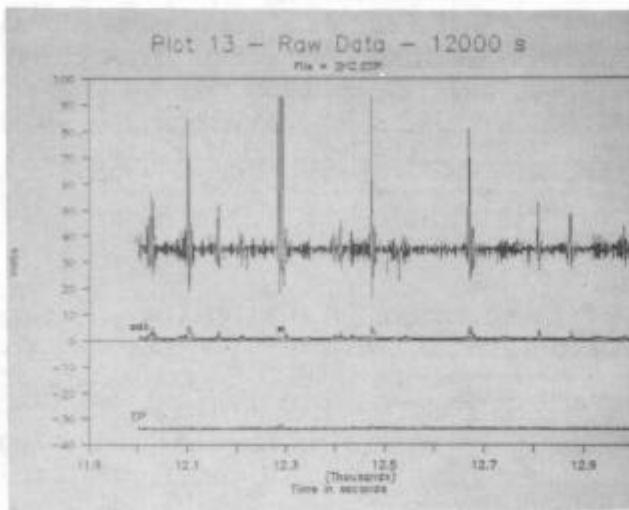
Figure 3. -- ESR 718 melt rates.

segregation in the ingots. (See Figure 3.) The fifth ingot was remelted at a 7% lower melt rate, without the slag conditioner. The two ingots that followed were remelted at 7% and 14% lower melt rates than the first two, but both were remelted with the addition of the slag conditioner. Slag volume was increased ~20% for the eighth ingot while holding the lower melt rate and retaining the slag conditioner addition. The final ingot was remelted utilizing a higher electrode "fill ratio," the 14% lower melt rate, and the slag conditioner.

During the remelting of several of these ingots, additional monitoring devices were used to augment the standard furnace equipment. A six channel high speed recorder and a couple of oscilloscopes were used to confirm that the Consarc Automatic Melt Control, specifically the voltage "swing" control portion, was functioning adequately to maintain the electrode/slag immersion depth control that was considered necessary. Signals monitored included furnace voltage, voltage "swing" detector input, swing detector output, the automatic voltage control signal to the ram drive system, ram drive system response, and electrode speed. The additional monitoring confirmed that the furnace and controls were working to specification and supplying the control deemed imperative to the consistent remelting of ESR 718. Since it has been recognized that the successful electro-slag remelting of 718 will require a relatively small process "window," an IBM compatible PC was set up to collect and record the same signals so that they could later be analyzed in detail. The ability of the computer to handle these signals and statistically analyze them will enable the small process "window" to be precisely defined as well as monitor compliance afterwards. Examples of the "hard" copy output from this monitoring equipment is shown in Figures 4 through 6.

In addition to the supplemental monitoring of the ESR furnace controls and functions, another recorder and more measuring devices were set up to monitor the partitioning of current flow between the two possible paths. The two paths being directly down through the ingot to the base plate and out through the slag to the crucible wall and down to the base plate. The purpose of this experiment was to study the effect that short time "events" or longer term practices might have on the partitioning of the current. It has been surmised by many that some short time "events" may result in an immediate slag skin thickening and a corresponding change in current flow towards the center of the ingot which might cause a deepening of the molten ingot pool and more segregation. This scenario was not confirmed in these trials. Figure 7 shows the results obtained on three ingots. While long term conditions do affect the partitioning; such as the larger "fill ratio" and related thicker slag skin on ingot L8353 R3, short time "events" which were purposely induced during the remelting of L8779 R9 had no major effect. (While the ingot product of L8779 R9 was not evaluated as part of this program, it was a 718 electrode used to test the furnace controls and the various supplemental monitoring devices.)

Billet conversion parameters for eight of the nine ingots were kept constant. Ingot homogenization consisted of a nominal 2150° cycle for 48 to 60 hours. The ingots were then press forged to 8- $\frac{1}{2}$ " billet using a straight draw fine grain practice. The fine grain practice was used to obtain the billet grain size required for many of the more highly stressed rotating discs and the low finishing temperatures result in a small amount of "delta" precipitation which accentuates any segregation that might be present in the macro-etch slices. One ingot, L8983 R5, was cut in half, with the bottom half converted by the same practice as the other eight ingots. However, the top half was converted by a "double-upset, double-homogenize" practice where the ingot is homogenized, upset and drawn back, re-homogenized, upset again, and finally drawn to final "hot" size.



Figures 4 and 5. -- Examples of computer generated voltage signals.

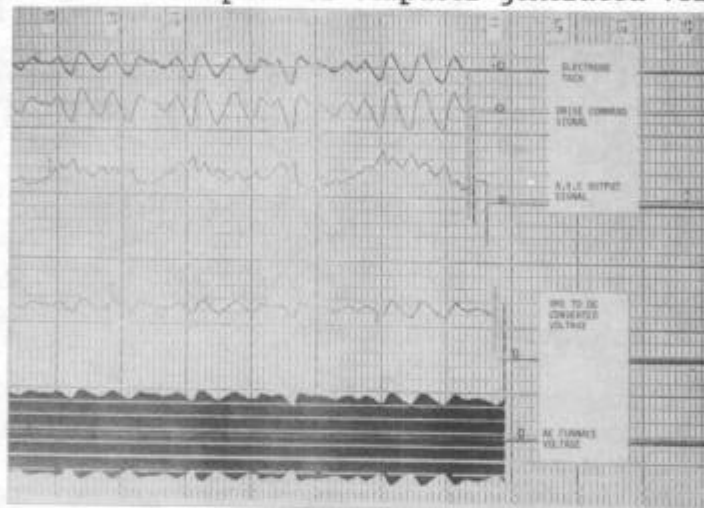


Figure 6. -- Example of high speed recorder chart.

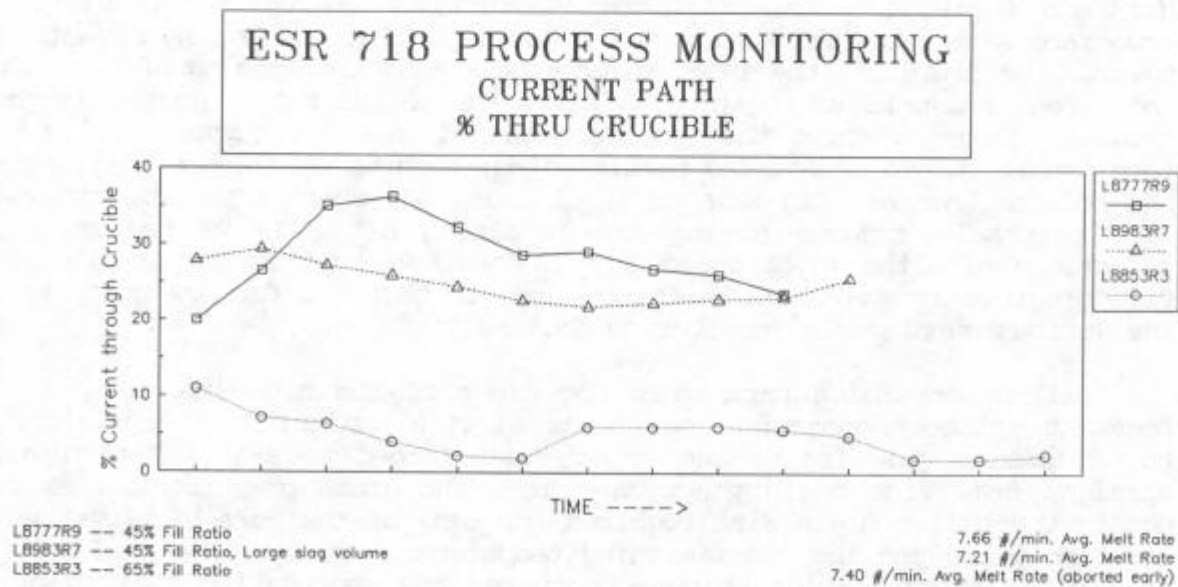
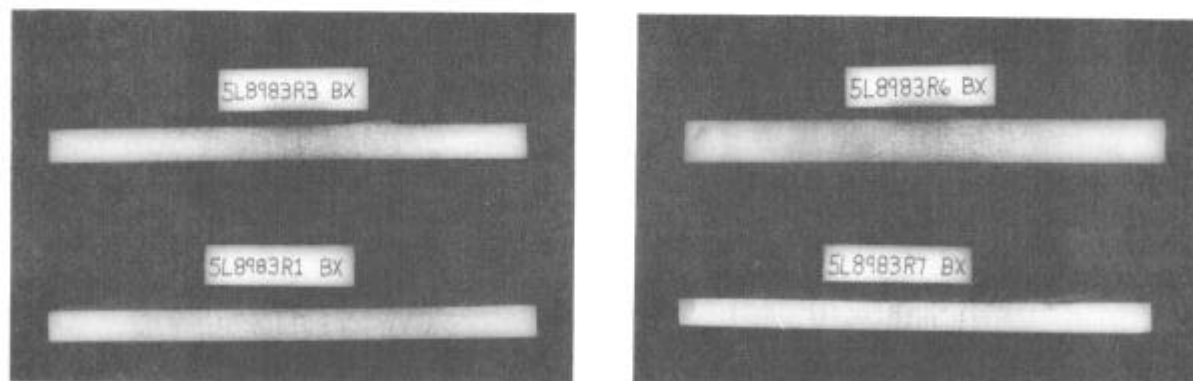


Figure 7. -- Current flow through crucible as precentage.

## Discussion of Results

The effect of the various remelt trials on the ESR ingot surface quality, slag skin thickness, and remaining slag cap volume was significant. The first two ingots remelted utilizing what were considered the "baseline" parameters had fair surface appearances exhibiting a slight "necking" of the top 12" of the ingots and 4" thick slag caps. The next two ingots remelted with the added slag conditioner had better slag caps at 4.5" and 5.5" respectively. Two methods of adding the slag conditioner were used for these two ingots. The one resulting in the larger slag cap was also the one allowing more consistency and control of the addition and was chosen to use for the remainder of the trials utilizing this slag addition. L8983 R4, remelted 7% slower without a slag addition had to be aborted with approximately 850 pounds of electrode remaining because a thicker slag skin used up too much of the slag covering. Only a 2.5" slag cap remained. The two ingots remelted at 7% and 14% lower melt rates with the slag conditioner exhibited to best ingot surfaces and finished with 6" slag caps. The ingot remelted at the low melt rate with 20% additional slag at the start showed a relatively heavy slag skin on the bottom 18" of the ingot and finished with 6.5" slag cap. The ingot with the larger electrode "fill ratio" also had to be aborted earlier due to a thick slag skin and running low on slag cover.

Billet slices were macro-etched in the "as-forged" condition in a solution of 90% hydrochloric and 10% nitric acid at 160°F. This procedure is excellent for revealing the slightest amount of center segregation that may be present in 718 wrought material. In general, the macro-etch results closely corresponded to the ingot surface quality and remaining slag cap heights. Overall, the best results were on ingots L8983 R5 and R6. However, the only segregation free product was from the top half of L8983 R5 which was converted to billet by the "double-upset, double-homogenize" practice. Other trends that became apparent were that the worst center segregation was found at the tops of ingots that had to be aborted early when the slag was running out. Ingots remelted at the higher melt rates or without addition of the slag conditioner exhibited more severe center segregation than those remelted at lower rates with the slag addition. As expected all the extreme bottom positions were free of center segregation. Representative photomacrographs of middle ingot positions are shown in figures 8 through 13.



Figures 8 and 9. -- Longitudinal sections exhibiting various degrees of center segregation.



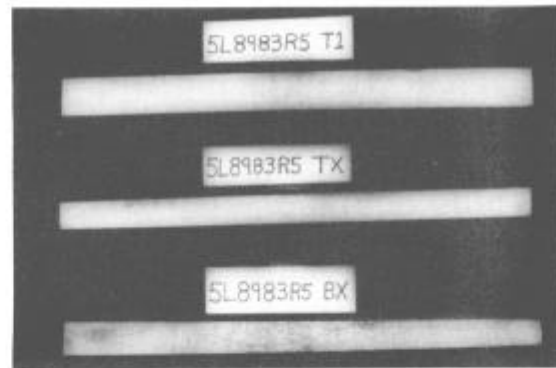
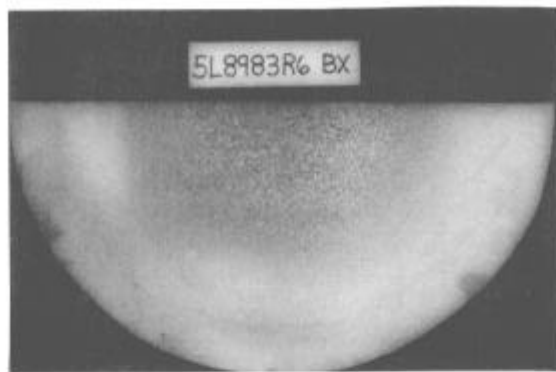
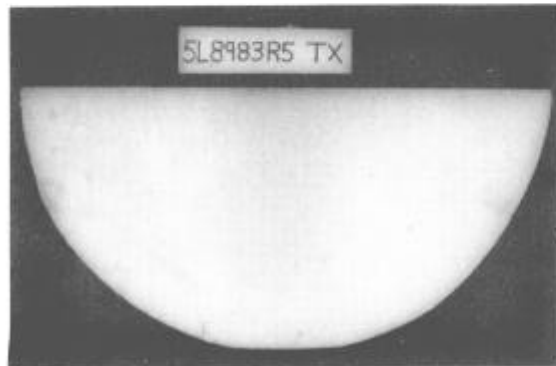


Figure 10. — Transverse section.

Figure 11. — Longitudinal sections of R5 ingot.



Figures 12 and 13. -- Adjacent transverse sections of R5 ingot.

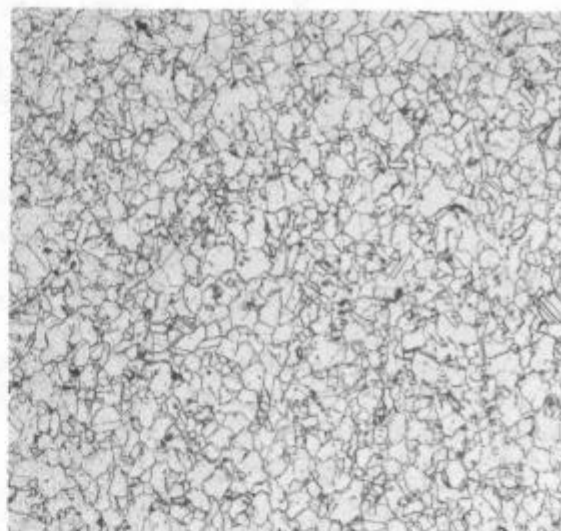
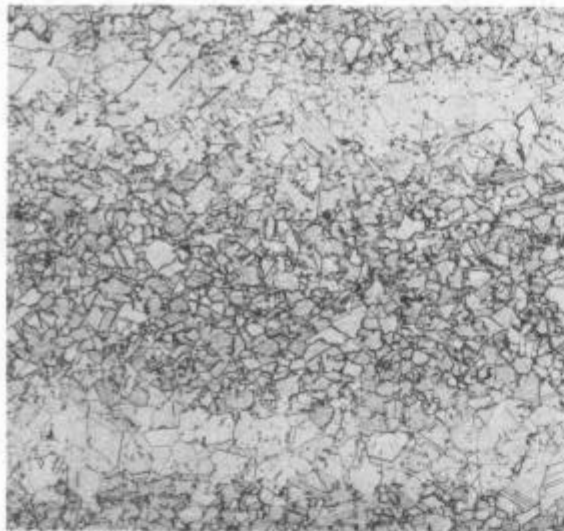
Samples were cut from the center position of each macro-etch slice for metallographic examination. The various degrees of center segregation evident on the macro-etch slices show up microstructurally as "banding." This banding may show up as simply a difference in grain size, or in more severe cases, as bands of heavy "delta" precipitation. Examples are shown in figures 14 through 17. Samples were given various aging or combination of solution treat and age heat treatments to preferentially precipitate "delta" phase in the higher columbium areas of the material. Results of the metallographic examination very much reflected the macro-etch findings. However, in instances where the macro-etch slices exhibited only slight center segregation, the microstructure revealed little evidence of the segregation.

### Conclusions

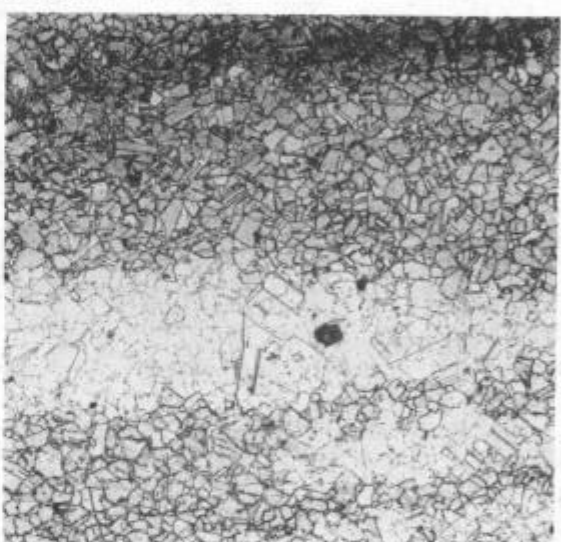
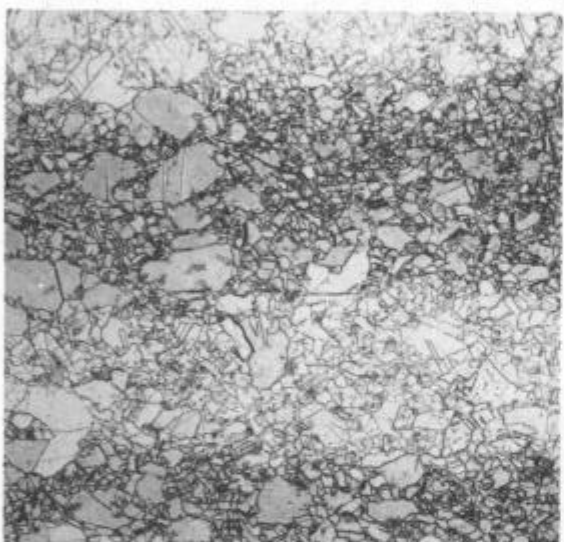
The ultimate objective of this program, that of producing a consistent, completely segregation free ESR 718 billet product to satisfy General Electric's requirements for critical rotating part applications, was not totally achieved. However, several conclusions as to the conditions which cause, or reduce, center segregation in the product were reached. The effects of slight macro center segregation on microstructure and some simple mechanical properties were seen and confirmed. In addition, ESR 718 material continues to function in many stator engine parts without problems or concern.

While the material results were not completely satisfactory, the ESR furnace refurbishment was successful. The supplementary monitoring devices did confirm that all furnace controls and drive systems were functioning





Figures 14 and 15. — Longitudinal sections exhibiting little and no center segregation. (~100x)



Figures 16 and 17. — Longitudinal sections exhibiting more severe center segregation. (~100x)

properly and providing the control considered essential. The use of the computer to collect and record pertinent input and output signals from the furnace itself for "real time" monitoring and subsequent analysis of data was demonstrated. In the future this will be a valuable tool for defining the "process window" for electro-slag remelting of 718 more precisely and accurately than would be possible by other means. The computer will also provide more assurance of compliance to a specified standard procedure and is easily adaptable to the SPC techniques for quality assurance for customer satisfaction.

Clearly, center segregation of various degrees has been, and still is, the single hurdle remaining to get over in order to gain acceptance of ESR 718 product for critical rotating discs in gas turbine engines. Although the degree of center segregation varied with the various remelt and conversion practices utilized in the program, the amount was very slight on the ingot product remelted under the most favorable conditions. The microstructures examined on billet slices with only slight macro-segregation present revealed only slight grain size banding with a

difference of only 1 to 2 ASTM grain size numbers. No differences were apparent in the basic mechanical properties, room temperature and elevated temperature tensiles and stress ruptures. Further work is scheduled to more precisely quantify the degree of segregation present in this material. Special "TAG"<sup>(3)</sup> heat treatments and subsequent SEM evaluation of the amounts of gamma' will be used along with chemical analysis via EDAX.

While there is no readily evident "cure" for the center segregation problem, several trends are apparent. Melt rate is still one of the most important parameters to control in order to affect pool depth and shape. Even the relatively small changes in melt rate investigated in this program were related to changes in the degree of segregation present in the ingot product. More effort will be expended to lower melt rate further, if that can be accomplished without causing the slag skin to thicken and increase resistance to heat flow out of the ingot and into the crucible cooling water. Controlling a very shallow electrode/slag immersion depth is also very critical to maintaining a thin slag skin; although, it does not appear that momentary "events" or disruptions are likely to greatly affect the slag skin thickness over the long term. As expected, the extreme bottom of the ingot, up to approximately one ingot diameter in height, does not exhibit any segregation. The extreme top, at least below the standard "hot top" crop, appeared to be no worse than the middle of the ingot over a total ingot height of approximately 100". The exception to this occurred when the slag volume was insufficient at the end of the remelt.

A minimum slag cap is required to maintain a consistent, desirable, molten pool profile. However, it appears that at the melt rates that are used for electro-slag remelting 718 that there is a practical limit on the volume of molten slag cover that can be maintained. The addition of a slag conditioner to the bulk slag composition proved to have a significant effect on the fluidity of the slag and resultant slag skin thickness and remaining slag cap volume.

The most dramatic effect, however, appears to have been the result of the ingot to billet conversion practices. The "double-upset, double-homogenized" fine-grain billet conversion practice showed a real reduction in the amount of center segregation present as compared to the single ingot homogenization, straight draw, billet conversion practice. This is further evidence that the segregation that is present is very slight and the remelting process is not far from possible complete success.

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