SOLIDIFICATION OF ALLOY 718 DURING VACUUM ARC REMELTING WITH HELIUM GAS COOLING BETWEEN INGOT AND CRUCIBLE

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Abstract

There is an increased demand for larger and better-quality vacuum arc melted superalloy ingots. However, as the ingot size increases, the tendency for segregation increases. The segregation can be minimized either by decreasing the melt rate or by improving the heat transfer from the ingot. The former technique results in decreased productivity and increased energy consumption during melting. The heat transfer from the ingot to the cooling water in VAR is mainly controlled by the heat transfer coefficient between the ingot and crucible. This heat transfer coefficient can be increased by introducing a gas of high thermal conductivity, like helium, in the shrinkage gap between the ingot and crucible. Even though this technique is being used by superalloys manufacturers, no systematic study has been carried out to quantify the effect of helium gas pressure. Hence, the present experimental work was undertaken to study the effect of helium gas cooling on the heat extraction rate, molten metal pool depth, mushy zone size and segregation during vacuum arc remelting of alloy 718. The experiments were carried out in a laboratory vacuum arc furnace capable of making 210 mm diameter ingots weighing up to 150 kgs.

In this paper, the effect of helium gas pressure on the solidification behavior of alloy 718, like molten metal pool depth, surface quality of the ingot, dendrite arm spacing, mushy zone size and Laves phase, have been discussed. The increase in helium gas pressure resulted in a decreased molten metal pool depth. For example, with 60 mm of helium gas pressure, the pool depth decreased from 200 mm to 127 mm, i.e., about 36% decrease. Measurements on dendrite arm spacing from edge to center of the ingot in the radial direction showed that, with the helium gas cooling, the dendrite arm spacing decreased at the edge as well as at the center of the ingot. The calculated mushy zone sizes using the DAS measurements showed a decrease in mushy zone size with the helium gas cooling. The amount of Laves phase formed decreased with helium gas cooling. The helium gas cooling between the ingot and the crucible has shown to improve the solidification characteristics and minimize segregation in alloy 718.

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Introduction

Vacuum arc remelting (VAR) is presently the most important remelting process in the production of advanced superalloy forgings for aerospace and other critical applications. Ingots up to 500 mm diameter and weighing approximately 4500 kg are made by vacuum arc remelting (1). However, beyond 400 mm, ingots of superalloys, like alloy 718, are increasingly prone to severe segregation of niobium which are known as freckles. Freckles contain a significant amount of Laves phase and result in poor mechanical properties. It is extremely difficult to eliminate these defects by any amount of thermo-mechanical processing. Hence, it is necessary to minimize the occurrence of these defects during the solidification stage.

The flow of solute-rich interdendritic liquid in the mushy zone is responsible for most types of macro-segregation (2,3). The movement of this interdendritic liquid occurs as a result of solidification contraction, gravitational force acting on a liquid of variable density and electromagnetic forces. The magnitude of the fluid flow in the interdendritic region depends on the depth of molten metal pool and mushy zone size. High power input results in a deeper metal pool and deeper mushy zone size, which enhances the interdendritic liquid flow. The problem becomes more severe as the ingot size increases. The technique generally used to minimize segregation is to melt at lower power inputs; hence, at lower melt rates resulting in a shallower molten metal pool and mushy zone. Lower melt rates lead to higher energy consumption and lower productivity of the plant. Hence, it is necessary to examine other techniques to minimize segregation without decreasing the melt rate. One technique is to increase the cooling condition of the ingot. By increasing the cooling rate of the ingot, it should be possible to reduce the molten metal pool depth and the mushy zone depth, resulting in reduced segregation.

As the ingot solidifies, it contracts and pulls away from the crucible wall, creating a gap between the ingot and the crucible. As the melting is carried out in vacuum, the gap is essentially a vacuum gap. In this condition, the ingot-crucible system may be regarded as a "Vacuum Flask" in which, with the exception of a narrow contact band at the top part of the ingot, heat transfer is effected mainly by radiation. The heat transfer rate in vacuum arc remelting is controlled by the heat transfer coefficient between the ingot and the crucible. If liquids or gasses having a good thermal conductivity are introduced in the gap between the ingot and the crucible, the heat transfer from the ingot to the crucible can be substantially increased. Examples of such substances are gasses of high thermal conductivity, like hydrogen and helium. Helium is, in fact, ideal for this purpose, as it has a high thermal conductivity, is nonexplosive and does not react with remelted material. With helium gas in the gap between the ingot and the crucible, the heat transfer takes place by radiation and by gas conduction, resulting in increased heat transfer rate. The contact between the crown and the crucible forms a seal which prevents leakage of the helium gas. Hence, by regulating the helium gas pressure, it is possible to vary the cooling rate of the ingot within a certain range.

The idea and technique of introducing helium gas into the gap between the ingot and the crucible during vacuum arc remelting was patented by Joseph M. Wentzell (4) and the patent was assigned to Special Metals Corporation, New Hartford, New York. Even though this technique is being used by superalloy manufacturers on a regular basis, no experimental investigation has been carried out to understand the effect of helium gas cooling on heat extraction rate, metal pool depth, solidification structure, mushy zone size and segregation. K. O. Yu (5) theoretically calculated the effect of helium gas pressure on the heat transfer coefficient. However, no experimental studies were conducted to quantify the effect of helium gas cooling.

This investigation was undertaken to study experimentally and theoretically the effects of helium gas cooling between the ingot and crucible on heat transfer rate, metal pool depth, solidification structure and segregation in VAR ingots. This paper specifically addresses the effects of helium gas pressure on solidification of alloy 718 ingots.

Experimental Procedure

The experimental work was carried out in a laboratory vacuum arc furnace capable of making ingots up to 210 mm diameter and 150 kg. Heat transfer studies were performed by measuring the temperature of the outside surface of the crucible. Eighteen electrically-isolated 1 mm diameter stainless steel sheathed chromel/alumel thermocouples were mounted on the crucible wall. A data acquisition computer was used to collect the temperature reading of each thermocouple every 15 seconds. Other important process variables viz. melting current, melting voltage, electrode position, vacuum, crucible cooling inlet and outlet water temperatures were also recorded. The complete description of the equipment and the heat transfer experimental work has been reported elsewhere (6,7).

Four melts of alloy 718 were analyzed in the present investigation. The alloy 718 electrodes of 108 mm diameter were melted in a 165 mm diameter crucible and the weight of each ingot was about 70 kg. The experimental details are given in Table I. In all the melts, the same melting parameters were used except the gas pressure for cooling. The current used was 3000 amps and the electrode gap was 15 mm. One melt was made with no gas cooling, two melts were made with helium gas cooling and one melt was made with argon gas cooling. The heat transfer particulars are summarized in Table II.

The important solidification-related parameters studied in the present investigation were molten metal pool depth, dendrite arm spacing, mushy zone size and Laves phase distribution. In order to reveal the molten metal pool profile, the ingots were sectioned longitudinally and etched electrolytically. Dendrite arm spacing measurements were made at the edge, center and mid-radius of each ingot. Mushy zone depths were computed empirically using the local cooling rate and ingot growth rate.

Table I. Experimental Details of Alloy 718 Melts

Parameter	Melt No. 47	Melt No. 49	Melt No. 50	Melt No. 53
Current (KA)	3.0	3.0	3.0	3.0
Voltage (V)	25	25	25	25
Gas Pressure (mm)	0.0	40	60	60 (Argon)
Flow Rate (LPM)	0.0	0.5	0.7	0.6
Vacuum (u)	8	12	17	20
Power (KW)	75	75	75	75
Ingot Wt. (kg)	62.25	72.70	70.00	69.00
Melt Time (min)	33	38	35	36.5
Melt Rate (kg/min)	1.89	1.9	1.94	1.89

Table II. Heat Transfer Particulars of Alloy 718 Melts

Melt No.	Gas Pressure (mm)	ΔT Water (0°C)	H.F. Flux Removed (KW)	Heat Removed %
47	0	4.9	64.6	86
49	40	5.7	75.11	100
50	60	5.9	77.75	103.6
53	60 (Ar)	5.5	72.5	96.6

Results and Discussion

From Table II, it is clear that about 17% more heat is extracted by the cooling water as a direct result of the helium gas (60 mm) between the ingot and crucible. The helium gas was found to be a significant factor in promoting heat transfer out of the solidifying ingot. This significant increase in heat extraction rate should influence the solidification structure of the ingot. This increased heat extraction rate should result in a corresponding decrease in molten metal pool depth, mushy zone size and segregation.

Molten Metal Pool Depth

A comparison of metal pool depths under various cooling conditions is illustrated in Figure 1. The molten metal pool depth for the case of no gas cooling was found to be 20 cm and with 60 mm helium gas cooling, it was 12.7 cm; i.e., about a 36% decrease in metal pool depth, which is very significant. It can also be seen that with gas cooling, the metal pool profile became cup shaped rather than conical shaped. The molten metal pool depth in the case of the ingot made with argon gas was not decreased substantially as compared to helium gas cooling. This is due to the much higher thermal conductivity of helium gas as compared to argon gas. The size and shape of the molten metal pool is the result of the rate of heat input into the metal pool, the rate of heat extraction from the ingot and various losses. With the helium gas cooling between the ingot and crucible, more heat was extracted from the ingot resulting in a shallower metal pool.

Surface Quality of the Ingot

The surface condition of the ingots made without gas cooling and with gas cooling are shown in Figures 2a and 2b, respectively. It can be seen that the surface quality of the ingot made without gas cooling is smoother as compared to the surface quality of the ingot made with gas cooling. Hence, the surface quality of the ingot deteriorated with gas cooling. This may be due to the combined effect of two factors. The first may be due to increased splatter deposition on the crucible inside wall for a gas-cooled ingot. The second factor might be connected with the higher ingot growth rate for the gas cooled ingot. Both of these might have resulted in only partial remelting of the splatter, producing a rough surface. During the melting process, the metal pool was observed through the viewing port for any disturbances, if any, occurring with gas cooling. Also, the whole melting cycle was videotaped. The metal bath seemed to be calm during melting with gas cooling and no bubbling action was observed. Also, the increase in pressure in the melting zone with gas cooling was only a few microns more (9 microns) as compared to no gas cooling. The ingots were cut and found to be sound.

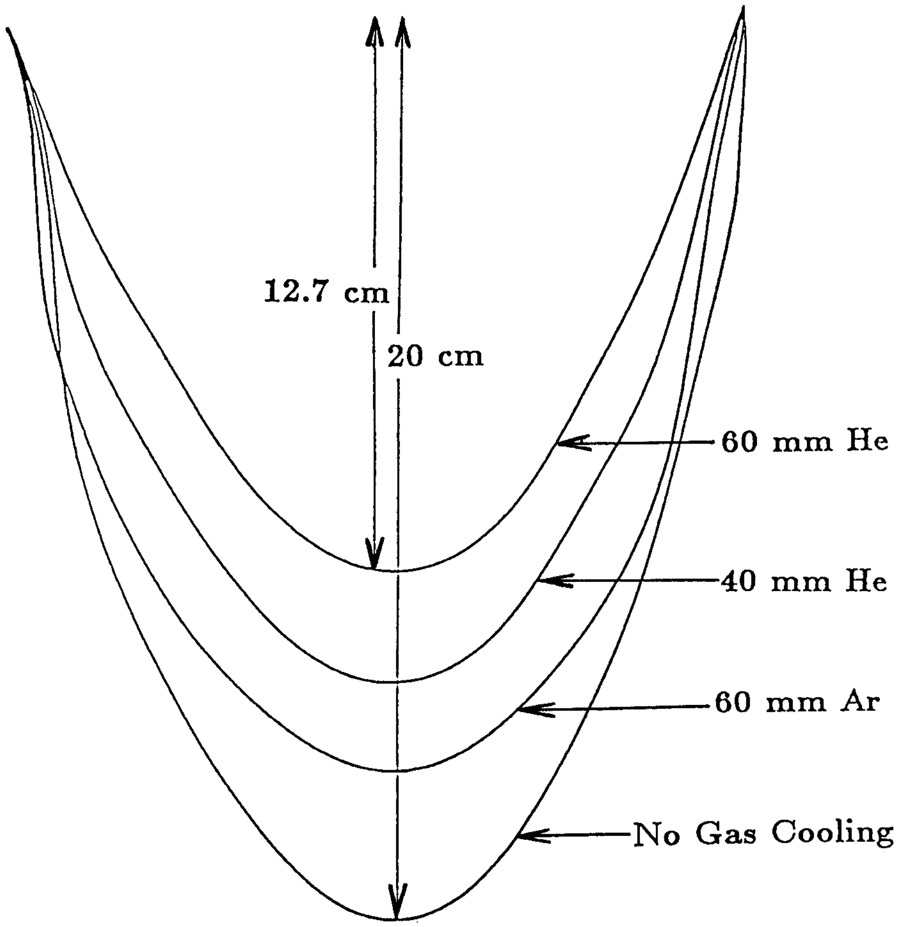
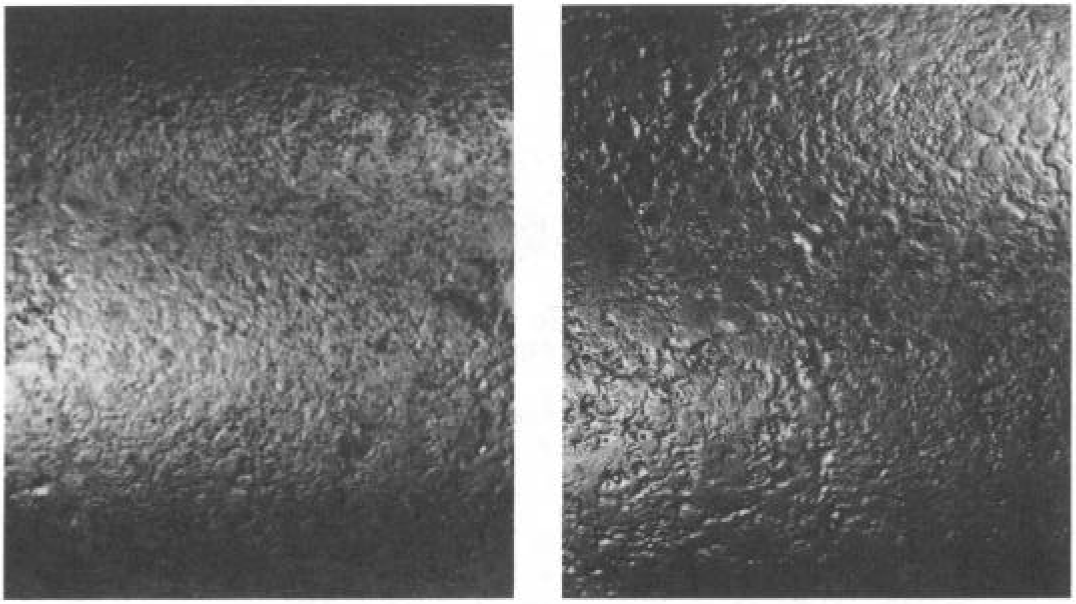


Figure 1 - Molten metal pool depth under various cooling conditions.

Dendrite Arm Spacing Measurements

Dendrite arm spacing measurements provide an estimation of the local cooling rates in the ingot and also can be used to determine the mushy zone sizes. One of the objectives of the present investigation was to see whether helium gas cooling had any effect on dendrite arm spacing, especially at the center of the ingot. Secondary dendrite arm spacing measurements were made at the edge, mid-radius and center of each ingot just below the molten metal pool. A minimum of 25 measurements were made on each sample from several photomicrographs. Figure 3 shows photomicrographs of the dendritic structure at the center of the ingots under various gas cooling conditions. Table III presents the measured secondary dendrite arm spacings. It can be seen that the dendrite arm spacing increased from the edge to center of the ingot, as expected. The cooling rate is highest at the edge of the ingot and lowest at the center of the ingot. The dendritic structure became finer with increased helium gas presure at the edge as well as at the center of the ingot. In fact, for cases of helium gas cooling using 40 mm and 60 mm helium gas, the dendrites at the center were finer than those measured on the edge of an ingot made with no gas cooling. This implies that the cooling rate at the center of all gas-cooled ingots was higher than the cooling rate at the edge of an ingot with no gas cooling.



a) b)

Figure 2 - Surface condition of ingots a) without gas cooling b) with gas cooling (60 mm He).

Table III. Dendrite Arm Spacing Measurements in Microns

	Dendrite Arm Spacings (in microns)		
Melt No.	Edge	Mid-radius	Center
47	63.6	66.6	74.0
49	47.0	53.2	58.9
50	42.5	52.2	55.7
53	55.2	60.0	62.3

Mushy Zone Size

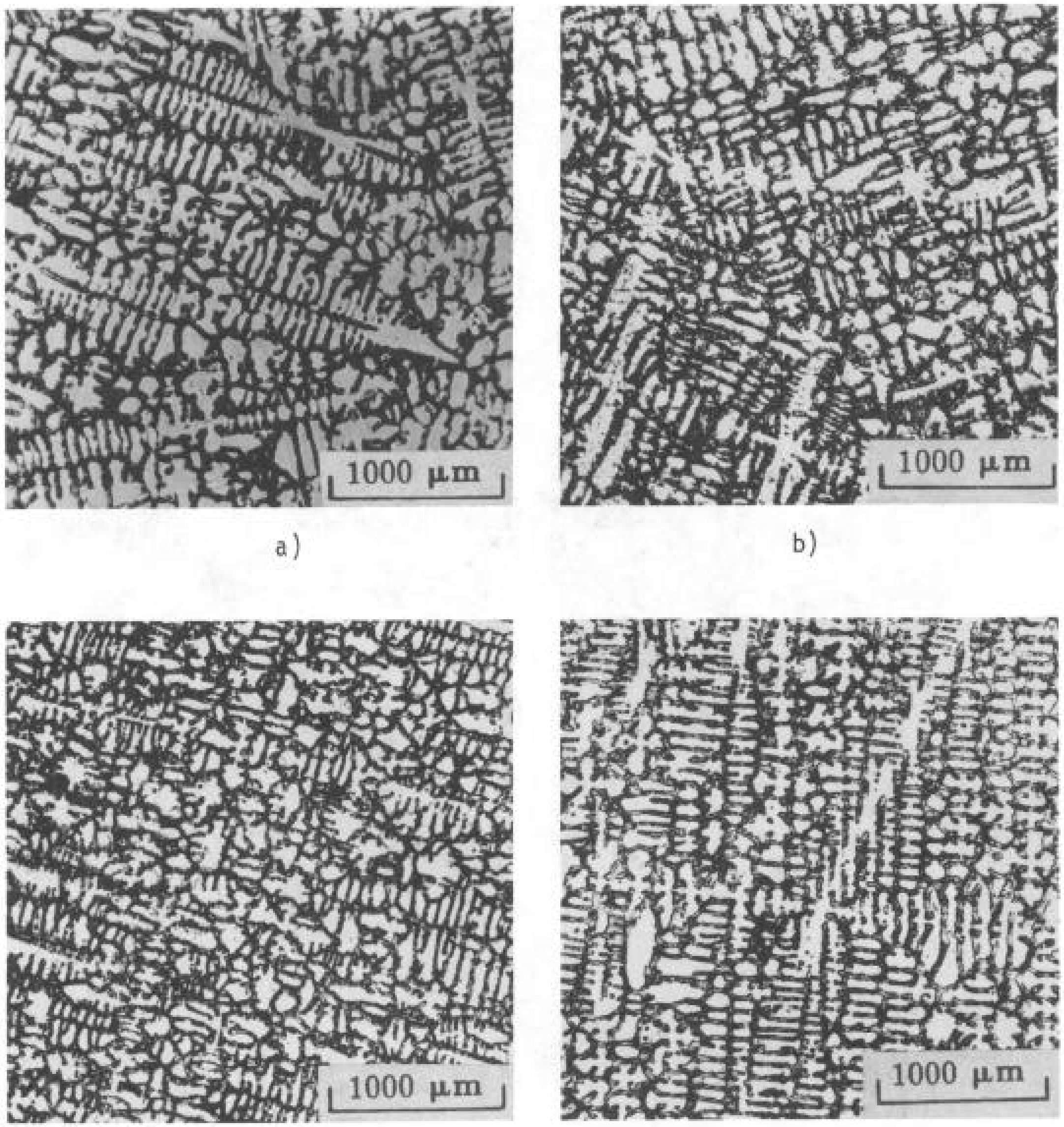
The mushy zone size and shape was estimated using the expression given below (8).

$$Z_L - Z_S = \Delta T\ R\ (d/a)^{-n} \qquad (1)$$

where,

$Z_L - Z_S$ = height of mushy zone at a given distance in mm
ΔT = liquidus minus solidus temperature of the alloy in C
d = measured secondary dendrite arm spacing in micron
a, n = constants
R = velocity of solidification front in mm

For alloy 718, $a = 33.85$ and $n = 0.338$, for secondary dendrite arm spacing (9) and $\Delta T = 65°C$.



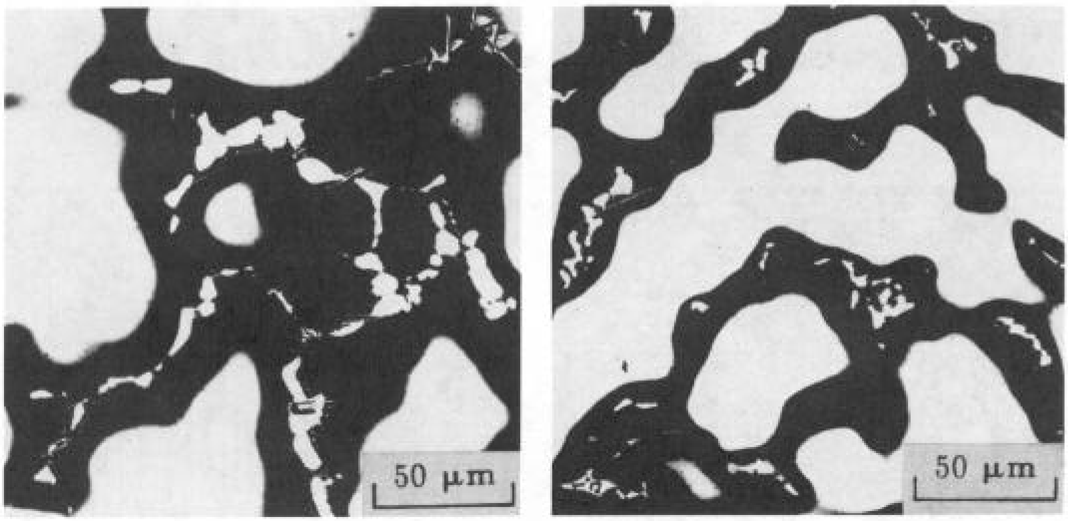
a) b) c) d)

Figure 3 - Photomicrographs of dendritic structure at the center of ingots a) without gas cooling b) gas cooling (40 mm He) c) gas cooling (60 mm He) d) gas cooling (60 mm Ar).

The calculated depth of mushy zone sizes for all the melts is shown in Table IV. It can be seen that the mushy zone depth decreases with the helium gas cooling. Copley et al. (10) have developed an expression for "freckle potential", which is a measure of freckle formation. According to the expression, the driving force for freckling decreases with the inverse square of the thermal gradient. Increasing the thermal gradient should effectively suppress the formation of freckles. The reduced molten pool depth and the decreased mushy zone size, in the case of gas-cooled ingots, imply an increased thermal gradient. Hence, gas cooling between the ingot and crucible should minimize the formation of freckles in VAR ingots.

Table IV. Mushy Zone Size in mm

		Mushy Zone Size (in mm)	
Melt No.	Edge	Mid-radius	Center
47	24.7	36.9	54.75
49	14.7	27.6	40.5
50	11.4	27.4	36
53	20.3	33.8	41.0



a) b)

Figure 4 - Photomicrographs of Laves phase distribution at the center of ingots a) without gas cooling b) with gas cooling (60 mm He).

Laves Phase

Figure 4 shows the Laves phase distribution in the center of the ingot with no gas cooling and with gas cooling conditions. It can be seen that the amount of Laves phase is high in the ingot which was done with no gas cooling and low in the ingot which was made with 60 mm helium gas cooling. This could be explained in terms of smaller metal pool depth, smaller mushy zone size and finer dendritic structure for the ingots made with gas cooling. The SEM/EDAX analysis of the dendrite core, interdendritic region and Laves phase was carried out for melts with no gas cooling and with gas cooling at various pressures. There was no significant difference in the Nb content of the Laves phase observed in the melts with gas cooling and without gas cooling.

Conclusions

Molten metal pool depth decreased with gas cooling. With 60 mm helium pressure, the metal pool depth decreased to 12.7 cm from 20.0 cm for no gas cooling, about a 36% decrease. Ingot surface quality deteriorated slightly with the gas cooling. The dendritic structure became finer with the increased gas pressure at the edge as well as at the center of the ingot. The mushy zone depth decreased with the gas cooling. The amount of Laves phase formed was decreased with the gas cooling. Hence, with gas cooling between the ingot and crucible, it is possible to minimize segregation in VAR ingots.

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