SOLIDIFICATION MODELING OF VACUUM ARC REMELTED

SUPERALLOY 718 INGOT

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Abstract:

A mathematical model has been developed to study the influence of helium gas pressure, electrode melt rate, cooling water flow rate and velocity on the heat transfer and solidification characteristics during vacuum arc remelting of superalloy 718. The objective of the present work is to produce a 500 mm Φ freckle free ingot. Even though the technique of helium gas injection is being widely used by super alloy manufacturers, no integrated approach has been undertaken to quantify the combined effect of these selected parameters on the solidification behaviour of the Alloy 718. In the present paper, the synergistic effect of these parameters, using the model, has been studied with reference to the molten pool depth and mushy zone size of a 500 mm Φ ingot. Mathematical equations were formulated and solved using Finite Difference Method (FDM) to predict temperature fields in the solidifying ingot. The temperature data generated is used to plot the liquid pool profile. The emphasis is placed, primarily on the computation of overall heat transfer coefficient between the solidifying ingot and the cooling water as a function of gas pressure, water flow rate, velocity and the shrinkage gap width. The model predicted a 30% decrease in the liquid pool depth for a helium gas injection pressure of 20 mm Hg for a 500 mm Φ ingot. The complete mathematical model has been validated with published data for various ingot sizes. A freckle free 500 mm Φ ingot has been produced using the optimized parameters thereby confirming the validity of the model on the industrial production. Furthermore, the results are supplemented with metallographic examination on the 500 mm Φ ingots with varying cooling conditions. Using the present model the operating parameters for manufacturing larger size freckle free superalloy 718 ingots can also be fixed.

Introduction

Vacuum Arc Remelting (VAR) is presently the most important remelting process in the production of Alloy 718. The alloy has got a wide melting range(65° C) and large number of alloying elements like Cr-19%, Nb+Ta-5.3%, Mo-4%, Fe-19%, Ti-1.0%, C-0.3%, Al-0.5% and Ni. The different alloying elements with strong density differences developing between liquid and solid phases during solidification together constitute a conducive atmosphere for segregation. Commercial scale VAR melted Alloy 718 ingot diameters normally range from 400 mm to 600 mm [1]. However, beyond 400 mm Φ Alloy 718 ingots are prone to severe segregation of Niobium, as freckles resulting in poor mechanical properties.

Freckles, a macro segregation defect results due to the flow of solute rich interdendritic liquid in the mushy zone[2]. This flow is caused because of the density differences in solid/liquid phases and gravitational force acting on the liquid of variable density. The magnitude of the liquid flow in the interdendritic region depends on the depth of the liquid pool and the mushy zone thickness. This kind of

macro segregation defect can be eliminated by maintaining the lowest liquid pool depth and Mushy zone thickness. At the same time precautions about the continuity of the ingot has to be taken care, while operating at lowest pool profiles. Lower pool depth and mushy zone thickness are achieved by enhancing the cooling rate of the ingot during solidification in VAR. It is well known that the bottle neck for the heat transfer in VAR is the shrinkage gap forming between the solidifying ingot and the copper crucible, where there is no conducting medium but vacuum in the gap. Injection of a high thermal conductivity gas into the shrinkage gap helps in enhancing the heat transfer between the ingot and the crucible.

The technique of introducing helium gas between the ingot and the crucible in VAR was initiated over 30 years ago. Even though the technique is now widely used in the production of VAR superalloys, very little has been published on the technology and actual improvements obtained on industrial conditions. Theoretical analysis on the effect of helium gas pressure on Heat Transfer Coefficient (HTC) was carried out by Yu [3]. Lab scale studies on helium gas cooling were conducted by Hosamani[4]. It was recently that the results on the effect of helium gas injection on a 500 mm Φ ingot were published[5].

In the present investigation the heat transfer/solidification phenomena of the ingot during VAR has been carried out by Mathematical simulation. Emphasis has been placed on the calculation of HTC. Liquid pool profiles were predicted for different operating conditions and sizes of the ingot. Based on the results of the Mathematical simulation one defect free 500 mm Φ ingot was manufactured with optimised helium gas injection pressure. Temperatures were measured over the copper crucible wall to confirm the increased heat extraction with helium gas injection. Macro and Micro examinations were carried out on the ingots manufactured with and without helium gas injection.

Mathematical modelling of the ingot:

A Two Dimensional (r-z direction) heat transfer analysis has been carried out for the ingot during solidification in VAR. Since the ingot is symmetrical about its axis along the length, one quarter of the ingot has been chosen for Modelling.

As the flux source is circular in nature for VAR, heat transfer in θ (angular) direction is ignored, this mode of analysis should give fairly good results. The ingot was discretised along the height (z-direction) and the radius (r- direction). The grid geometry is shown in Fig.1. Eventhough only a few grids are shown in the figure, actual grid numbers are much higher. As the ingot was building up new grids in the z- direction are added and the subsequent updating was taken care in the model.

The differential equation for a two dimensional situation can be written as:

$$\rho \underbrace{\delta T}_{\delta t} = \underbrace{\delta \{K \underline{\delta T}\}}_{\delta r} + \underbrace{\delta \{K \underline{\delta T}\}}_{\delta z} + S$$

ρ = Density K = Thermal conductivity
T = Temperature S= Source term

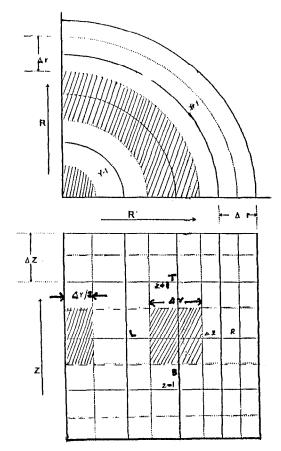


Fig.1. Grid Geometry used for the solidification modelling of the VAR ingot.

-> (1)

The discretisation equation for an element which is at the middle of the ingot height and at midradius can be written as:

Similarly discretisation equations were written for all the elements. Control volumes at the bottom and at the edges in contact with the crucible would have the Heat Transfer Coefficient terms. Alternating Direction Implicit (ADI) [6] technique was used for solution of the equations. By solving the above mentioned equation with the appropriate boundary conditions the temperatures at all the locations of the ingot were determined as the ingot was solidifying. The temperatures so derived were used to plot the isotherms of liquidus temperatures resulting the liquid pool profiles. A computer program was written in Fortran language to solve the equation. The execution time for the program is about two hours on a PC incorporating Intel's Pentium processer for the case of a 2.0 Ton 500 mm Φ ingot. With further refinements of the programme, scope exists for cutting down the computational time.

Evaluation of Heat Transfer Coefficient:

The overall heat transfer coefficient between the solidifying ingot and cooling water can be expressed as[7]

$$h = \frac{1}{1 \quad \Delta xc} \frac{1}{1} \qquad \qquad (3)$$

$$----+----+----+----+ -----+ h_r + h_g \quad K_c \quad h_s \quad h_w$$

 $\begin{array}{ll} h_r & = \text{HTC due to radiation} & h_g = \text{HTC due to rarefied gas conduction} \\ \Delta X_c = \text{Thickness of the copper crucible} & K_c = \text{Thermal conductivity of crucible} \end{array}$

h_s = HTC of scale deposit

h_w = HTC between crucible outer surface and cooling water.

HTC due to radiation of the ingot surface (h_r) can be expressed as [4]

$$h_r = \varepsilon \sigma \frac{T^4 - T^4 c}{T - T_C}$$
 (4)

 ε = Emissivity of Material

σ = Stefan-Boltzman constant

 $T = Temperature of the ingot surface <math>T_c = Temperature of crucible (inside)$

At very low pressures the HTC due to conduction through the rarefied gas between the ingot and crucible (hq) can be written using the analogy of the conduction through the rarefied gas between coaxial cylinders used by Mc.Adams [8].

$$h_{g} = r_{i} \{ \ln \underline{r_{c}} + \underline{q_{i}} + \underline{q_{c}} \} \qquad ---->(5)$$

$$r_{i} \quad r_{i} \quad r_{c}$$

r = radius

 K_g = thermal conductivity of gas g = temperature jump distance

Subscripts

I --> ingot c --> Crucible

HTC of the scale deposits (hs) from water was assumed as 5680 J/K.m.Sec [9]

HTC between the crucible and water (h_W) is calculated using the Colburns equation[10] proposed based on the analogy of HTC for turbulant flow in an annular tube. (h_W) is part of the Stanton number in Eq.6

St = Stanton number

Re = Reynolds number

Pr = Prandtl number

The overall Heat Transfer Coefficient calculated as above is used in the discretisation equation to determine the temperature distribution in the ingot. As the temperatures vary from top to bottom of the ingot, HTC is calculated at each location across the height of the ingot independently every time. Similarly material properties like Thermal conductivity and Specific heat are updated depending upon the temperatures existing around the control volumes during the execution of the program.

Experimental

Mishra Dhatu Nigam Limited (MIDHANI), is a superalloy project catering to the diversified needs of critical and Infrastructural sectors including a few overseas clients. MIDHANI has got a VAR unit capable of melting ingots upto 570 mm Φ and weighing 5.0 Tons exclusively used for superalloy manufacture. With the expertise in the manufacture of large tonnage of 400 mm Φ Alloy 718 ingots successfully, attempts were initiated to manufacture ingots of 500 mm Φ to cater to the demad of larger size feed stock for aerospace applications. To begin with one electrode of 440 mm Φ weighing 2.0 Tons was remelted into the 500 mm Φ crucible at a predetermined melt rate. Since Freckles were observed in the ingot the material had to be rejected from further processing operations. Attempts were made to inject helium gas into the shrinkage gap in the subsequent campaigns.

It was at this point that the need for a thorough understanding of the heat transfer and solidification phenomena was felt. On this background simulation of the entire VAR process was initiated and the present Mathematical Model was developed.

After simulating the solidification and liquid pool geometry of the VAR ingot, manufacture of the 500 mm Φ Alloy 718 ingot was undertaken. A 2.0 Ton Vacuum Induction Melted (VIM) 440 mm Φ electrode was chosen for the purpose. The electrode was remelted in the 500 mm Φ crucible with optimised helium gas pressure based on the predictions of the Mathematical Model. All other operating parameters were kept constant as that of the previous campaigns except that of helium gas pressure and a water guide tube in between the crucible and the water jacket, to increase the water velocity with same mass flow rate as that of the previous campaigns.

The ingots manufactured with different cooling conditions in VAR were evaluated by Macro and Micro examination.

Helium gas Injection Facility

The 500 mm Φ crucible was modified to facilitate the helium gas injection. A 5 mm Φ hole was drilled through the bottom ring of the crucible. The hole was coupled to a copper tube which was run along the crucible wall and taken out through the crucible flange for carrying the helium gas. From the top flange the line was connected to the helium gas reservoir through a pressure gauge, and two sets of pressure control valves. The helium gas injection facility used for VAR is shown in Fig.2.

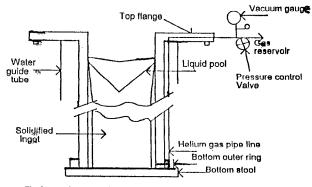


Fig.2. Helium gas injection facility for the VAR process

Based on the results of the Mathematical model the particular helium gas pressure to be used was finalised. To take care of the increased heat transfer from the crucible by water, it was decided to increase the water velocity over the crucible surface. Since increasing the water velocity calls for additional pumping capacity and replacement of the existing pipelines requiring huge capital investment, alternatives were thought of. It was decided to decrease the annular passage gap between the crucible and the water jacket. This is achieved by placing a water guide tube between the crucible and the water jacket. Accordingly a water guide tube was designed and fabricated and placed between the crucible and the water jacket. With this arrangement the water velocity with the same mass flowrate could be increased by over 70 %.

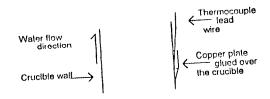
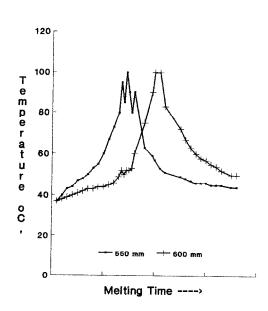


Fig.3 Thermocouple fixing arrangement over the crucible surface.

To monitor the increase in heat transfer from the crucibles, crucible surface temperatures were measured during remelting. Grounded 1.2mm Chromel-Alumel thermocoupoles were fixed over the crucible surface by fixing a copper plate over the thermocouple lead and the crucible surface with the help of a conducting adhesive as shown in Fig.3. The leads of the thermocouple were taken out of the water jacket through the rubber O-ring of the crucible below the top flange. These leads were connected to a continuous temperature recorder. Three thermocouples were Fig.4. Crucible surface temperatures measured during melting fixed at two different heights of 550 mm and 600



process.

mm (two thermocouples at 650 mm in opposite directions). The maximum temperatures recorded at these particular points was 100°C. During the process of remelting with helium gas injection, gas injection into the crucible was intentionally interrupted for few minutes. Temperature raise on the crucible surface was noticed with the interruption of the gas injection, confirming the increase in heat extraction with helium gas injection. The crucible wall temperatures recorded during the process of remelting is shown in fig.4.

Macro and Micro Examination of the Ingots

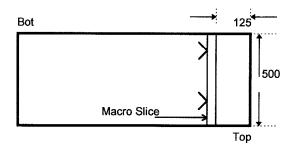


Fig.5. Location of the Sample chosen from the ingot for Macroexamination.

A location of 125 mm below the ingot top was chosen for Macro and Micro examination of the Alloy 718 ingots manufactured with different cooling conditions. This is chosen since hot topping of the ingot starts from this location. The location of the macro sample cut from the ingot is shown in fig.5. 20 mm thick Macro samples were cut from the ingots with the help of a Electric Discharge Cutting Machine. The surface of the macroslices were machined in order to obtain a perfect plane. Machined surfaces were subjected to milling and polishing operations for achieving smooth surface. The slices were etched with HF+HNO₃ solution. The macrostructure so developed was compared among the ingots manufactured.

Samples for Microexamination were cut from the macroslices. Four locations across the slice were subjected for Microexamination. These include, one at the periphary, two samples on the radial axis each at a distance of 80 mm from periphary and centre and one sample from the centre location of the slice. The location of the microsamples examined is shown in fig.6. These 10 X 10 mm samples were extracted from the Macrosamples with the help of a Electric Wire Cutting Machine. All the samples were polished and etched with HF + HNO₃ solution and examined with the help of a optical microscope for dendritic structure.

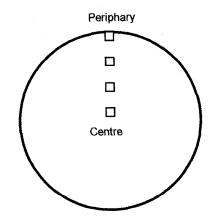
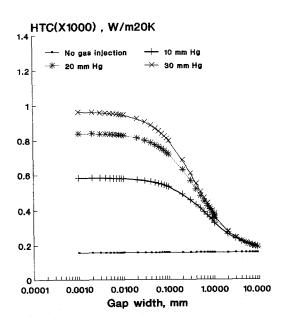


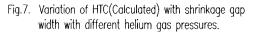
Fig.6. Location of the Samples chosen for microexamination from macro sample.

Results & Discussion

Mathematical Model:

Initially HTC was evaluated with the operating parameters in practice(without helium gas injection) and with different helium gas injection pressures. As could be seen from the fig.7 the HTC increases by over three and four times with the injection of helium gas of 10 mm and 20mm Hg respectively, at shrinkage gap widths less than 0.1 mm for the case of a 500 mm Φ ingot with specified operating conditions.





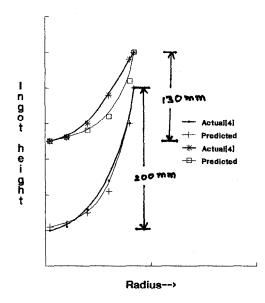
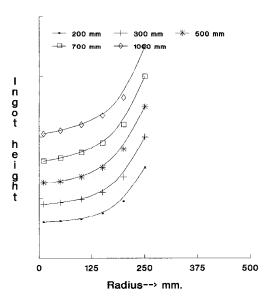


Fig.8. Comparison of Actual[4] .vs. Predicted liquid pool profiles with and without helium gas injection.

The model has been validated against the measured liquid pool depths by Hosamani[5] for identical operating conditions of a lower size ingot. As is seen in the fig-8 the predicted liquid pools does match with those of the measured (published) results for both the conditions of with and without helium gas injection. Based on the confidence gained with the matching of published .vs. predicted pool profiles, a series of liquid pool profiles were generated for the melting conditions of a 500 mm Φ Ingot. The evolution of the liquid pools is shown in fig.9. As can be seen from the fig.9, at Ingot heights equal to or less than the diameter of the ingot the pool was almost flat at the centre. This is due to the significant amount of heat extraction taking place from the bottom of the ingot. As the ingot builds up above the height equal to the diameter of the ingot the pool profile tends to change from a flat 'U' Shape to a near 'V' shape and maintain a consistant shape and depth as seen from the pool profiles in fig.9. This is due to the diminishing contribution of heat extraction taking place from the bottom of the ingot.



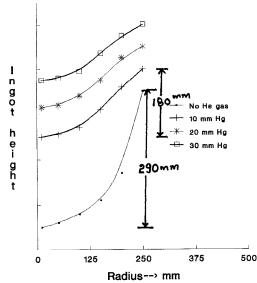


Fig.9. Evolution of liquid pool profiles (predicted) at different heights of a 500 mm Dia. ingot.

Fig.10. Variation of liquid pool profiles (predicted) with helium gas injection for a 500 mm. Dia. ingot.

The pool profiles also change with the injection of helium gas. The variation of pool shape and depth with various helium gas injection pressures is shown in fig.10. As can be seen the pool shape changes from a near 'V' shape to a flat 'U' shape with the injection of helium gas. The slope of the liquid pool has decreased with the helium gas injection. This is associated with a decrease in the pool depth. According to the predicted results with the injection of 20 mm Hg of helium gas, the pool depth for a 500 mm Φ ingot decreases from 290 mm to 180 mm. The predicted pool depths in this case are in agreement with the measured[5] published results with and without helium gas injection.

As can be seen from fig.10, there is a marginal difference in pool profiles with 10 and 20mm Hg gas injection, but the pool profiles are identical with 20 and 30 mm Hg gas injection, for identical operating conditions. From this analysis it is clear that solidification characteristics will not differ much with 20 or 30 mm Hg of gas injection pressure for given operating conditions for the case of a 500 mm Φ ingot. In addition if the pressure is increased above certain limiting pressure there exists the danger of puncturing of the liquid seal, resulting in disturbance in the arc behaviour and poor control over the melt rate. This was experienced during the melting of steel ingots in the preceding campaigns. Based on the feed back from the Mathematical model and the operating experience an optimum operating pressure was chosen for manufacturing the 500 mm Φ Alloy 718 ingot.

Experimental work:

The Macrophotographs of the Alloy 718 ingots manufactured both with and without helium gas injection are shown in figs.11 & 12. The ingot produced without helium gas injection has exhibited the Niobium rich segregation spots, i.e. Freckles at large number of locations situated around the mid radius of the ingot, fig.11. Freckles are identified by the circled black spots in photographs. The dendrite size was observed to be very coarse in this ingot. In the case of the ingot produced with optimised parameters no freckles were observed fig.12. The dendrite size was relatively small and uniform from centre to edge of the Ingot indicating favourable cooling conditions across the ingot with helium gas injection. With the injection of helium gas, slight deterioration of the surface quality of the ingot was observed.

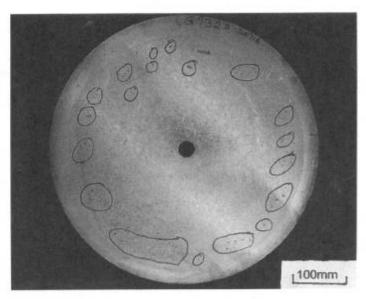


Fig.11. Macrophotograph of the 500 mm Dia, Ingot manufactured without helium gas cooling showing freckles.

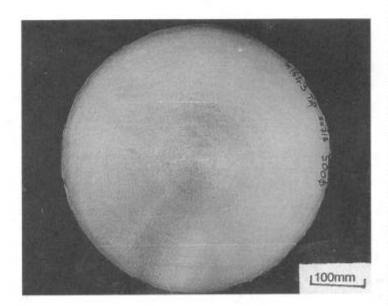


Fig.12. Macrophotograph of the 500 mm Dia. Alloy 718 ingot manufactured with optimised helium gas cooling conditions.

The photomicrographs of the ingots produced with the two different cooling conditions are shown in Figs. 13-14. As can be seen from Fig.13(a), the Alloy 718 ingot produced without helium gas injection has got larger dendrites indicating slow cooling conditions existing during the process of solidification. Ingot produced with optimised conditions has got finer dendrites as can be seen by the size of the dendritic axis's in the photographs fig.14(a). centre locations of the ingots lower interdendritic areas were observed as the cooling conditions are improved for the case of ingot manufactured with optimised parameters, fig.14(b-d). However the quantification of the decrease in the dendritic size could be drawn only after the measurement of the dendritic arm spacings. The work on dendritic arm space measurements is in progress at the time of writing this paper.

The successfully manufactured 500 mm Φ ingot was forged down to 165 mm Φ and supplied to customer after stringent quality evaluation on the forged billet.

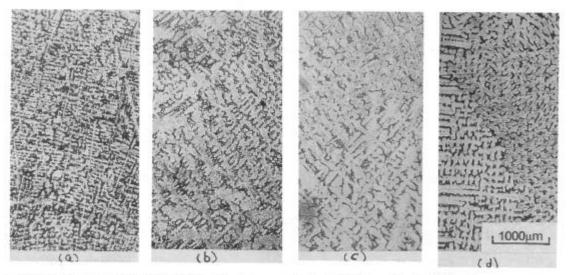


Fig.13.Microphotographs of the VIM-VAR (without helium gas cooling) melted 500 mm Dia. Alloy 718 ingot a)Periphary b)80 mm from periphary c)80mm from centre d)Centre.

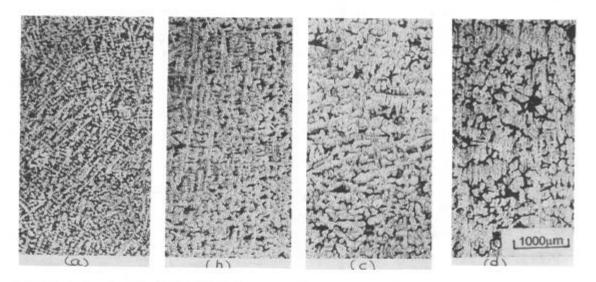


Fig.14.Microphotographs of the VIM-VAR (with helium gas cooling) melted 500 mm Dia. Alloy 718 ingot a)Periphary b)80 mm from periphary c)80mm from centre d)Centre.

Conclusions and Summary

Heat Transfer Coefficients for an Industrial scale VAR has been quantified. A Mathematical Model for the prediction of the solidification behaviour of the Alloy 718 ingot during VAR is formulated, executed and validated with that of the published measured results for different ingot sizes. A thirty percent decrease in the liquid pool depth is predicted by the mathematical model with a 20 mm Hg helium gas injection pressure for the case of a 500 mm Φ Alloy 718 ingot. Based on the out come of the model operating parameters for helium gas injection into VAR were derived and a freckle free 500 mm Φ Alloy 718 ingot could be produced. The liquid pool profiles were generated for a 500 mm Φ Alloy 718 ingot with different helium gas injection pressures and at various locations/heights of ingot without helium gas injection.

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