# EFFECT OF HELIUM COOLING ON VAR INGOT QUALITY OF ALLOY 718

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## Abstract

Increasing requirements for premium quality and properties, and for larger ingot sizes of vacuum arc remelted (VAR) superalloys have been largely met through the use of highly computerized furnace control equipment and developments in process technology aimed at significant improvements in ingot heat transfer and solidification.

The industrial procedure of introducing a gas with high thermal conductivity, such as helium, into the shrinkage gap between ingot and crucible wall has a very favorable effect on heat extraction, molten pool depth and ingot solidification.Heat transfer from ingot to crucible depends primarily on helium gas pressure in the gap up to a certain pressure above which the cooling effect appears to level off. When using helium injection on industrial size ingots about 20 % more heat is being removed by the crucible cooling water. At a given melt rate the higher cooling rates reduce the molten pool depth by 30 % in 500 mm diameter ingots of Alloy 718 and other superalloys. These improvements in solidification result in finer, more uniform cast structures, elimination of macrosegregation defects and a decrease of microsegregation. Power input or melt rate can be increased around 20 % with helium injection, or a larger ingot may be reliably produced under optimum remelting and gas cooling conditions.

The application of a limited partial gas pressure up to 2 mbar above the molten pool in combination with helium injection into the shrinkage gap results in additional improvements in heat extraction, smaller pool depth and macrostructure refinements.

No deterioration of ingot surface quality has been observed with correct gas injection parameters. Ingot forgeability and intermediate billet yields are generally slightly better than with non- gas cooled ingots.

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## Introduction

The increasing requirements of "hitech" industries for premium quality and various property improvements as well as for larger sizes in vacuum arc remelted superalloy ingots have been largely met through the development of sophisticated highly computerized furnace control equipment and refinements in process technology aimed at significant enhancements of ingot heat transfer and solidification. During cooling of the solidified ingot it shrinks away from the crucible wall forming a vacuum gap in which heat transfer is by radiation only. Injecting gases with high thermal conductivity into this gap increases heat transfer rate by gas conduction which results in a remarkable improvement of ingot cooling rates. Helium and hydrogen have both exceptionally high thermal conductivities in comparison to air and other gases.

The industrial development of introducing helium gas between ingot and crucible in VAR was initiated over 30 years ago (1). Two patents on using helium in the shrinkage gap region of ingot solidification were issued 1967 (2). The technique is now widely used in production of VAR superalloys but little has been published on the technology and actual improvements obtained under industrial conditions. Theoretical considerations and calculations of the effect of helium pressure on the heat transfer coefficient were presented by Yu (3) and experimental studies on gas cooling were conducted by Hosamani (4). Investigators in the USSR have reported heat transfer studies with helium gas in VAR (5). The technology and practice of gas cooling in vacuum arc remelting were described in a recent publication (6). In this paper results are reported on the effects of helium gas cooling mainly on heat transfer and pool depth of industrial size ingots of Alloy 718.

## Helium Cooling Technique

In VAR the heat transfer mechanism from the ingot across the shrinkage (vacuum) gap to the copper crucible and cooling water is primarily by radiation. Direct contact with the crucible wall exists only at the top of the growing ingot by a narrow band just below the meniscus of the molten pool. In the vacuum gap the heat extraction rate from the ingot surface can be substantially increased through the introduction of gases with high thermal conductivity. The band of contact with the crucible wall at the ingot top forms a limited "liquid seal" by the soft metal skin thus reducing the leakage of injected gas through the top and permitting the build-up of a certain pressure in the shrinkage gap over that in the space above the molten pool (6). The heat extraction rate in the gap depends on gas thermal conductivity, gas pressure and flow, and on gap width between ingot and crucible wall (3). The thermal conductivity of gases in general is strongly influenced by pressures below about 70 mbar and at lower levels it decreases linearly with pressure (7). Hence, the rate of energy transfer is proportional to pressure and temperature difference whereby the thermal conductivity of gases increases with rising temperature. Besides helium only hydrogen has still better thermal properties but for obvious reasons its practical application has drawbacks.

The presence of certain gases and vapors in the arc zone has pronounced effects on the behavior of the "vacuum arc" and on the partition of the elctric power between cathode (electrode) and anode (molten pool). In presence of small partial pressures of monatomic gases (like helium) arc stabilization and melting efficiency can improve but these effects are limited to certain furnace specific pressure ranges. An influence on drip short characteristics of the arc at low pressures appears to be insignificant without affecting advanced arc control systems operating at tight arc gaps.

Arc behavior strongly depends on operational parameters, such as melting current, arc length, ambient gaseous environment and pressure, electrode condition and chemistry. The preferred diffuse arc is stabilized by high currents, short arc gaps and low CO pressure, as reported by Zanner et al (8). High vapor pressure elements enrich the plasma chemistry which may destabilize the arc.

The use of a limited partial helium pressure above the molten pool in combination with gas injection into the shrinkage gap can provide addtional benefits in VAR operation and ingot heat extraction. These efforts are aimed at establishing smoother, more stable arc conditions for a reduction of metal splattering, shelf and crown build-up on the crucible wall which can be the source of structural defects. Advantageous effects are expected from the continuous removal of unwanted and harmful gases from the arc zone through a dynamic flushing action of helium gas passing up around the ingot circumference into the annulus between the electrode and crucible wall.

## Gas Cooling Procedure and Operation

The application of helium gap cooling requires the installation of a gas supply and control system on the VAR furnace, and a modification of the copper crucibles for reliable gas injection during the melting cycle. Different layouts are possible depending on local conditions and equipment design (6).

Generally, the injection of helium into the shrinkage gap between ingot and crucible is made at the very bottom of the crucible through a few small openings in symmetrical arrangement around the circumference. Feed lines to the upper crucible flange and through the flange lead to quick disconnect couplings which hook up with the gas supply system.

Feeding the helium to the crucible may be controlled either by metering the gas flow and monitoring the dynamic back pressure in the supply line, or by controlling the true pressure in the shrinkage gap through a separate set of tubes and adjusting the gas flow accordingly. Both systems are readily automated with mass flow meters and gas pressure sensors. For each installation the specific correlation between gas flow and pressure must be determined (see Figure 1). Computer programming, process control and continuous monitoring of pressure and flow data are standard features on modern furnace equipment for complete surveillance of operations and process management. The helium gas is of five-nine purity (>99.999 vol.%) and usually supplied in bottles.

In VAR operation using gap cooling a small helium flow is started early during arc initiation and gradually increased to the preset level when establishing a full molten pool. The helium pressure in the shrinkage gap or gas feed line may now be used as principal control parameter and kept constant throughout the melting and hot topping cycle by adjusting the gas flow. Conversely, the flow rate of helium can be maintained constant and letting the pressure establish itself within certain limits according to the liquid seal condition. The furnace pressure as measured in the mid-section is generally not affected by normal helium injection rates. Sometimes small pressure spikes may occur periodically when gas passes through the seal. Very small variations in gap pressure are seen during the steady melt rate phase with a constant helium flow unless instabilities are experienced that affect the seal. The operating voltage and drip short pattern are not affected but the melt rates have shown a tendency to increase slightly with a given power input.

During hot topping the seal becomes less effective due to the ingot shrinking away more and, hence, the set gas pressure in the gap has to be maintained with an increased gas flow. With constant helium flow the pressure in the gap decreases a little as hot topping progresses. Helium injection is discontinued a short time after turning off the melting power.

The helium pressure attainable in the shrinkage gap depends on remelting parameters affecting the liquid seal at the top of the growing ingot, such as power level (melt rate), arc length variations, electrode/ingot geometry and arc instabilities. High power inputs result in a better seal due to less shelf build-up and, hence, higher helium pressures are possible. A strong disturbance of the seal by excessive helium flow must be avoided because rough ingot surfaces and possible subsurface porosity may result.

The gas cooling parameters for different ingot sizes may vary over a relatively wide range depending not only on equipment and control setup but largely on remelting conditions. Specific flow rates based on feed line back pressures between 20 and 30 mbar and the inner crucible circumference range from 0.030 to 0.060 l/min/cm. The optimum pressure in the helium supply line just after the shut-off valve is between 8 and 35 mbar while the static pressure readings in the shrinkage gap using a separate line are lower by 20 to 30 % depending on the gas system layout. For maximum heat extraction rates the helium pressure is selected as high as compatible with the remelting parameters and the resulting ingot surface quality.

The same basic procedure was also employed when melting experimental ingots with a certain gas pressure above the molten pool to further increase heat extraction rates and study the influence on arc behavior. For nickel-base alloys top pressures from 0.1 to 6.6 mbar have been evaluated. However, variable unstable arc conditions (constricted arcs) were frequently experienced at furnace top pressures over 2 mbar. The pressure limit causing instabilities depended on furnace design, electrode/ingot geometry and location of the pressure sensor. Elevated furnace pressures were established by throttling the pumping speed and allowing the pressure to build up by the gas passing from the shrinkage gap through the ingot seal. With a small cross-section bypass line and motorized control valve the top pressures were maintained within variations of $\pm$ 5 % of the pressure readings.

## Results of Industrial Practice

Production and experimental vacuum arc remelts have been investigated and evaluated during the development of advanced melting procedures with helium cooling and extending the practice to larger ingot sizes. Typical results and benefits are reported to illustrate the effectiveness of the gas cooling technology and to outline potential further improvements in the VAR process.

### Melt Rate

The melt rate during steady state operation of VAR increases in a linear function of the power input or melting current, respectively, since the arc voltage remains practically constant. When using helium injection, the average melt rate increases by about 4 % compared to non-helium heats at the same current input. An evaluation of Alloy 718 remelting data showed the following relationship of melt rate (kg/h) with common industrial steady currents (kA):

| | |
|---|---|
| No helium | $m_1$ (kg/h) = 43.3(kA - 0.9) |
| With helium | $m_2$ (kg/h) = 43.5(kA - 0.7) |

In general, the specific energy consumption (kWh/kg) in VAR tends to decrease with increasing power inputs which was confirmed in this evaluation.

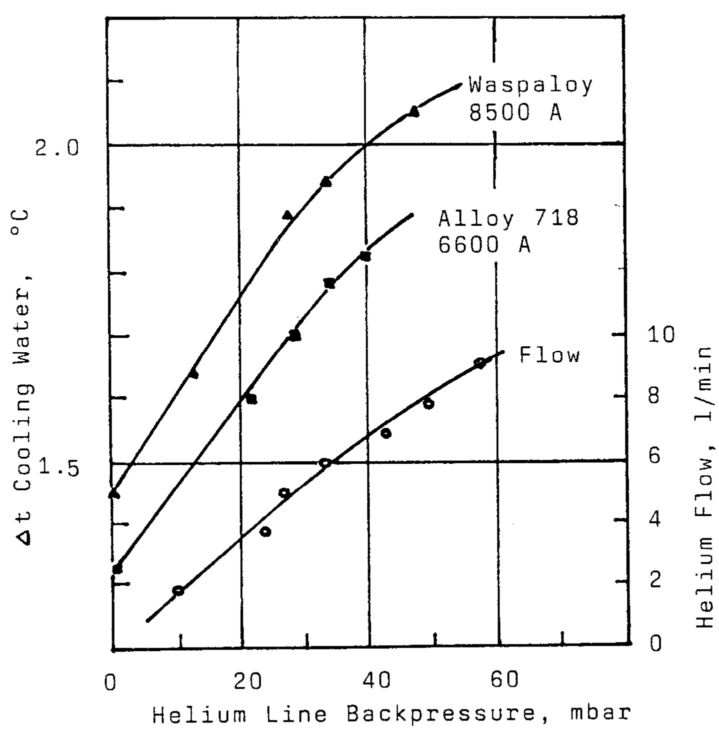



Figure 1 - Effect of helium pressure on Δt cooling water during VAR of Alloy 718 and Waspaloy in 500 mm dia. crucible at water flow rates between 1350 and 1410 l/min.

## Ingot Heat Extraction

To determine the increased heat extraction achievable with helium gas cooling, test melts were performed with different gas flow rates and pressures in the gap while melting under vacuum at $\leq 0.02$ mbar and with limited partial helium pressure above the molten pool in the furnace top. For this purpose the crucible cooling water temperature was measured and recorded with precision chromel-alumel thermocouples (reproducibility $\pm$ 0.05°C) at the inlet and outlet ports. From the temperature differential $\Delta t$ and the water flow rate, the heat removed by the cooling water can be calculated. The relationship between gas pressure as measured in the feed line and $\Delta t$ of the cooling water at constant flow rate is shown in Figure 1 for Alloy 718 and Waspaloy. Because $\Delta t$ increases continually with melting time as the ingot grows, the data were averaged for the middle 40-50 % of an ingot when quasi-steady state thermal conditions prevail. Several investigations showed that the straight line relationship begins to deviate at 40-50 mbar indicating that the cooling efficiency decreases at higher gap pressures. This point usually coincides with the appearance of a much rougher ingot surface. The overall heat transfer coefficient and heat extraction rate increase with the helium pressure in the gap. The behavior of line pressure and gas flow for this installation is also shown in the graph of Figure 1. For 500 mm dia. ingots optimum cooling conditions are obtained with helium flow rates between 3.5 and 6 l/min at pressures of 20-35 mbar. It was calculated that 17-23 % more heat is being removed by the cooling water with helium injection which means that less sensible heat remains in the ingot.

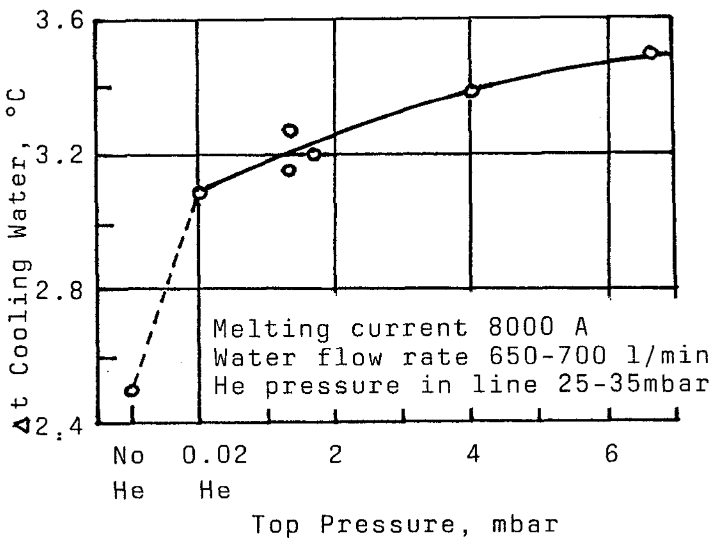
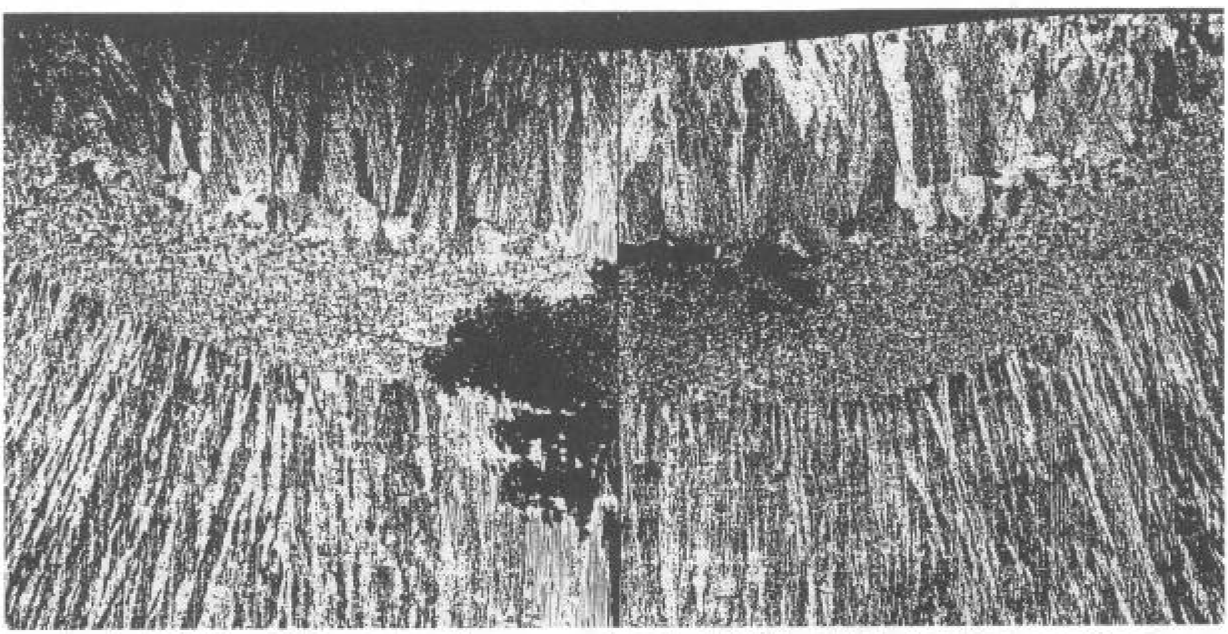



Figure 2 - Effect of helium top pressure on heat transfer of 500 mm dia. ingots of Alloy 718.

Remelting experiments were carried out with elevated furnace top pressures from 0.1 to 6.6 mbar helium. The increase in $\Delta t$ with higher pressures above the molten pool is presented in Figure 2. An additional improvement in heat extraction can be realized with this procedure. However, arc instabilities occurred at top pressures above 2 mbar dependent on melting current level. Under stable conditions up to 10 % additional heat can be conducted to the cooling water. Part of this increase may come from higher gap pressures obtained with constant helium flow and a smaller pressure differential between gap and melting zone.

## Pool Profile and Macrostructure

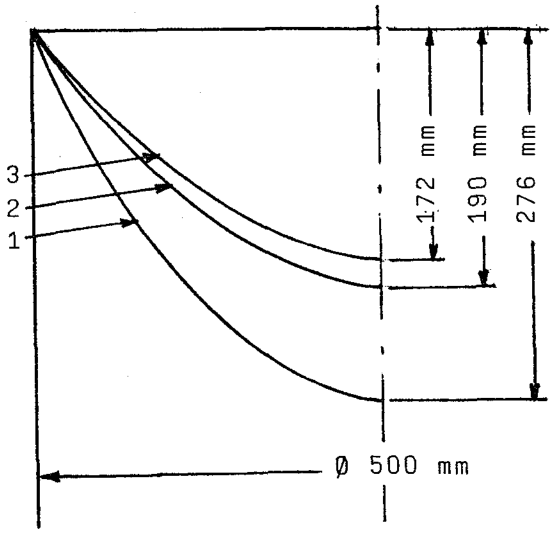
Investigations of pool depths and macrostructure were made on several alloys under different melting conditions with helium cooling to obtain pictorial evidence of the effect of improved heat extraction on ingot solidification. In a test serie on Alloy 718 ingots of 500 mm dia. no hot topping was performed before terminating the melt. Immediately before turning off power, a dead short was initiated to cause a strong disturbance of the solidification which results in a well marked outline of the molten pool profile in the ingot macrostructure. The top part of each ingot melted at different power levels was cut longitudinally through the center and macroetched. The molten pool configurations of two ingot tops are illustrated in Figure 3. One ingot was melted conventionally without helium cooling and the other one with the melting current increased by 17 % and using helium injection resulting in a pool depth still smaller than in the conventional ingot. Even though modern drip short arc control systems permit safely higher melt rates without risking metallurgical problems, a further increase in melt rates of around 20 % can be realized in nickel-base alloys with helium injection.



| Heat 51070: Without helium<br>Melting current 100%<br>Pool depth 215 mm | Heat 51071: With helium cooling<br>Melting current 117%<br>Pool depth 200 mm |
|---|---|

Figure 3 - Molten pool depths at top of 500 mm dia. ingots of Alloy 718 without and with helium gap cooling. (Courtesy Saarstahl AG-DHS, Germany)

A finer macrostructure is observed in transverse sections of gas cooled ingots. As Figure 3 shows, the macro grain size is relatively uniform from center to edge of the ingot which indicates uniform cooling rates in radial direction. The pool depth and grain growth angle increase with power input. Near the shelf region the grain growth angle is high because of a steep thermal gradient. Towards the center a more vertical grain growth direction is evident.




1 Without helium cooling
2 With helium gap cooling
3 With gap cooling + 1.3 mbar top pressure

Figure 4 - Molten pool depths obtained with different cooling conditions in 500 mm dia.ingots of Alloy 718 remelted with 6500 A.

In another test serie the molten pool depths were evaluated using the same melting power but varying the gas cooling method and adding a partial helium pressure above the molten pool.These results are summarized in Figure 4. A reduction in pool depth of 30 % was achieved with helium injection in the shrinkage gap. Applying a pressure of 1.3 mbar above the molten pool resulted in a further decrease in pool depth and it produced a more refined macrostructure. The gas cooled ingots were free of freckles while a few midradius segregation spots were observed in the ingot melted without He injection. A decrease in pool size and mushy zone width and an increase of the solidification thermal gradient are effective in minimizing the risk of freckle formation. Although interdendritic fluid flow increases with power input due to stronger electromagnetic forces, a more U-shaped pool configuration seems to have a greater tolerance for macrosegregation because of a more uniform mushy zone.

Limited microstructural work and measurements of dendrite arm spacings revealed a small decrease of midradius dendrite arm spacings with increasing melt rates and a reduction of the amount of Laves phase in interdendritic areas.

## Larger Ingot Sizes

The standard production ingot sizes for Alloy 718 range from 350 to 500 mm dia. Early attempts to increase the ingot size met with mixed results, but applying more advanced gas cooling and melting procedures led to the successful development of 600 and 650 mm dia. ingots. Medium high power levels and elevated helium pressure in the shrinkage gap, partly in combination with increased top pressures, were key parameters in this effort.

## Ingot Surface Quality

No deterioration of the ingot surface has been observed when melting with correct settings of helium injection and limited top pressure. In general, a uniform and dense ingot surface is obtained with the higher melting currents permissible with helium cooling. A rougher, more textured orange peel type surface is seen at elevated gap pressures with increased helium flow.

Due to increased heat extraction from the ingot, a steeper vertical temperature gradient exists between bottom and top. After stripping of 500 mm dia. ingots of Alloy 718 the surface temperature gradient can be 50-100°C higher on gas-cooled ingots compared to conventionally melted ingots. This condition increases the cracking propensity of larger ingot sizes.

### Ingot Forgeability and Yields

At the surface the grain growth direction in VAR ingots is nearly perpendicular to the surface and this can promote grain boundary cracking in the subsurface grain structure during initial forging. Generally, ingots made with helium cooling have not been more susceptible but are rated to show a slightly better hot working behavior than non-gas cooled ingots.

An evaluation of pressforged intermediate billet sizes from 500 mm dia. ingots showed a yield increase of 2-4 %. Top end ultrasonic defects remained on average at a slightly lower level with reduced scatter from ingot to ingot than experienced with non-helium treated standard ingots.

## Conclusions

Helium injection into the shrinkage gap between ingot and crucible wall and the use of a limited partial pressure above the molten pool provide significant advantages to the VAR process technology of nickel-base superalloys:

- Ingot heat transfer rates increase linearly with gap pressures up to 40-50 mbar
- Helium pressures above the molten pool are limited to <2 mbar
- About 20 % more heat is removed by crucible cooling water
- Reduction of molten pool depth by 30 % in 500 mm dia.ingots
- Increase of power input/melt rate around 20 % without incurring macrosegregation defects
- No deterioration of ingot surface quality
- Minor improvement of ingot forgeability
- Slight increase in intermediate billet yields
- Realization of larger ingot sizes

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