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Optimal Beam Pattern to Maximize Inclusion Residence Time in an Electron Beam Melting Hearth*

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Abstract

Approximate probabilities of inclusion survival through an electron beam melting hearth are computed from nitride dissolution rates, flotation velocities, and residence times. Dissolution rates were determined by measuring shrinkage rates of pure TiN and nitrided sponge in small pools of molten titanium in an electron beam melting hearth. Flotation velocities were calculated using correlations for fluid flow around spheres, and show that particles sink or float unless their densities are extremely close to that of molten titanium. Flow field characteristics which lead to effective inclusion removal are discussed in terms of heat flux pattern required to produce them, based on the electron beam's unique ability to impart a nearly arbitrary heat flux pattern to the melt surface.

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I. Introduction

Because of its reactivity, molten titanium has always put us in an interesting position with regard to inclusions: it can dissolve small inclusions easily, but large inclusions cannot be filtered, for the melt would dissolve the filter. These large inclusions therefore represent a threat to the mechnaical properties of anything made from the metal, to the extent that three vacuum remelt steps are required to eliminate a satisfactory fraction of them to qualify the material for use in aircraft engines.

The recent increased use of hearth melting processes goes a long way toward solving this problem, as the cold hearth traps high-density and hard-α inclusions which would otherwise sink to the bottom of the molten pool in vacuum arc remelting. For this reason, studies like this one are being conducted to characterize the inclusion removal performance of hearth melt furnaces and make improvements where possible.

For a given inclusion, three random variables can be said to govern its probabilitiy of survival: its size, density and residence time in the hearth. Size correlates with dissolution time; size and density determine buoyancy force and drag which in turn give terminal rising/falling velocity; and if residence time is greater than either the dissolution or flotation time then the inclusion will not enter the final product.

In the experimental section, we present data on dissolution rates of pure TiN and nitrided sponge which can be used to calculate inclusion dissolution time. In the next section, we calculate terminal floating/sinking velocity as a function of size and density based on well-established drag correlations for spheres. Based on this analysis, we conclude that only a very small fraction of inclusions can be considered "neutral density" such that they will not float or sink while passing through the hearth.

In the last section, we discuss the use of rapid scanning capabilities of electron beams to control surface temperature and Marangoni surface tension gradients, which allows for some degree of flow field control to prevent inclusions from leaving the hearth.

II. TiN Dissolution Rate

A. Experimental Procedure

Dissolution rates of pure dense titanium nitride and Timet nitrided sponge (15 wt% nitrogen) in molten titanium were measured in the Sandia National Laboratories electron beam melting furnace. Rods of each material $\frac{3}{8}''$ (0.95 cm) long and $\frac{1}{8}''$ (0.32 cm) in diameter were fabricated, inserted into holes drilled $\frac{1}{2}''$ (1.27 cm) deep into the c.p. titanium hearth, and covered with a $\frac{1}{8}''$ (0.32 cm) plug of titanium, as shown in figure 1a. These holes were arranged as shown in figure 1b.

The furnace's 250 kW electron gun was then used to melt small pools of titanium around the nitride rods. Spot diameter was approximately one inch (2.54 cm) and the gun was run at a power of 35 kW. The beam was switched between the small molten pools, where it spent 4.2% of its time, and a larger pool visible at the left side of the hearth in figure 1b, so that only 1.5 kW of power was directed at the pools. Switching frequency between the two molten pools was 21 Hz. Metal over the rods was kept molten for 5 to 60 minutes.

Blocks of metal containing the nitride rods were cut from the hearth and sectioned in order to measure the length of undissolved rods. Two such sections can be seen in figure 1c and 1d, including one pure nitride rod and one nitrided sponge rod. The difference

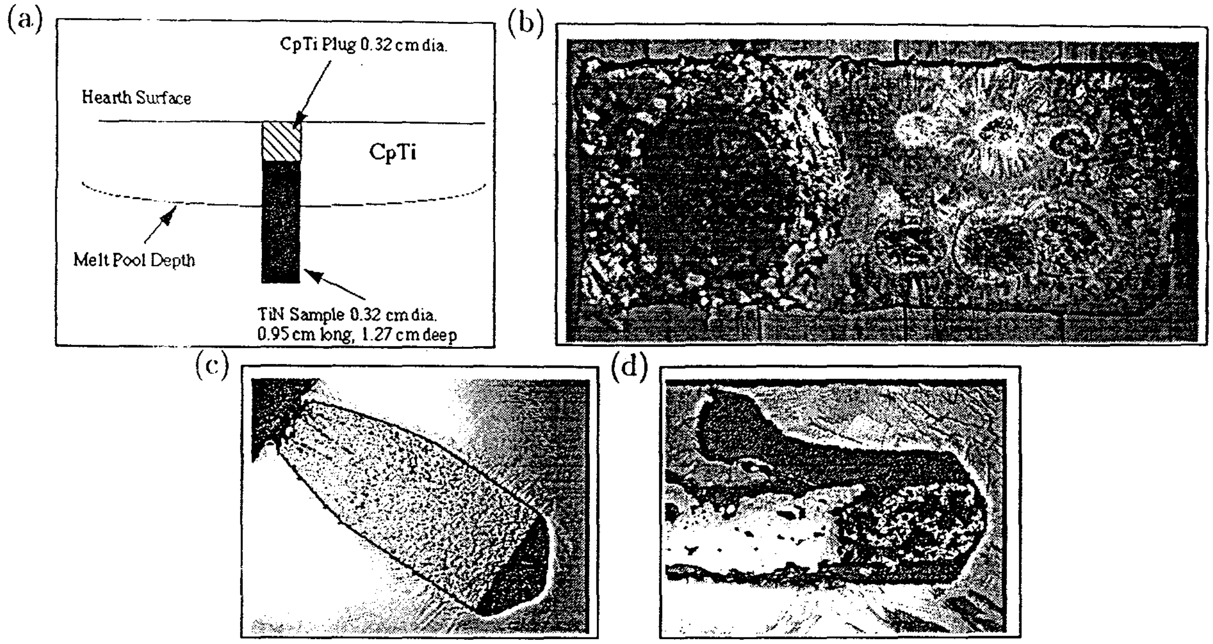

Figure 1: (a) Schematic diagram showing nitride rod placement in the titanium hearth; (b) Hearth top view showing location of molten pools after an experiment; (c) TiN rod after 10 minutes in the melt; (d) Nitrided sponge rod after 2 minutes in the melt.

between prior length and dissolved length is shown as a function of dissolution time in figure 2 for both types of nitride rods.

Examinations of the Ti/particle crossections after melt showed that the pool depths, as depicted in figure 1a, increased with exposure time. This was caused by a gradual increase in the solid hearth temperature below the pool. The pool depths never extended below 1.27 cm, since in all cases the bottom of the particle remained fixed in its original location.

B. Results

The dissolution time and dissolved length for pure nitride exhibit a linear relationship

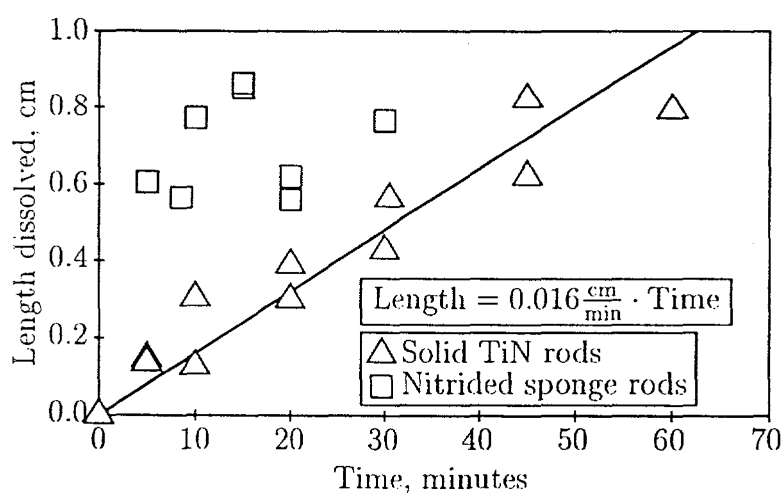

Figure 2: Titanium nitride dissolution rate.

with a dissolution rate of approximately $6.25 \times 10^{-3} \frac{\text{in}}{\text{min}}$ $\left(0.16 \frac{\text{mm}}{\text{min}}\right)$. Nitrided sponge dissolution data do not show such a clear correlation, but dissolution rates for sponge rods are all at least 50% higher than those of pure nitride.

III. Inclusion Flotation

Flotation is the primary method of separating out large inclusions. Inclusions which sink remain on the bottom of the melt pool until they dissolve; similarly, particles which rise to the surface can be kept from passing through the hearth by using Marangoni forces to manipulate surface flows. The large neutral-density particles are therefore of greatest concern, as they do not completely dissolve, sink or float.

Roughly speaking, an inclusion floats (sinks) if its rising (falling) velocity is greater than the hearth depth divided by residence time. Hearth depth is easily measured, and residence time readily estimated, and so it remains only to calculate the flotation velocity.

Flotation velocity of nitride inclusions can be estimated using the well-known empirically determined relationship between friction factor and Reynolds number in flow past a spherical particle, which is shown in figure 3. The friction factor f is the ratio of drag force F to the product of particle cross-section area A and dynamic pressure $\frac{1}{2}\rho u^2$ (ρ is the fluid density and u the particle velocity relative to the fluid). The Reynolds number is defined here as $\frac{\rho u D}{\mu}$, where D is the particle diameter and μ the fluid viscosity. Drag force is thus given by

$$F = f(\text{Re}) \cdot \frac{1}{2}\rho u^2 \cdot A \tag{1}$$

For non-spherical particles, the friction factor is usually lower than that of the smallest sphere which contains it (always lower in Stokes flow), particluarly if there are edges which promote flow separation.

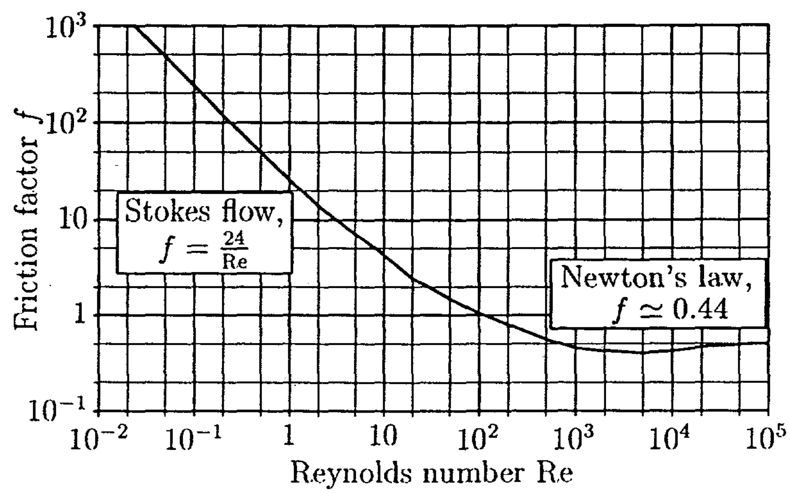

Figure 3: Friction factor vs. Reynolds number for flow past a sphere (from Bird, Stweart and Lightfoot [1]).

If the melt is stagnant, the particle quickly reaches a terminal rising or falling velocity, which can be calculated by setting drag force equal to buoyancy force $(\rho_p - \rho)gV$ where ρ_p is the average inclusion density. Substituting in the volume and cross-section area of a sphere gives the result

$$\frac{\pi}{6}D^3(\rho_p - \rho)g = f(\mathrm{Re}) \cdot \frac{1}{2}\rho u^2 \cdot \frac{\pi}{4}D^2 \tag{2}$$

which simplifies to

$$(\rho_p - \rho)gD = \frac{3}{4}\rho u^2 f(\mathrm{Re}) \tag{3}$$

Figure 4 shows a few calculated terminal velocity contours plotted in density-diameter space, with an assumed melt density of 4.1. For a given pool depth and residence time, one can divide them to find the approximate minimum velocity for complete flotation/sinking, and the inclusions whose density and size fall outside of that velocity contour on the plot have a very weak chance of surviving into the mold. (Many of those inside the contour will float/sink as well.) For example, for a hearth with 5 cm melt depth and minimum residence time of 20 seconds, any inclusions with rising/sinking velocity greater than 0.25 $\frac{\mathrm{cm}}{\mathrm{sec}}$ (i.e. whose density and size put it above the 0.25 $\frac{\mathrm{cm}}{\mathrm{sec}}$ contour) will almost definitely be removed.

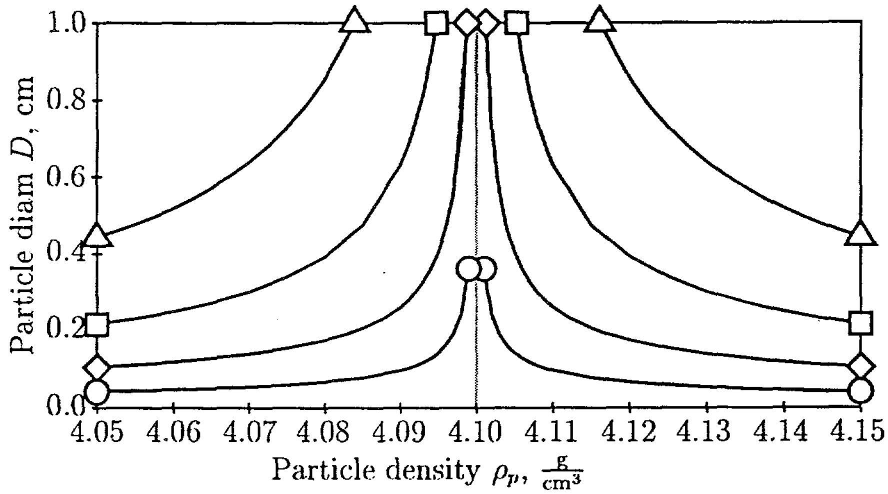

Figure 4: Terminal velocity contours for spherical particles in molten titanium: ○ $0.25\frac{\mathrm{cm}}{\mathrm{sec}}$, ◇ $1\frac{\mathrm{cm}}{\mathrm{sec}}$, □ $2.5\frac{\mathrm{cm}}{\mathrm{sec}}$, △ $5\frac{\mathrm{cm}}{\mathrm{sec}}$.

It is worth noting just how narrow that neutral density window is. Even if the relatively high flotation velocity of 1 $\frac{\mathrm{cm}}{\mathrm{sec}}$ is required for complete flotation, a 3 mm diameter inclusion must be within 0.01 $\frac{\mathrm{g}}{\mathrm{cm}^3}$ of the melt density in order to have a chance of survival. If such inclusions spend at least 10 minutes in the melt, even at the very low dissolution rate of pure TiN they are guaranteed to dissolve completely.

The advantage of hearth melting over vacuum arc remelting is also clearly shown here: all of the inclusions with density greater than the melt (those to the right of the gray line) will fall very quickly through the melt into the mushy zone, where they can act as nucleation sites for new grains.

IV. Beam Pattern Selection

Whereas everything presented until now has been general enough to apply to electron beam, plasma and vacuum arc melting, what follows is dependent upon the unique ability of electron beams to control heat flux distribution through the melt surface. Controlling fluid flow in electron beam melting is difficult but relatively straightforward: the beam's ability to impart arbitrary heat flux patterns to the melt surface gives the operator control over the top surface temperature distribution, with which one can drive fluid flow using Marangoni forces.

An important consideration to control against is the formation of a melt flow channel which takes molten metal through the hearth quickly, a phenomenon known as "short circuiting". A second consideration which is necessary for the complete removal of floating inclusions is the presence of a region spanning the hearth in which fluid flow on the surface is entirely in the backwards direction, so it sweeps floating inclusions away from the pour spout. Third, it is important to minimize longitudinal mixing and unsteady or turbulent flow in order to prevent scattering of inclusions in the hearth.

Beam patterns which accomplish these goals should have strong heating in the region near the hearth exit, with a gentle gradient to a relatively even power distribution over the rest of the hearth. Scan frequencies should be high in order to minimize flow transients and excess evaporation.

Because of the high power density required to melt material in the hearth, excess heat can result in strong Marangoni shear forces pulling the melt away from newly fed scrap, resulting in strong mixing. This is believed to be the cause for well-mixed conditions in the Sandia melting hearth [2]. For this reason, a well-designed hearth will have a barrier of some kind between the melting and refining regions so that unsteady mixing does not inadvertently spill over into the refining region.

V. Conclusions

Experiments characterizing dissolution rate of pure titanium nitride in liquid titanium yielded a dissolution rate of $0.16\frac{\text{mm}}{\text{min}}$. Sponge nitrided to 15 wt% nitrogen did not show an clear correlation, largely because of variations in porosity and nitride fraction in the nitride particles used.

Based on well-established drag correlations for flow past a sphere, it is shown here that nitride particles must have a density extremely close to that of liquid titanium in order to be considered "neutral density" such that they will neither rise to the surface nor sink to the bottom of a refining hearth melt pool. This results in a great advantage for hearth melting techniques since dense inclusions remain trapped in the bottom of the hearth instead of sinking vrey quickly into the mushy zone of the ingot.

Finally, effective removal of all inclusions requires that careful attention be paid to the flow field in the hearth so that low-density inclusions are directed away from the hearth exit. Transient flow, mixing, and stray flows from the melting region should be minimized in order to promote production of inclusion-free material. Such fluid flow control is possible by intelligent manipulation of electron beams to control surface temperature and thus Marangoni shear forces on the melt surface.

Acknowledgements

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[2] A. Powell, J. Van Den Avyle, B. Damkroger and U. Pal "Prospects for Titanium Alloy Composition Control by Electron Beam Scan Frequency Manipulation," *Proc. Conf. EBM&R State of the Art (1996).*