The Influence of VAR Processes and Parameters on White Spot Formation in Alloy 718

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Significant progress has occurred lately regarding the classification, characterization, and formation of white spots during vacuum arc remelting (VAR). White spots have been generally split into three categories: discrete white spots, which are believed to be associated with undissolved material which has fallen in from the shelf, crown, or torus regions; dendritic white spots, usually associated with dendrite clusters having fallen from the electrode; and solidification white spots, believed to be caused by local perturbations in the solidification conditions. The characteristics and proposed formation mechanisms of white spots will be reviewed and discussed in the context of the physical processes occurring during VAR, such as fluid flow and arc behavior. Where possible, their formation mechanisms will be considered with respect to specific operating parameters. In order to more fully understand the formation of solidification white spots, an experimental program has been begun to characterize the solidification stability of Alloy 718 and variants with respect to changes in growth rate and thermal environment. A description of the experimental program and preliminary results will are included.

INTRODUCTION

In recent years, the performance requirements for nickel-based superalloys have been steadily increasing, resulting in, among other things, a trend toward lower thermomechanical processing temperatures and finer grain sizes. Although improved control of melting processes has reduced the incidence of many melt-related defects, such a freckles, the trend toward finer grain sizes has brought into increased prominence solute-lean defects, or white spots, which are generally associated with VAR. As a result, a great deal of emphasis has recently been placed on the identification and classification of white spots, their effects on mechanical properties, and on their formation mechanisms. An ASM Committee has been formed to address these issues as well.

This paper will briefly review the classification and formation mechanisms of white spots which have been published in recent years. Each of the identified classes of white spot will be discussed with respect to how they are formed, how these mechanisms interact with the physical processes occurring during VAR, and where possible, how their formation might be affected by VAR process parameters and operating conditions. The eventual goal is to be able to describe the formation mechanisms in terms of process fundamentals such as arc behavior, thermal environment, and fluid flow characteristics, using numerical simulations to evaluate the relationships between process parameters and these aspects. An experimental program has been initiated to examine the solidification stability of Alloy 718 under solidification conditions representative of VAR.

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CLASSIFICATION AND FORMATION MECHANISMS OF WHITE SPOTS

Recent efforts to classify observed types of white spots by the Gas Turbine Superalloy Committee of the Aerospace Division of ASM International have resulted in identification of three types of white spots: discrete, dendritic, and solidification white spots (1). Although each type is distinguished by microstructural and compositional differences, and by their mechanisms of formation, they share several common characteristics. In general, white spots appear as localized light etching areas which stand out from the surrounding matrix. Most often, white spots are found during inspections of etched forgings or billets. Typically, white spots are lean in solute elements, particularly Nb and Ti, and may have a coarser grain structure than the surrounding matrix. The detection of white spots in ingots is rare for three reasons: only a relatively small amount of ingot material is inspected in practice, overall segregation features often obscure the local areas, and the material has not been subjected to thermomechanical processes which can accentuate the microstructural differences between the white spot and matrix (1- 3).

Dendritic white spots have a coarse dendritic structure, are usually continuous with the matrix, and are typically depleted in Nb and other alloying elements by only a few tenths of a percent. They can be as large as several cm and are found at the center of the ingot (1-4). The structure of dendritic white spots has been found to closely correspond with primary dendrites present in the electrode material. This has led to the speculation that they result from clusters of dendrites falling from shrinkage gaps in the electrode into the molten pool, a mechanism Mitchell has shown to be possible (4). This is shown schematically in Figure 1. The average composition of dendrite clusters is slightly lower in rejected solute elements since some low melting interdendritic liquid undoubtedly flows off the cluster of dendrites before they fall from the electrode. Smaller dendrites would dissolve, with the critical survival size depending on pool superheat and fluid flow conditions. Because the molten pool surface is often coated with oxide and/or nitride debris, the fall-in mechanism explains the association of oxides/nitrides with dendritic white spots, referred to as "dirty" white spots (1,4).

The distinguishing characteristics of discrete white spots (1-4) include the largest depletion in alloying elements, a distinct interface between the white spot and the matrix, and location from the center to mid-radius of the ingot. Nb levels may be depleted by -0.75 to -3.0%, with the higher depletion typical of first-solidified dendrite core material. Discrete white spots can be round or odd shaped, greater than 10 mm in diameter, and typically have an internal microstructure which differs from that of the surrounding matrix. It has been shown that the structure and composition of discrete white spots are similar to "shelf" material. This leads to the proposal that these white spots are undissolved remnants of shelf material which have fallen into the molten pool (1,2,4). Specifically, it has been proposed that shelf (crown, or torus) is dislodged by an instability in the molten pool or surrounding thermal environment, falls into the molten pool, and lacks sufficient time at temperature to be dissolved, Figure 1. In addition to the structural evidence, this mechanism is consistent with models for the thermal and fluid flow environments in VAR (5,6).

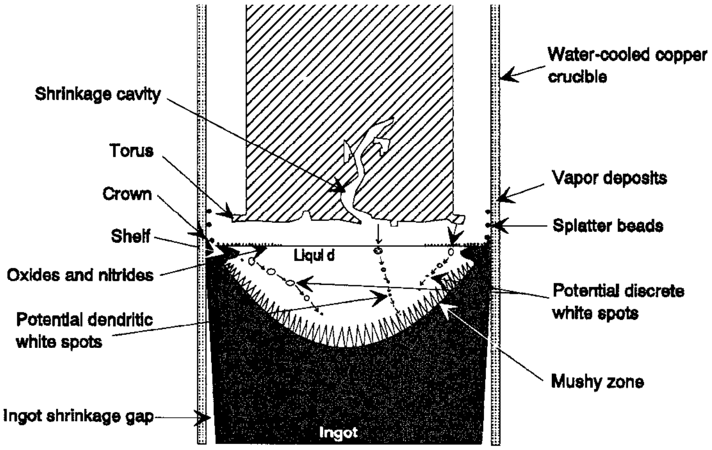

Figure 1. VAR process geometry showing locations of sources for fall-in particles.

Crown material is made up of a combination of condensed high vapor material from the arc as well as spatter deposits of material ejected from drip shorts or gas bubbles. Spherical spatter droplets could account for the observed round white spots sometimes seen (2), although it seems likely that the average spatter particle would have the bulk alloy composition. Shelf material, which solidifies first around the top of the melt pool, is low in solute composition due to flow-driven depletion of rejected solute-rich liquid in front of the primary dendrites (1,4). Typical shelf elemental compositions, low in Nb, Ti, Mo, Al, and C, are consistent with discrete white spot compositions. As is the case with dendritic white spots, discrete white spots are seen both with and without oxide inclusions.

Solidification white spots (1-3) are light etching regions found between the surface and mid-radius of VAR product. Observed in billet or forgings, these regions are generally thin linear areas that have a ring, arc, or hook shapes concave toward the center of the ingot and range from 0.1 to 1 mm thick and are up to a few mm long. They are lightly depleted in Nb, and may have average compositions still within alloy specifications. Generally, solidification white spots have a microstructural processing response midway between typical 718 matrix material and a discrete white spot (3). Their light etching behavior is often due to a coarser grain size and reduced amount of delta phase precipitation when compared to the adjoining matrix. Maurer, et al., have speculated that the coarser grain size results from thermomechnaical processing which, due to compositional differences, occurs in a temperature regime above the delta solvus temperature of the white spot material but below that of the matrix (2).

The mechanisms of solidification white spot formation are still poorly understood. Maurer (2) has proposed a formation mechanism whereby a local interruption, or slowing of the solidification process results in the formation of an area in which the primary dendrite spacing remains constant, but the dendrites themselves are coarsened, leading to the initial coarse dendrite structure and the local composition being shifted toward that of primary dendrites, Figure 2. In this aspect, solidification white spots are closely related to the ring banding often seen in VAR ingots and associated with general solidification instabilities. The authors have proposed that the formation of solidification white spots requires a melting back of the solidification interface or a local change in fluid flow to replace the enriched interdendritic liquid with liquid of the bulk composition. Melt operating conditions which favor solidification white spots include low heat input operation, which produces a shallow molten pool, and startup conditions, where high heat transfer leads to shallow melt pools. Shallow pools have low thermal inertia, and variations in local arc conditions can strongly affect local solidification conditions (1,2).

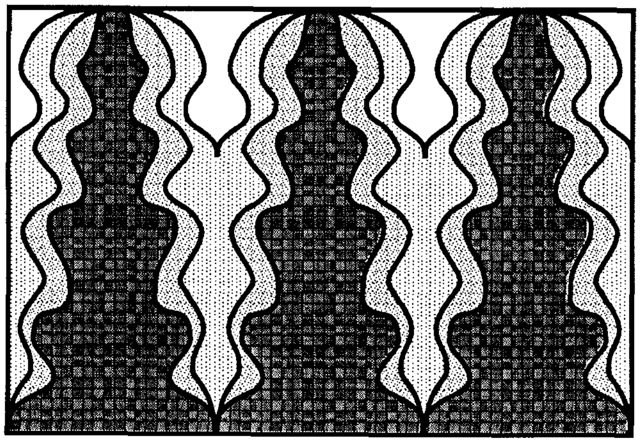

Figure 2. Coarse dendrite structure resulting from interruption or slowing of local solidification front.

Each of the three classes of white spots has unique characteristics and formation mechanisms, resulting in a different set of interactions with the VAR process, so each type will be discussed individually. In examining the effects of VAR process practices and parameters on white spot formation, an initial distinction may be made between dendritic and discrete white spots on one hand, and solidification white spots on the other. The former are generally associated with the remnants of material which has fallen into the pool. In the case of these two, the VAR process may be analyzed with respect to formation of the defect source, its detachment, and its success in surviving the molten pool.

DENDRITIC WHITE SPOTS

Of the three types of white spots which have been discussed, discrete, dendritic and solidification, the dendritic white spots are those that are least affected by VAR processing parameters. Looking first at their source, dendrite fall-in, the primary means of preventing their occurrence is use of sound electrodes, typically addressed via the incorporation of an intermediate ESR melting step between VIM and VAR, i.e., triple-melt. Little if anything can be done within the VAR process itself to affect the likelihood of a dendrite cluster being introduced into the molten pool. However, a number of VAR processing parameters can be evaluated with respect to their potential effect on dendrite dissolution in the molten pool.

The likelihood that a piece of electrode will dissolve in the molten pool depends mainly on four parameters: the size of the dendrite, the amount of superheat in the pool, the prevailing fluid flows and the initial temperature of the dendrite. As the size of the dendrite increases, so do its dissolution time and chance of survival. However, dendrite size is determined by the structure of the electrode and, to a first approximation, not influenced by VAR processing parameters. The second and third considerations, the fluid flow and thermal environment in the molten pool, are controlled by the VAR parameters, whether they be selected process inputs or inherent instabilities.

To increase the probability of dendrite dissolution, parameters should be chosen which maximize the time at temperature experienced by the dendrite cluster. These goals are best achieved by operating at a high melting current, which has the effects of increasing the pool superheat and pool volume (7,8), and maximizing the time the dendrite spends in the superheated region by lowering the outward velocity at the pool surface (8). The increases in both molten pool volume and superheat that occur with increases in melting current are well established. The connection between melting current and fluid flows has been a subject of much recent research (8,9). It has been shown that steady-state fluid flows in VAR result from a competition between two forces, thermal buoyancy and magnetohydrodynamic. The former dominates at low currents, and causes liquid directly under the electrode to rise, be driven outward to the crucible, then down the sides of the pool. MHD driven flows, which dominate at very high currents (>9kA for 510 mm (20") 718 ingots), are exactly the opposite. Liquid under the electrode moves down to the pool center, then up along the liquid/solid interface, and inward on the pool surface (8).

Recent simulations of 430 mm/510 mm (17"/20") 718 melting at various current levels indicate that typical 718 melting conditions are near the limit of the thermal buoyancy dominated regime. Therefore, the MHD components can significantly reduce overall fluid velocity. Conceptually then, increases in melting current improve the dissolution of dendrites deposited at the pool center by increasing the time the dendrite spends in the highly superheated region under the electrode. Although the fluid flow and thermal fields may now be characterized reasonably well under steady-state conditions, both the nature of process fluctuations and the characteristics of the dendrite clusters themselves are essentially unknown, making accurate predictions of particle paths and time-temperature histories difficult. It is reasonable, however, to suggest that increased current levels will aid dissolution, via increased superheat, deeper pools, and increased residence time.

DISCRETE WHITE SPOTS

Discrete white spots (1,4) have been reported to result from fall-in of torus, crown, or shelf material. High speed photography of VAR furnaces in operation has clearly shown the formation and detachment of these materials (8). Studies characterizing crown and torus material however, have shown that their sources are spatter and vapor deposition, respectively. Therefore, the composition of these materials should either match that of the bulk material, in the case of spatter, or be significantly enriched in C, S, or Mn, in the case of vapor deposited material (8,9). These characteristics cannot be reconciled with the reported compositions of discrete white spots, which show depletion in Nb and Ti, and no excess of the high vapor pressure elements (1). Further, given its structure, Figure 3, it seems unlikely that macroscopically large agglomerations of crown material could survive the environment of the molten pool. A more likely contribution of crown material is to reduce the mechanical cohesion between the shelf and the crucible wall.

Contrary to the cases of crown and torus, shelf is composed of primary dendrites which grow from the mold wall in regions of good thermal contact. In these areas, the high thermal gradient will result in material with a high growth rate and fine dendritic structure (1,4). The high fluid velocities at the pool edge suggested by simulations (> 10 cm/s for 510 mm 718 @ 6kA) continually remove any solute build up ahead of the advancing interface, resulting in primary dendrites growing into liquid of the bulk composition. The net result is shelf material which is solute-lean, and has been shown to closely match the composition of discrete white spots (1,4).

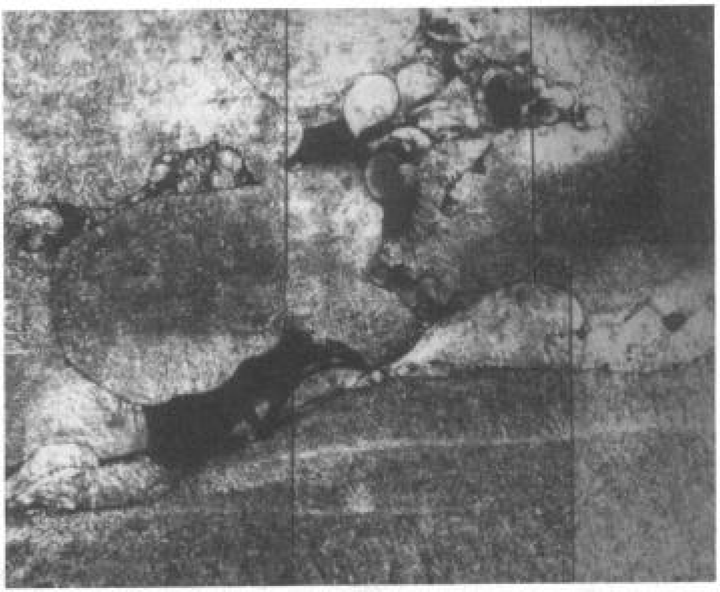

Figure 3. Crown remnant behind a section of shelf showing a source of potential mechanical decohesion (2.8X).

Formation of shelf however, does not guarantee the presence of discrete white spots in the resulting ingot. In order for the shelf to become a white spot, it must become detached from the crucible and sink before it re-melts into the pool. Figures 3 and 4 illustrate two mechanisms whereby this break off may occur. Figure 3 shows a section of shelf which has formed against a piece of crown, recognized by the roughly spherical pieces of spatter. The cracks and voids associated with the crown provide an unstable substrate for the shelf and a potential source for mechanical de-cohesion as conditions change. The ingot solidification structure shown in Figure 4 suggests that a local vortex existed in the molten pool directly under the shelf. The effect of such a vortex would be to undercut the shelf, causing an intact chunk of shelf to be dropped into the pool. Another proposed means of detaching a piece of shelf is via perforation of the metal ligament directly under the shelf, when the ligament loses good thermal contact with the crucible and heats rapidly. Finally, high-speed films of VAR molten pool surfaces show that shelf material typically does not get melted back, but is instead covered with molten metal when the meniscus at the shelf tip breaks down (8). Once covered, both detachment and melting of the shelf seem to be likely possibilities.

As discussed by Mitchell, particle dissolution and VAR pool models suggest that pieces of shelf deposited in the edge of the molten pool, Figure 1, exist at or near the threshold of dissolution (2,5,6). It is not unreasonable then, to expect the specifics of the thermal and fluid flow conditions to affect the survival of these defects. The effects of melt parameters on particle dissolution which were discussed with respect to dendritic white spots are equally valid in the case of discrete white spots. Increases in current will increase the superheat and volume of the molten pool, and reduce the magnitude of the flow velocities, all contributing to increased time at temperature and enhanced dissolution. In the extreme, when melting currents are high enough to reverse the sense of the flow (>9kA in 510 mm 718), any particles deposited at the pool edge will be swept directly into the hottest section of the molten pool, and their survival seems unlikely. Although both the detachment of shelf and the dissolution of the particles will be affected by VAR parameters, assessing the direct effects of parameter selections on these processes is extremely difficult. As a result, the best mechanism for the minimization of discrete white spots remains the avoidance of conditions which promote the growth of shelf. This requires control and stability of the heat flow through the molten pool. In the case of heat extraction from the pool, standard best practices result in a situation where the stability of the heat flow is governed by the narrow ingot-to-crucible contact zone. This occurs when the ingot cooling gas is delivered at sufficient pressure to ensure that heat transfer out of the ingot is governed by conduction through the ingot itself, making the system relatively insensitive to any pressure changes. An example calculation of this sort would suggest a pressure of several torr is adequate for a 510 mm (20") 718 ingot. Pressures in excess of this level will not improve the cooling, and may in fact contribute to instability of the system by intermittently interrupting the molten pool-to-crucible contact area, causing local reductions in the heat transfer at the interface and leading to the formation of shelf.

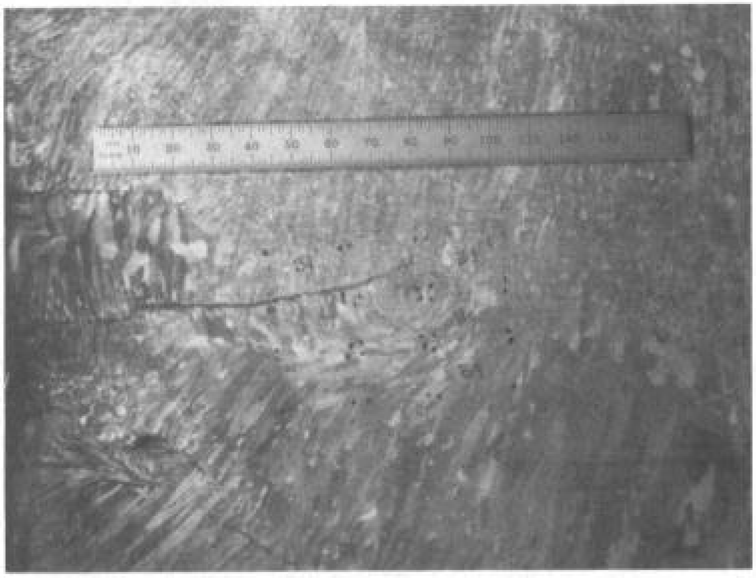

Figure 4. Solidification structure resulting from a vortex which formed beneath a shelf, showing evidence of locally increased fluid velocities

Simulations have shown that in addition to its contribution to shelf formation, heat transfer at this interface is the predominant factor in controlling the pool geometry and fluid flows (10). Unfortunately, the pool-to-crucible contact area is inherently unstable, as evidenced by the uneven appearance of the surface of most VAR ingots. As a result, the most direct method available for minimizing shelf formation is control of the arc, specifically maintenance of a stable, diffuse arc. Perturbations in the arc, either global, such as a glow condition, or local, such as a constricted arc, result in the rapid formation of shelf (8,11). In terms of operational parameters, experience and a large data base show that a stable diffuse arc is more readily achieved using high (6-9 kA) currents, a short electrode-to-pool gap, vacuum practices which minimize the level of molecular or diatomic gasses in the furnace atmosphere, and control of magnetic fields which could influence the arc.

Operating at a high current results in an increased number of cathode spots, and a more stable and "stiffer" arc (12). Additionally, higher current operation has been shown to reduce the susceptibility of the arc to either constriction or glow (8). A small electrode-to-pool gap has two effects. The first is to minimize the amount of crown which forms, by reducing the angular window available for deposition. The second is as follows. With a short gap, contact between drip shorts and the pool surface occurs much earlier in the process of forming a protuberance. As a result, more drip shorts will occur at a given current level. The drips which form will be larger in diameter, and rebound shorts (8,9) will occur more often. Combined, this creates a situation where the arc is being re-ignited in a diffuse configuration far more often, and a time-averaged map of the arc will be far more uniform. The presence of molecular or diatomic gasses in the furnace atmosphere will significantly diminish the stability of the arc. Even with a low leak rate, CO pressures of 50μm or less can initiate either a glow or constricted arc condition (8). CO is chemisorbed onto local regions of the electrode, increasing the work function of the metal and altering the behavior of the cathode spots (9). Non-uniform magnetic fields may also facilitate the growth of shelf by pushing the arc and creating a cold spot where shelf may begin to form. Functionally, magnetic field concerns are addressed through coaxial furnace design, and in some cases, by the application of an external field to control arc behavior (13).

SOLIDIFICATION WHITE SPOTS

Solidification white spots are generally believed to result from local changes in the solidification environment. Maurer (2) has proposed that an interruption of the solidification process allows dendrites to coarsen behind a static interface, thus increasing the proportion of solute lean primary dendrites, a mechanism which was shown in Figure 2. In earlier experiments where the solidification process was halted for one minute, Mitchell showed that interruption of solidification produced a coarse dendrite, solute-lean region of a size appropriate to function as a white spot precursor (4). Although the primary dendrite arm spacing does not increase, solidification proceeds by coarsening of the dendrites due to diffusion of the solute out of the interdendritic regions. Along similar lines, a similar result would occur if conditions in the molten pool resulted in a local melting back of the dendrites, again, effectively replacing the enriched interdendritic liquid with liquid of the bulk composition. Another similar mechanism suggests that a local change in fluid flow due to external perturbations alters compositional gradients established between and in front of the dendrites. Given the instabilities in heat transfer, current path, and arc characteristics that are inherent to VAR, this seems to be a likely possibility. Finally, it has been proposed that the ring structure often seen in solidification white spots results when a small particle of the bulk composition falls into the molten pool and acts as a micro-cooler (2). The particle is quickly coated with solute-lean primary dendrites, then sinks into the mushy zone and remains intact. Schved has actually proposed such a mechanism, coupled with enhanced diffusivity of Nb and Ti in the molten pool, as a mechanism for the formation of not solidification, but discrete white spots (14).

In general, coarsening of dendrites may occur in VAR whenever the local solidification rate undergoes a sudden decrease, such as would be associated with a change in the shape of the molten pool. Fluctuations in pool shape may occur as a result of uneven heating associated with arc instabilities, changes in the balance between thermal buoyancy and MHD driven flows, or changes in the ingot-to-crucible contact. Although such changes are inherent in VAR, a relatively short term fluctuation in arc stability or heat transfer conditions will have no net effect on the ingot structure, as the thermal inertia of the pool will flatten out any short term fluctuations. Based on typical white spot dimensions, solute diffusion rates in the liquid, and VAR melt rates for Alloy 718, the time scales associated with defect formation can be calculated to be on the order of 1-10 minutes. These longer term fluctuations are required to overcome the thermal inertia of the pool. This is in agreement with the empirical observations that solidification white spots are associated with locations and conditions where the pool is very shallow (1,2). It should be noted that the onset of glow and subsequent recovery seem likely to be able to produce the sort of conditions that might result in the above described coarsening. As with discrete white spots, arc control is of paramount importance in the minimization of solidification white spots.

In addition to the above formation mechanisms, the authors propose an additional method which is due to locally high fluid flow velocities. Figure 4 provides evidence of a vortex within the molten pool that occurred as a result of the interaction between the usual VAR fluid flows and a piece of shelf. It is proposed that such vortices are associated with locally higher fluid flows, a condition which would effectively sweep away solute at the dendrite tips and cause the material to solidify at a solute lean composition. It is of interest to note that the location, shape and scale of the area affected by such a vortex is well within the bounds observed for solidification white spots. Similarly the formation and decay of such a vortex and the associated changes in fluid velocity may also explain the relatively low composition gradient associated with this type of defect. This mechanism is supported by the simulations of Bertram and Sackinger (10). They have shown the existence of a similar vortex characterized by high flow velocities, with a strength that was affected by the proportion of the arc current which flows down through the pool. Changes in ingot/mold contact result in changes in this vortex and its associated velocities. If such a change in current partitioning is non-uniform then the variations in the vortex will also be non-uniform thereby resulting in localized changes in velocity which could produce white spots.

In considering solidification whites spots, all of the factors discussed previously with respect to stability of the thermal, fluid flow, and electrical environments are applicable here. The time scale associated with defects (1-10 minutes) effectively eliminates short-term process fluctuations from consideration. However, a large number of fluctuations remain which are of appropriate time scales. The previously discussed contact area variations are one such source. Observations of ingot surface condition and thermal analyses of VAR crucibles confirm that changes in contact condition and heat transfer can last several tens of minutes. In addition to the thermal considerations, local changes in current path, due either to contact changes or arc fluctuations, can severely disturb the local fluid flow conditions. Even if the steady-state fluid flow remains dominated by thermal buoyancy, local electrical conditions can result in intense, isolated MHD driven cells. As previously stated, the importance of a stable diffuse arc, which is typically maintained via tight gap control cannot be over emphasized.

EXPERIMENTAL PROGRAM

Solidification white spots are presently the subject of much debate, concern, and research in the superalloy community. In addition to questions about their formation, their effect on mechanical properties remains in question. Both questions are currently being investigated by the ASM White Spot Committee, and are the subject of research at Sandia National Laboratories. The preceding discussion on the interrelation of solidification white spots and the VAR process was based on assumptions put forth by Maurer (1), Mitchell (2), and Evans (3). These assumptions are that a) solidification white spots are, in fact, local areas with a slightly coarsened dendrite structure and slightly reduced Nb and Ti content, b) the etching response of solidification white spots is due to a coarsened grain structure produced in thermomechanical processing, and c) that these defects result from local perturbations in the solidification process that may be described in terms of thermal gradient and solidification velocity, as shown schematically in Figure 2.

An experimental program has been initiated to develop a better understanding of the third of these assumptions. The intent of this program to characterize the solidification stability of Alloy 718 and compositional variants with respect to typical VAR process conditions. A laboratory scale, high temperature vacuum furnace has been modified to allow the study of solidification under thermal conditions similar to those which occur during VAR. The goals of the program are to:

- Establish well characterized steady state solidification conditions, then characterize the corresponding solidification behavior and structures;
- Perturb the steady state conditions to encompass variations over the range of VAR solidification conditions;
- Perform identical experiments with alloy variants in order to observe the effects of composition, i.e. to assess the sensitivity of white spot precursor formation to alloy chemistry variations;
- Assess the importance of solidification parameters on the formation of potential white spot precursors and relate these to conditions which occur during solidification of VAR ingots.

This program is concentrating exclusively on the parameters associated with growth rate and thermal gradient. The use of a directional solidification configuration and the absence of an arc or induction fields minimizes thermal buoyancy and MHD driven fluid flows respectively, allowing a stable compositional gradient to be established for each set of conditions. Cylindrical specimens approximately 140 mm long and 18.5 mm diameter are placed on a water-cooled hearth in a tubular alumina crucible. The thermal gradient is established by varying the liquid superheat at the specimen top, and growth rates are controlled by controlled withdrawal of the specimen and/or controlled reduction of the furnace power. The furnace also has a movable water cooled copper hearth which can be lowered rapidly into a molten indium-tin-bismuth quench bath to freeze partially solidified structures and capture compositional gradients surrounding the dendrites. An initial series of experiments has been performed in which specimens were solidified under conditions selected to approximate a 610 mm (24") diameter VAR ingot at melt rates of 1.8, 3.6, and 7.2 kg/minute (4, 8, and 16 pounds/minute, respectively). Specimens were withdrawn at rates of 0.76 mm/minute, 1.52 mm/minute, and 3.05 mm/minute (0.03, 0.06, and 0.12 inches/minute), through a thermal gradient of approximately 3.5°C/mm. Growth rates closely matched the withdrawal rates for the two slower speeds but the growth rate corresponding to the fastest withdrawal rate was measured to be about 1.78 mm/minute (0.07 inches/minute), corresponding to a melt rate of 4.3 kg/minute (9.4 pounds/minute).

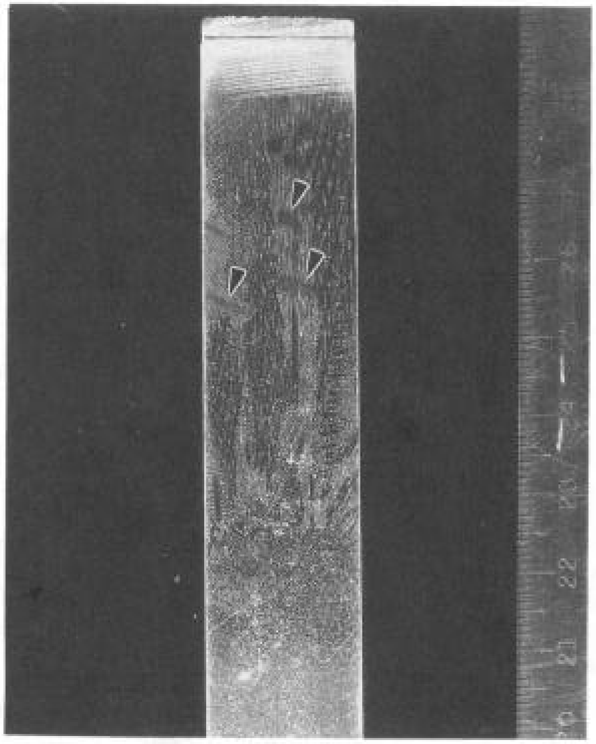

Figure 5. Centerline macrostructure of directionally solidified Alloy 718 bar showing grain structure similar to VAR ingot solidification structure. Withdrawal rate was 0.76 mm/minute. Several Nb lean areas are indicated. Scale is in mm.

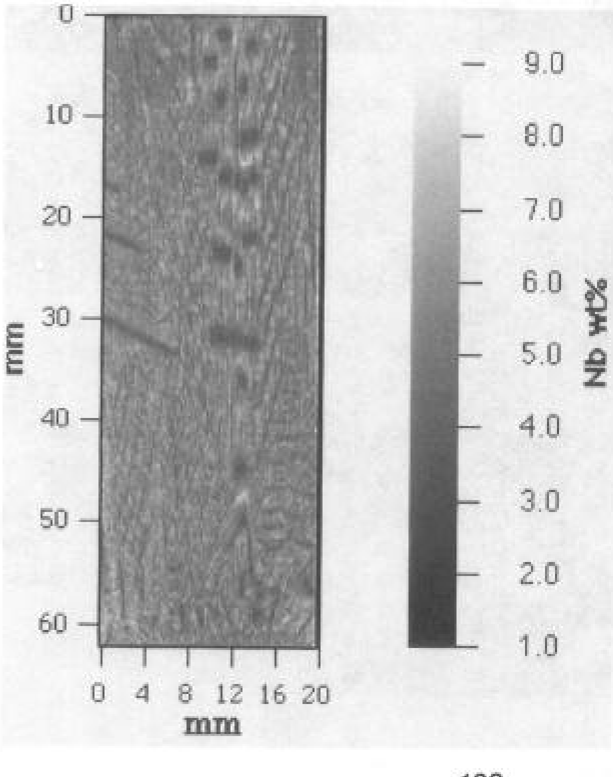

Figure 6. Quantitative x-ray fluoresence map of the same sample, showing Nb concentration variations and macroscopic Nb-lean areas.

The test specimens were sectioned and characterized using x-ray fluorescence (XRF), optical and electron microscopy. The initial goals of achieving directional solidification and approximating VAR ingot structures were achieved, Figure 5. Interestingly, XRF mapping revealed that some samples contain relatively large Nb-lean areas, having Nb concentrations approximately 2-3% lower than the bulk chemistry, as shown in Figure 6. The corresponding Mo, Cr, Fe, and Ni XRF maps indicated that such areas are slightly enriched in Cr and Fe. Metallographic analysis of the specimens also revealed that the primary dendrites are continuous across the Nb-lean areas, Figure 7, but these areas do have a coarsened dendritic structure, or apparently reduced amount of interdendritic structure, Figure 8. Although these results reflect only a preliminary examination of the initial specimens, it is interesting that areas were produced which have some of the characteristics believed to be associated with solidification white spot precursors. Future work will include continued evaluation of the initial test specimens and future experiments in which a) specimens are subjected to perturbations in the solidification rate; b) specimens are quenched and the compositional gradients characterized both before and after the perturbations; and c) compositional variants of 718 are used.

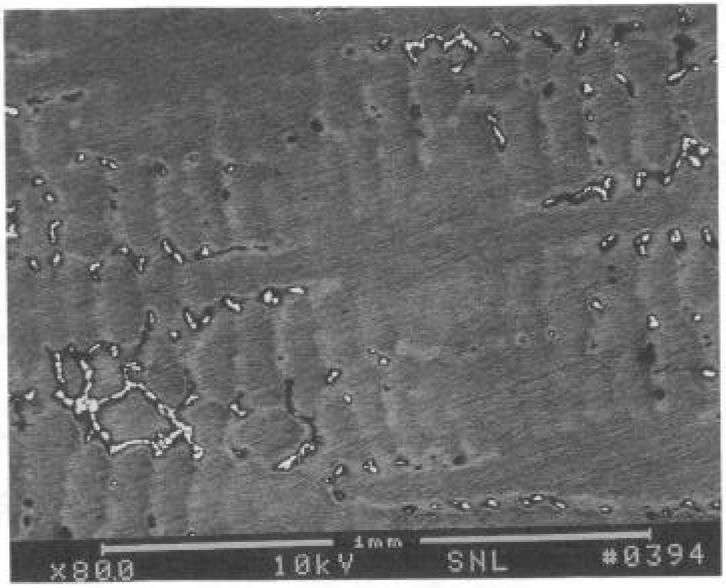

Figure 7. Backscattered electron micrograph of a large Nb-lean area, showing the significant decrease in interdendritic fluid present in such areas. The scale of the primary dendrites compared to the lean area is evident, as is the continuity of the primary dendrites across the area.

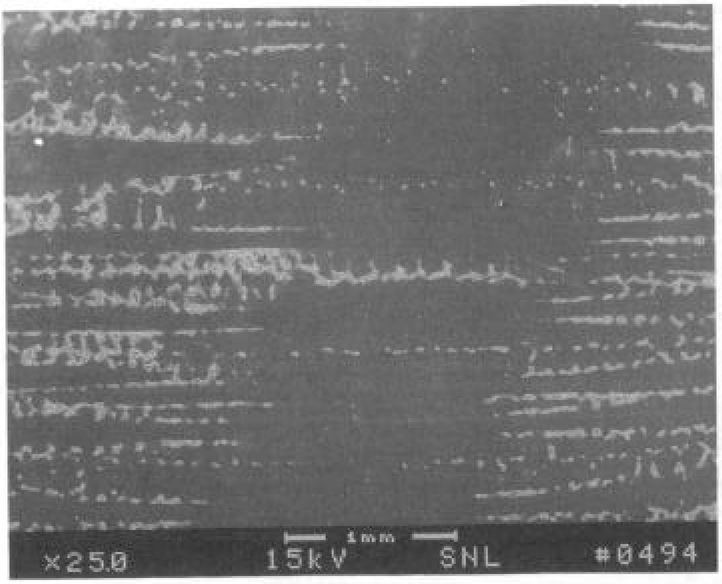

Figure 8. Secondary electron image of a large Nb-lean region taken from area of sample of Figures 6 and 7 showing reduced amount of interdendritic fluid.

SUMMARY

White spots are a large and growing concern in the superalloy community, and the focus of a great deal of research. In many cases, white spots are uniquely associated with VAR processing, precipitating the inclusion of an intermediate ESR melt step in critical materials and a desire, in some cases, to eliminate VAR altogether. Recent studies of white spots have resulted in a new level of understanding of their characteristics and formation mechanisms. This understanding, combined with a fundamental understanding of the VAR process, a large experience and data base, and newly developed simulation techniques, provide powerful tools for the critical evaluation and further development of VAR processes. In this paper, we have attempted to take a first look at the currently accepted characteristics and sources of white spots with respect to the physical processes occurring during VAR and to relate these, if possible, to specific operational considerations. At present, there are no easy ways to eliminate white spots in VAR material without causing other, equally undesirable consequences. However, if we are successful in defining white spot formation in terms of the physical processes occurring in VAR, numerical simulations will permit parameters to be carefully evaluated with respect to their effects on the critical physical processes. An experimental program has been begun to address these issues, and the initial results suggest that this approach may be a viable means of building the necessary knowledge base.

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