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An examination of the factors influencing the melting of solid titanium in liquid titanium

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ABSTRACT

The melting behavior of a solid in liquid titanium has been investigated with the aid of an Electron Beam Button Furnace (EBBF) to understand the phenomena contributing to the melting of exogenous solids introduced into liquid titanium during melt processing and casting. In this work, cylindrical rods of commercial purity (CP) titanium were dipped into a molten CP titanium pool for various periods of time to investigate the melting behavior in the absence of compositional effects. The dimensions of the dipped rods were measured before and after various immersion times allowing for quantification of the evolution of the solid/liquid interface and melting rate. The temperature within the dipped rod was also monitored during immersion to provide additional quantitative data on heat transport for analysis. The results show that the liquid titanium initially freezes onto the cold rod sample when it was immersed, resulting in the formation of a solid/solid interface between the immersed rod and the frozen titanium. It was found that the solid/solid interface exerts a significant resistance for heat transfer. After a short period of time, the frozen titanium melted followed by melting of the rod. A numerical model has been developed to describe the experimental process, the results of which are shown to correlate well with the experimental observations and measurements. Analysis with the model has confirmed that thermally induced buoyancy and, in particular, thermally induced Marangoni forces have a considerable impact on the transport of heat and momentum, and consequently on the melting kinetics. For the convenience of use in practical industrial-scale applications, effective interfacial heat transfer coefficients (EIHTCs) have been calculated based on the numerical model results. In addition, EIHTCs were also solved from the similarity solution after simplifying the problem description, showing that they can correlate satisfactorily if an appropriate reference temperature is selected.

1. Introduction

Primary melt processing of titanium and its alloys is utilized as a refining operation in addition to serving as a consolidation step. Ideally, the process is designed and operated to eliminate a number of feedstock related defects including high-density inclusions (HDIs) and high interstitial defects (HIDs) [1]. In addition, if not operated correctly, melt processing and the associated ingot casting process can give rise to Type II – alpha stabilized defects. These are Al-rich regions that occur in Al-bearing alloys like Ti6Al4V due to either excessive pipe formation toward the end of the casting process, improper ingot cropping (top removal) or a "drop-in" event, the latter being more relevant to the Electron Beam Cold Hearth Remelting (EBCHR) process [1]. The effective removal of HDIs, HIDs and material related to "drop-in" events hinges on understanding the kinetics of melting and/or dissolution of these materials in a given process.

Starting first with a broader look at the metallurgical industry as a whole, the melting/dissolution of solids (alloying additions) has been extensively studied in the steel industry. Example studies have considered both high and low melting point additions – i.e. alloys or metals with melting temperatures above liquid steel processing temperatures, such as titanium [2] and niobium [3], and below, such as aluminum [4]. It has been established that the melting/dissolution process basically consists of two distinct periods, the shell formation period and the free melting/dissolution period. The first is an initial transient associated with liquid solidifying onto the cold solid to form a shell. Once the shell melts, the second period, free melting/dissolution, begins. In this period, the melting/dissolution process can be controlled either by mass transfer, when the solid possesses a melting temperature higher that the liquid, or by heat transfer, when lower.

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Nomenclature

Symbol	Description
γ	surface tension, N/m
ε	emissivity, –
η	pseudo-similarity variable, –
θ	dimensionless temperature, –
μ	viscosity, Pa s
μ_x or μ_y	position of the center of the beam spot, m
ξ	transformed axial coordinate, –
ρ	density, kg/m^3
σ_{EB}	standard deviation of the Gaussian distributed EB power, m
σ_M	Marangoni stress, N/m^2
σ_{rad}	*Stefan–Boltzmann* constant, W/(m^2 K^4)
τ	stress tensor, Pa
$A_{s/l}$	area of the solid/liquid interface, m^2
C_P ($C_{P,e}$)	specific heat capacity (effective), J/(kg K)
D	diffusivity, m^2/s
D_{SV}	a microstructure dependent constant, m^{-2}
K_{perm}	permeability, m^2
L ($L_m, L_{\alpha/\beta}$)	specific latent heat (for melting and for α/β phase transformation), J/kg
Nu_x	local Nusselt number, –
P	pressure, Pa
Pr	Prandtl number, –
P_{EB}	EB power, W
$Q_{s/l}$	total amount of heat transported through the solid/liquid interface, J
Q_{rad}	heat transported by radiation at the rod's surface, J
Re_x	local Nusselt number, –
S_M ($S_{M,darcy}$)	momentum source term (for Darcy attenuation), kg/(m^2 s^2)
T	(T_{bulk}, $T_{mold,side}$, $T_{mold,bottom}$, T_{pool}, $T_{chamber}$, $T_{ceramic\,sheath}$, $T_{s/l}$) temperature (bulk liquid temperature, mold side temperature, mold bottom temperature, pool temperature, chamber temperature, ceramic sheath temperature, solid/liquid interface temperature), K
T_m	melting temperature, K
T_{ref}	reference temperature, K
U (U_{bulk})	velocity (bulk velocity), m/s
V (V_0)	volume of the remaining solid (original volume) of the immersed solid below the pool's surface, m^3
f	reduced stream function, –
f_{abs}	absorption factor, –
f_s or f_α	solid fraction or α phase fraction, –
f_{EB}	EB scanning frequency, Hz
h_{cnt}	contact heat transfer coefficient, W/(m^2 K)
h_{eff} or h_x	effective interfacial heat transfer coefficient or local interfacial heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
q_{EB}	heat flux input for EB heating, W/m^2
q_{cnt}	heat flux by contact heat transfer, W/m^2
$q_{s/l}$	heat flux through the solid/liquid interface, W/m^2
r_0, r_t, r_b, h_0 and l_c	dimensions of the transformed geometry (see Fig. 19 for details), m
r_{EB}	radius of the circular EB scanning pattern, m
r_V	melting ratio based on volume, –
t	time, s
x, y or r	distance in x, y or r direction, m
ΔT	temperature change at a given location during the time interval Δt, K
Δt	time interval, s
ΔV_s	volume change of solid during the time interval Δt, m^3

Turning to the titanium system, some relevant investigations have been carried out on the dissolution behavior of HDIs and HIDs in liquid titanium. For example, Ghazal et al. [5] dipped cylinders of tungsten and molybdenum (metals that result in HDIs) into various molten titanium alloys melted in a small EBBF to quantify their dissolution rates. In another study on HDIs, Yamanaka and Ichihashi [6] investigated the dissolution of tungsten, tantalum and vanadium particles in a molten pool by utilizing a Vacuum Arc Remelting (VAR) furnace. For HIDs, Powell et al. [7] investigated the dissolution of a TiN rod in liquid titanium. The dissolution rate was found to obey a linear correlation with time of 0.16 mm/min under the experimental conditions in his study. Ghazal et al. [8] also studied the dissolution rate of TiN in liquid titanium with emphasis on developing a mathematical model. The model was reported to make predictions on the dissolution behavior of the TiN particles as well as their trajectories within the molten pool of a VAR furnace.

Al-rich type II defects in Ti6Al4V can degrade fatigue performance and thus are not acceptable for rotor grade applications [1,9]. As previously mentioned, the regions of increased Al concentration can be associated with "drop-in" events in EBCHR processing. The associated Al(rich)-Ti solid possesses a melting temperature and density lower than the bulk liquid. Therefore, this material is expected to float and melt at a rate limited by heat transfer. While floating, heat transfer will be dependent on both the melt flow conditions in proximity to the solid and whether the material is irradiated by the electron beam (EB). Work undertaken by Ou et. al. [10] on ice/water and frozen ethanol/water as analogous systems for studying aluminum melting in titanium, has shown that both thermal and compositional gradients in the liquid adjacent to the solid are present and that they result in both surface tension driven (Marangoni) flows on the free surface and buoyancy driven flows. Together with the bulk flow conditions, these local flow drivers will contribute to the development of the flow field and heat transfer in proximity to the solid.

As part of a broader program to understand the melting of Al(rich)–Ti solids in liquid titanium, this manuscript presents the findings of a study in which solid CP titanium rods were dipped into a CP titanium melt in an EBBF. The use of CP titanium for both the solid and the liquid was initially studied in order that composition related phenomena could be excluded, prior to moving to a system in which compositional flow drivers are present. In addition to experimental work, a numerical model, which incorporates the significant transport phenomena, has been developed and validated against the experimental observations and measurements to allow a more comprehensive and detailed characterization of the melting process. The modeling methodology follows an approach previously published by the authors on the ice/water and frozen ethanol/water systems [10].

2. Experimental methods

Solid CP titanium samples in the form of cylindrical rods were immersed into a molten titanium pool for various periods of time and removed to observe the extent to which the solid was melted.