

EFFECTS OF CHEMISTRY ON VADER PROCESSING OF

NICKEL BASED SUPERALLOYS

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ABSTRACT

VADER's unique solidification mechanisms produce continuous cast ingots characterized by a relatively fine equiaxed grain structure. The understanding of these mechanisms and how they are affected by various alloy and process modifications is essential to the optimization of VADER casting. In addition, this information will enable the formulation of new alloys which can fully utilize the capabilities of VADER.

This study was designed to elucidate how alloy variations alter the response of VADER casting. Alloy chemistries were designed to alter the volume of interdendritic fluid and the amount of carbide phase present during the final stages of solidification. Five heats of modified UDIMET® Alloy 720 were VIM/VAR/VADER processed. They included three heats containing 0.01, 0.03 and 0.06% carbon and two heats containing 1% of a carbide stabilizer, niobium, with 0.01 and 0.02% carbon. Analysis included characterization of ingot solidification and determination of the structural and chemical uniformity of the ingot at various radial locations.

It was observed that the 1% addition of a carbide stabilizer effectively reduced chemical and structural gradients near the ingot surface. Alloys with intermediate carbon levels of 0.02 and 0.03% produced relatively uniform ingots while alloys with high and low levels, .06 and .01%, exhibited substantial structural gradients. Intermediate carbon in combination with the addition of a carbide stabilizer produced an ingot which exhibited less of a chemical gradient than a typical VAR ingot of the same size.

Observations were made that increased the understanding of VADER solidification mechanisms and clearly defined useful parameters to develop alloys specifically for VADER processing.

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INTRODUCTION

Vacuum arc double electrode remelting (VADER) is a unique casting technology that is capable of producing uniform fine grained ingots of various superalloys, including P/M type alloys that could not be made using conventional cast-wrought technology. What makes VADER unique is that casting is carried out at temperatures slightly below the liquidus. Semimolten metal, dispersed with solid nuclei, is dripped into the mold where solidification proceeds with the formation and growth of fine equidirectional dendrites. VADER's characteristic fine grained cellular structure results not from rapid solidification but from the simultaneous growth of many evenly dispersed solid nuclei in a low temperature gradient. A relatively slow rate of solidification avoids the formation of microporosity associated with other fine grained casting techniques (1,2) by allowing the intercellular flow of liquid metal.

Previous literature (3-6) comparing the microstructure of VADER ingots to those of ESR and VAR indicates that VADER ingots, are in general, more homogeneous. However, sharp chemical and structural variations have been observed near the surface of VADER ingots. These variations are the result of an interaction between the solidifying ingot and the rapidly cooled solid ingot surface, whereby microporosity in this outer skin is filled by the drawing of interdendritic fluid from the semi-liquid region inside the solid-mushy zone interface.

It follows that the observed surface inconsistencies can be controlled by increasing the resistance to intercellular liquid flow. Previous work indicates that minor chemistry variations can effectively alter the permeability of the mushy zone (7). It is anticipated that increasing carbon and/or increasing the stability of the carbides formed will reduce chemical and structural gradients by decreasing this permeability. The following report explores the effectiveness of these modifications in controlling chemical and structural gradients in VADER ingots.

EXPERIMENTAL PROCEDURE

Five 200 Kg heats with chemistries given in Table I, were VIM/VAR/VADER withdrawal cast as 20 cm diameter ingots. All alloys were modifications/versions of the high strength nickel based superalloy UDIMET Alloy 720. Alloys 1 and 3 are low and high C versions, respectively. One percent niobium was added to Alloys 4 and 5 for carbide stabilization. Alloy 4 was a low C version and 5 had an intermediate carbon level; both alloys had a reduced level of chromium in order to prevent the formation of sigma phase.

Transverse sections were cut from each ingot at a location representative of the steady state portion of the continuous cast ingot (approximately 50 cm from the bottom of the ingot). Center-to-edge micros were prepared for the determination of structural uniformity and phase identification. Chemical analysis and differential thermal analysis (DTA) were subsequently performed at several radial locations for each heat.

TABLE I. ALLOY CHEMISTRIES (Wt%)

#	Ni	Co	Cr	Mo	W	Nb	Ti	Al	B	Zr	C
1	BAL	14.9	17.9	3.1	1.2	---	5.0	2.5	.031	.030	.007
2	BAL	14.9	17.9	3.1	1.2	---	5.0	2.5	.032	.030	.033
3	BAL	14.9	17.9	3.1	1.2	---	5.0	2.5	.031	.031	.061
4	BAL	14.5	14.6	3.0	1.2	1.0	4.9	2.5	.031	.029	.010
5	BAL	14.5	14.6	3.0	1.2	1.0	4.9	2.5	.030	.030	.023

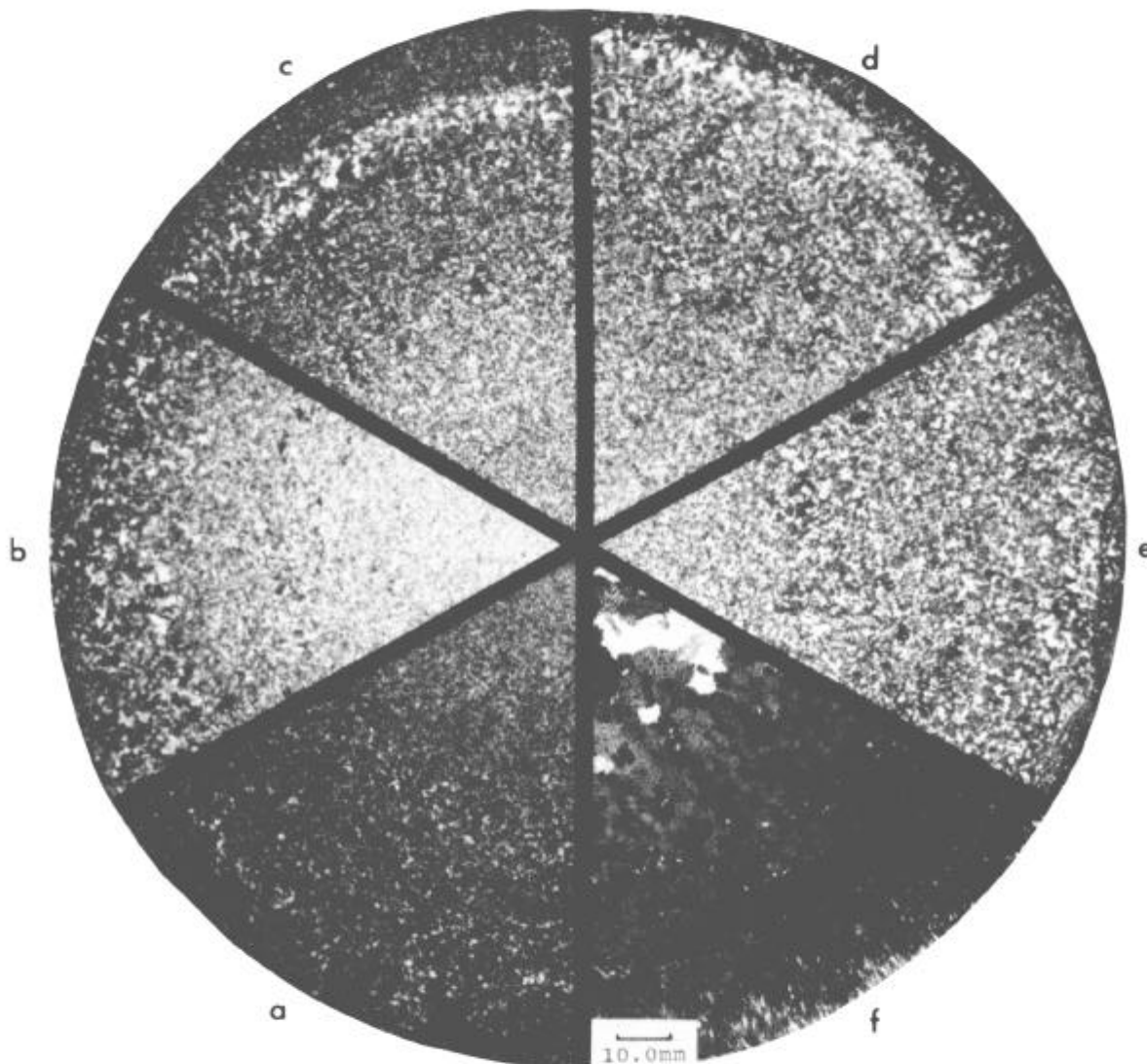


Figure 1. VADER ingot macrostructures, etched in HCl and hydrogen peroxide. a) Alloy 3 (high C) b) Alloy 2 (standard U-720) c) Alloy 1 (low C) d) Alloy 4 (low C and carbide stabilized) e) Alloy 5 (carbide stabilized) f) U-720 VAR ingot.

RESULTS

A comparison of the as cast VADER macrostructures (Figure 1) revealed a definite effect of carbon on the structural uniformity of the ingot. The low carbon heat (Alloy 1) showed the most severe grain size variation while Alloys 2 and 3 exhibited only slight variations. The effect of carbide stabilization was also obvious. The carbide stabilized low

carbon heat, Alloy 4, showed much less grain size variation than the low carbon heat, Alloy 1. Likewise, the carbide stabilized heat, Alloy 5, was more uniform than the standard heat, Alloy 2. Alloy 5 produced the most uniform grain structure of all the heats observed.

Typical center-to-edge microstructures of VADER ingots are exhibited in Figure 2. At a depth of about 0.6cm beneath the ingot surface, the structure consists entirely of fine irregularly shaped grains. At 1.2cm into the ingot, these irregular grains have been partially replaced by a fine dendritic structure. At a depth of 1.8cm, the structure was observed as dendritic with a cellular appearance. The micrograph taken at 5 cm is representative of the remainder of the ingot and shows the characteristic VADER fine equiaxed cellular grain structure.

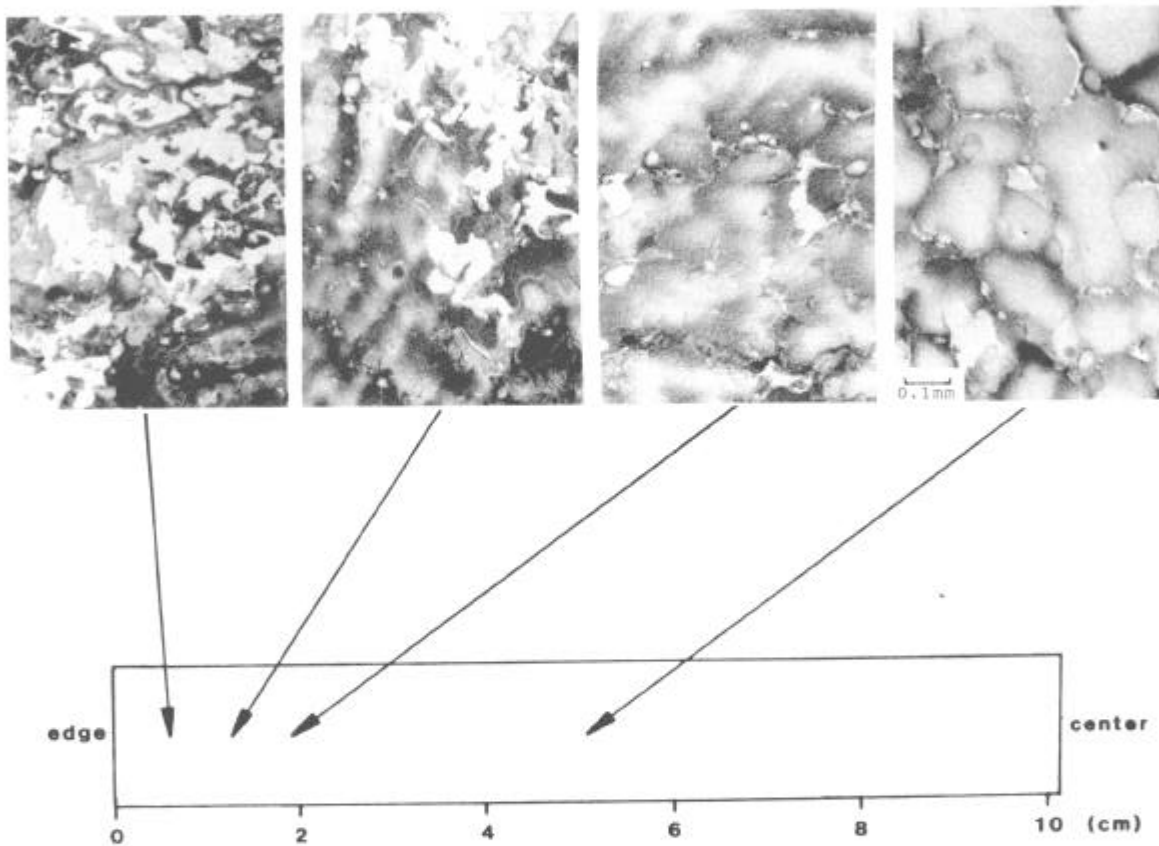


Figure 2. Typical center-to-edge VADER microstructure of UDIMET Alloy 720. Transverse section, Kalling's etch. Drawing shows approximate location of photomicrographs.

The variation of titanium with respect to location (Figure 3) further emphasizes the effect of carbide stabilization on ingot uniformity. These heats, Alloys 4 and 5, exhibit noticeably flatter chemical profiles than their non-carbide stabilized counterparts. As expected, increasing carbon content from a low level, 0.007%, to an intermediate level, 0.033%, dramatically reduced the chemical gradient. However, increasing carbon to a high level, 0.061%, resulted in an obvious chemical gradient which was not observed in the macrostructure. Again the carbide stabilized heat, Alloy 5, exhibited the most uniform center-to-edge chemistry, comparable to a typical VAR ingot of the same size.

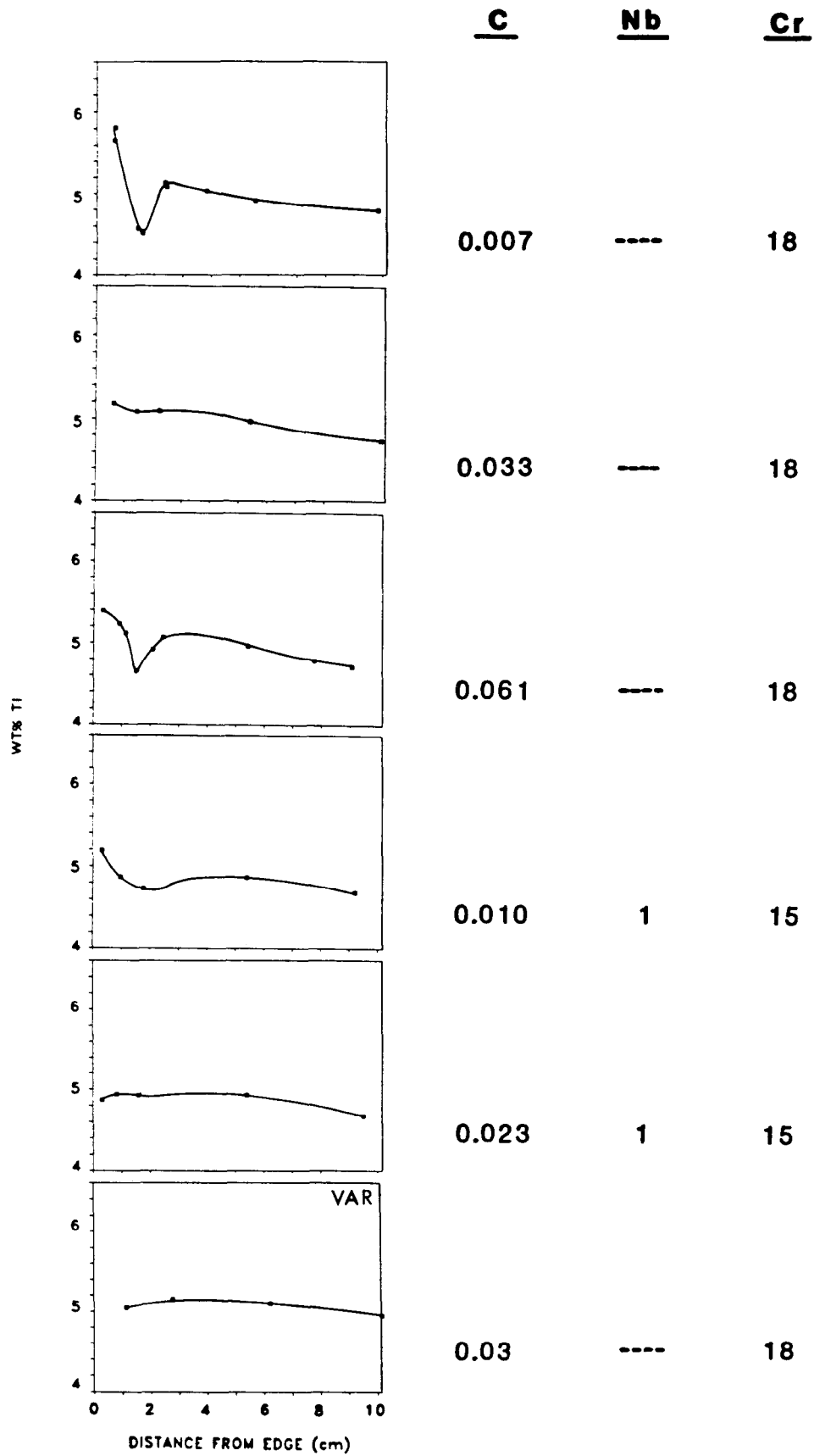


Figure 3. Titanium concentrations of VADER ingots as a function of center-to-edge location. The titanium profile for a VAR ingot is also given for comparison.

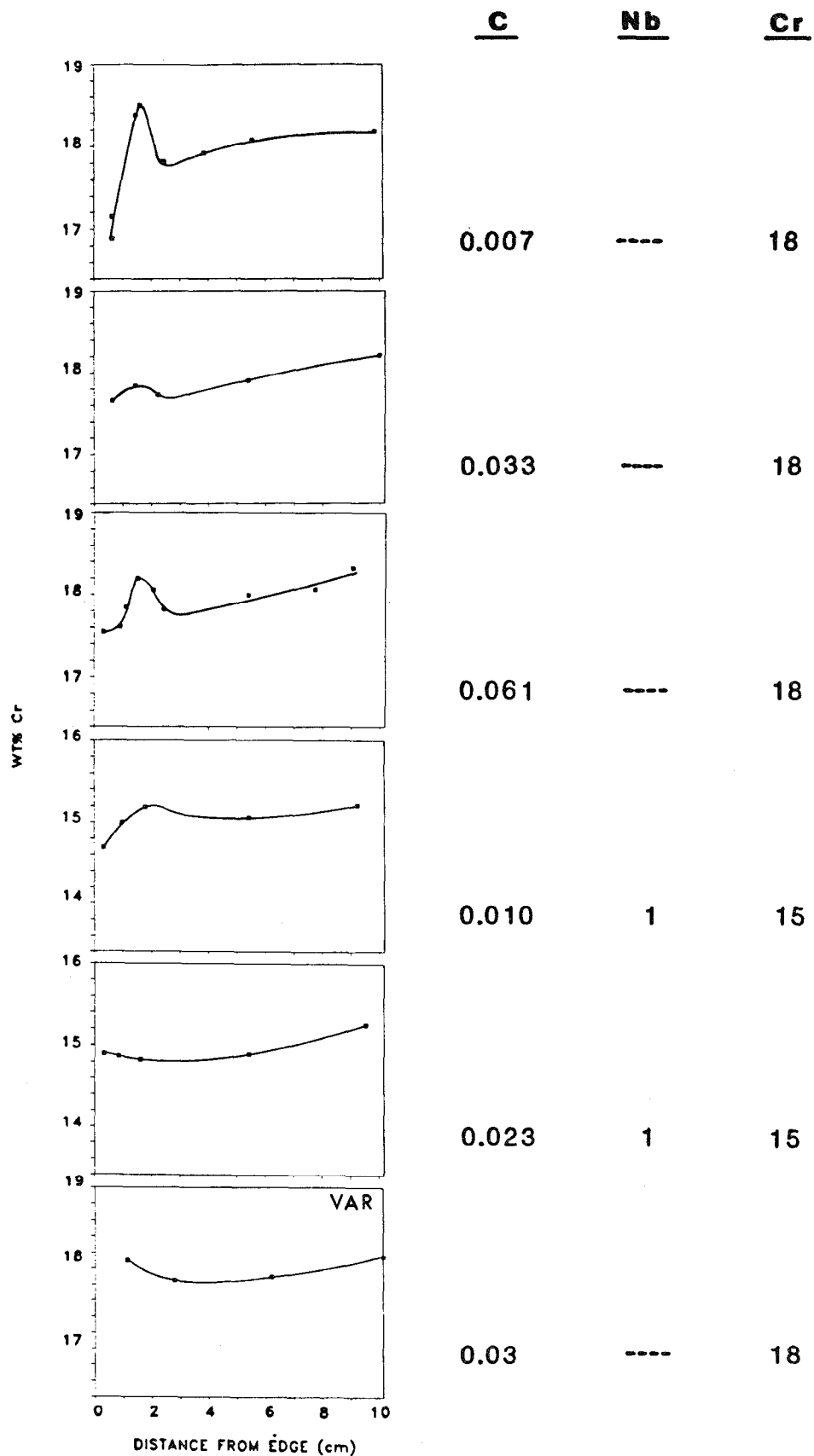


Figure 4. Chromium concentrations of VADER ingots as a function of center-to-edge location. The chromium profile for a VAR ingot is also given for comparison.

The variation of chromium content, Figure 4, exhibited the same trends as titanium but in the opposite direction (i.e., high levels of chromium were observed where low levels of titanium existed). This is due to the relative increase in chromium content as titanium-rich intercellular liquid metal moves toward the surface of the ingot, leaving the chromium-rich primary cellular dendrites in the interior.

The micrographs in Figure 5 represent typical cast microstructures of Alloys 1, 3, 4 and 5 (photos A, B, C and D respectively). SEM-EDX analysis of each ingot revealed that all alloys contained phases similar to VAR cast UDIMET Alloy 720, including eutectic gamma-gamma prime, primary borides, titanium-rich MC-type carbides and small amounts of eta, and that these structures were not noticeably affected by changes in carbon content. The precipitation of titanium-rich globular gamma prime and acicular eta phases (light phases in Figure 5) was greatly increased by the addition of niobium. In addition to increased amounts of globular gamma prime and eta, carbide stabilized alloys also exhibited MC-type carbides containing equal amounts of titanium and niobium. In general, all ingots contained porosity comparable to VAR ingots.

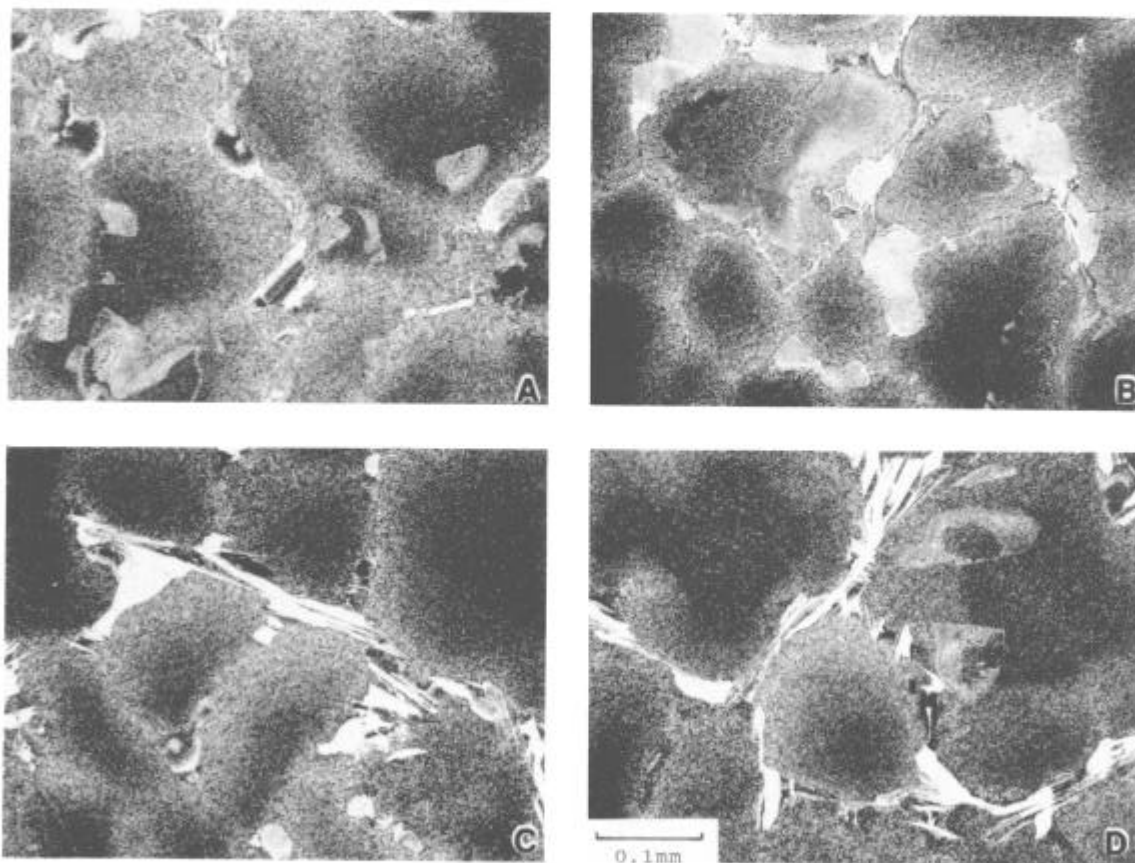


Figure 5. Midradius microstructures. A) Alloy 1 (low C) B) Alloy 3 (high C) C) Alloy 4 (low C and carbide stabilized) D) Alloy 5 (carbide stabilized).

The DTA results for each alloy, in the VIM cast condition, are presented in Table II. The data from Alloys 1, 2 and 3 shows that carbon depresses the solidus temperature, T_s , but does not alter the liquidus, T_l , or incipient melting points,

I.M.. As a result the melting range, T_1 - T_s , increases with carbon. Alloys 4 and 5, however, do not demonstrate this carbon effect. Both alloys exhibit a melting range of about 90°C.

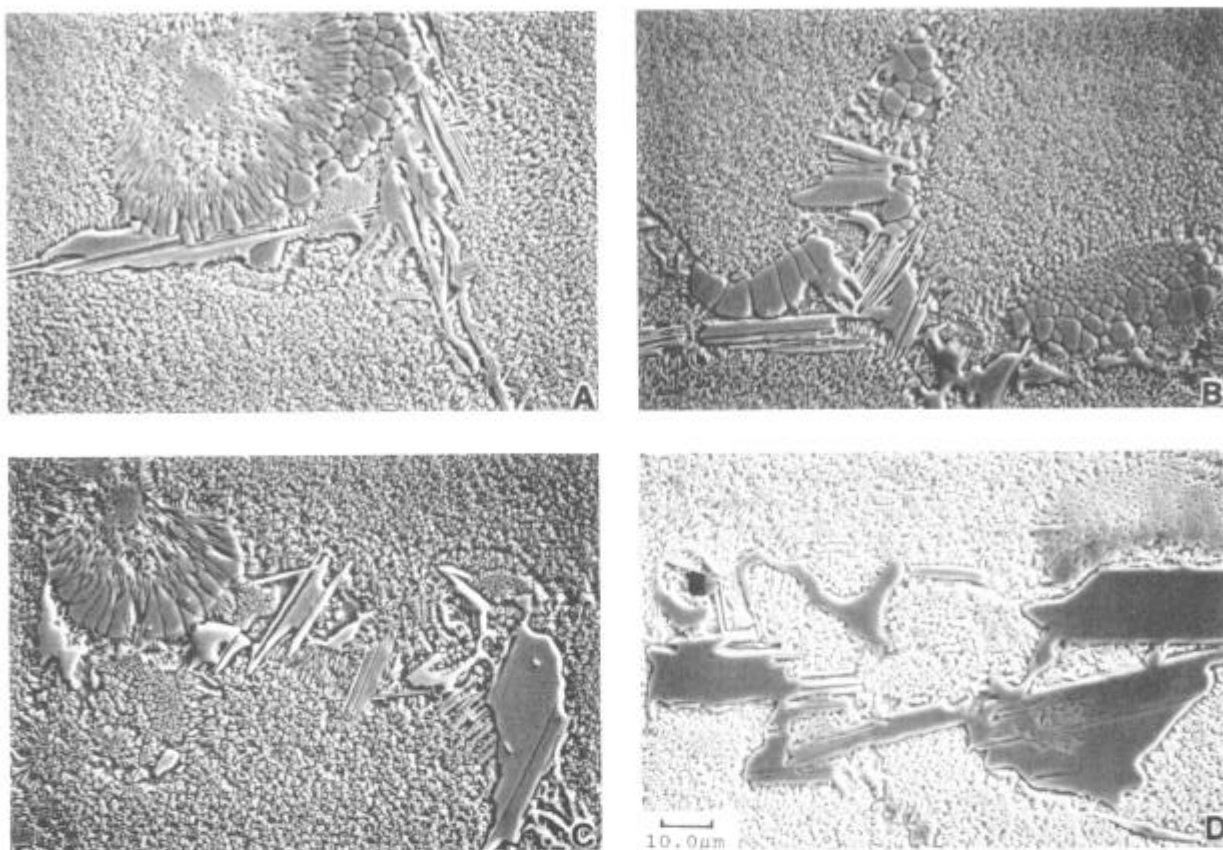


Figure 6. Midradius SEM micrographs of VADER ingots showing observed phases. A) Alloy 1 (low C) B) Alloy 2 (standard U-720) C) Alloy 4 (low C and carbide stabilized) D) Alloy 5 (carbide stabilized).

TABLE II. DTA RESULTS FROM VIM CAST ALLOYS (°C)

ALLOY #	T_1	T_s	$T_1 - T_s$	I.M.
1	1331	1242	89	1172
2	1334	1233	101	1158
3	1332	1222	110	1168
4	1338	1246	92	1173
5	1333	1246	87	1172

DISCUSSION

The mechanisms by which chemical and structural gradients are thought to form during VADER solidification are based on the flow of intercellular liquid to the surface. The driving forces for this material transport include shrinkage of the solid surface, centrifugal forces and thermal gradients. VADER casting basically consists of dripping semimolten metal into a rotating water-cooled mold. Material in contact with the mold wall is rapidly cooled, forming a thin solid layer and establishing a steep thermal gradient. As this skin shrinks, micropores are formed which draw liquid from the contained

solid+liquid mass. Further shrinkage results in the separation of the skin from the mold wall causing a reduction in the thermal gradient and a decrease in the rate of solidification. The advancement of the solid+liquid interface is greatly reduced, effectively increasing the extent of liquid flow by extending the time for material transport.

Current technology is not capable of eliminating these thermal and solidification gradients. However, chemical gradients may be reduced by other means, such as reducing melting ranges or by impeding liquid flow. Narrower melting ranges reduce gradients by limiting the amount of liquid available for filling the interdendritic gaps at the rapidly cooled surface. Higher concentrations of carbides or other precipitates stable during solidification reduce chemical gradients by impeding the flow of liquid in the intercellular region.

Additions of carbon increase both the concentration of carbides and the melting range. The combined effects of these opposing properties are evident in Alloys 1, 2 and 3. Alloy 1 contained an insufficient concentration of carbides; as a result, intercellular liquid flow was not effectively inhibited during solidification. Even with the benefit of a relatively narrow melting range, a steep chemical gradient was observed. At high levels of carbon (Alloy 3) the increased carbide concentration was incapable of overcoming the effect of a relatively broad melting range. The carbon level of Alloy 2 produced sufficient carbides to control liquid flow without deleteriously increasing the melting range; as a result, a relatively smooth chemical profile was produced.

Carbide stabilization was expected to increase the range of temperatures at which carbides could impede liquid flow. This particular study employed niobium as a carbide stabilizer; however, it is anticipated that other elements such as tantalum or vanadium could also be effectively used. The improvement in chemical uniformity through the addition of niobium is observed in the comparisons of Alloy 1 with 4 and Alloy 2 with 5. Both low carbon Alloys, 1 and 4, exhibited steep chemical gradients due to insufficient amounts of carbides; however, the carbide stabilized alloy produced a noticeably smoother chemical profile. Comparing the chemical uniformity of Alloys 2 and 5 further demonstrated the benefit of carbide stabilization. The addition of niobium also eliminated the detrimental effect of carbon on the melting range. It appears that the formation of stable carbides effectively removes carbon from solution, thereby eliminating the melting range effect.

Although the addition of niobium enhanced the VADER processibility, it also resulted in an increase in the formation of globular gamma prime and eta. The effect of these phases on mechanical properties has not been determined, but it is expected that, if they cannot be eliminated by thermomechanical processing, they will decrease the strength of the alloy by virtue of tying up gamma prime formers. A simple chemical equivalence calculation shows that only about 0.25 wt% niobium is required to form NbC with all of the available carbon. The niobium-bearing carbides observed contained approximately equal amounts of titanium and niobium.

Therefore, it is possible that about 0.13% niobium would be sufficient to stabilize the carbides. This would effectively reduce the tendency of the alloy to form globular gamma prime and eta as well as stabilize the alloy with respect to sigma formation. PHACOMP calculations suggest that a niobium content of about 0.15% would be stable at chromium levels on the order of 17.5%.

CONCLUSIONS

The chemical and structural uniformity of VADER withdrawal cast ingots can be altered by alloy modifications. Modifications, which affect the relative amounts and stability of precipitates or affect the amount or characteristics of the liquid during solidification, can greatly influence the relative structural and chemical uniformity of the ingot.

Insight into the relationships of alloy chemistry and VADER uniformity clearly demonstrates the potential for alloy design to optimize the process.

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