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On the avoidance of ripple marks on cast metal surfaces

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ABSTRACT

A mathematical model is derived for the purposes of predicting how to avoid unwanted defects, known as ripple marks, in the casting of metal ingots; the model is based around the momentum and heat transfer that occurs when a cooling molten metal meniscus rises between two parallel and vertical chill-mould walls. By using asymptotic techniques, the model is reduced systematically to a form that requires the numerical solution of a moving boundary problem involving just one partial differential equation. Numerical results are presented, and the significance of the model for predicting the depth and spacing of ripple marks in the casting of ingots and oscillation marks in continuous casting are discussed.

1. Introduction

The casting of metals is a well-established application of heat and mass transfer [1–7], the understanding of which is essential for avoiding or limiting defects that occur in industrial casting processes. Ripple marks are one example of such defects. Also called surface marks, wrinkles, striations or grooves, they are defects that develop on the surface of static ingots during casting; in general, they have a certain spacing, typically of the order of millimetres, and depth, typically of the order of tens of micrometres, and lie parallel to the meniscus surface. Although interest in ripple marks had subsided considerably since the early 1980s [8–10], there is now renewed interest in them [11], because the mechanism for their formation is thought to be related to that for the formation of oscillation marks in the much more prevalent continuous casting process [12–15]. In both ingot and continuous casting, there is a need to either minimise or avoid such marks completely, and mathematical modelling represents one way to gain insight into how this can be achieved.

In considering the formation of such marks, a knowledge of what happens in the region where the molten metal meniscus meets the cold mould wall is thought to be critical. However, the situation prevalent in continuous casting, where there is the combination of a solidifying meniscus and an oscillating mould, makes for a challenging modelling problem; in this context, the case of ingot casting, wherein the mould is stationary, represents a more suitable starting point. Even so, there appear to be no models available for this problem. Moreover, whereas a model predicting the depth and separation of ripple marks as a function of process parameters would be of scientific interest, it is of technical interest to know rather how ripple marks can be avoided; this will be the premise of this paper.

Although there are other ways to generate ripple marks [9], we focus here on the uphill casting-type configurations considered by Tomono et al. [8] and Jacobi and Schwerdtfeger [11]. A schematic is given in Fig. 1, which shows melt passing down from a tundish through the upper opening of a feeding channel, entering into an interior mould space through a hole at the bottom and subsequently rising. As the mould is cooled, the melt will also cool, leading eventually to the onset of solidification at the mould walls. Ripple marks are believed to occur via either an overflow or a flowback mechanism. In both cases, the shell solidifies along the curved meniscus profile to form a pointed tip. If the shell is strong enough to avoid deformation, the melt meniscus overflows the tip; otherwise, if the shell is too weak, its tip bends back under the rim pressure, i.e. a folding mechanism. As stated in the previous paragraph, our goal will be to determine how this situation can be avoided; however, the results of this analysis can nevertheless become the starting point for future modelling of actual ripple mark formation.

The layout of the paper is as follows. In Section 2, we formulate a mathematical model for the fluid flow and heat transfer in a melt with a rising meniscus; in Section 3, we nondimensionalize the model and identify the key dimensionless parameters. In Section 4, based on the characteristic values of these parameters, we formulate a reduced asymptotic model that leads to a moving

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Nomenclature

B	dimensionless constant, $\lambda Pe^{-1/2}$
B_{crit}	critical value of B
Bo	Bond number, $\rho g W^2/\gamma_{LG}$
C	constant determined by Eq. (20) [Pa]
C^*	dimensionless constant determined by Eq. (20) [Pa]
c_p	specific heat capacity [J kg^{-1} K^{-1}]
Fr	Froude number, V_{cast}^2/gW
g	gravitational acceleration [m s^{-2}]
h	meniscus height [m]
H	dimensionless meniscus height
$\bar{H}$	scaled dimensionless meniscus height
h_0	initial meniscus height [m]
H_0	initial dimensionless meniscus height
k	thermal conductivity [W m^{-1} K^{-1}]
L_e	latent heat of vapourization [J kg^{-1}]
M	molecular weight [kg mol^{-1}]
p	pressure [Pa]
P	dimensionless pressure
p_a	atmospheric pressure [Pa]
Pe	Péclet number, $\rho c_p V_{cast} W/k$
Q	mould-wall heat flux profile [W m^{-2}]
$\mathcal{Q}$	dimensionless mould-wall heat flux profile
$[Q]$	characteristic scale for Q [W m^{-2}]
Re	Reynolds number, $\rho W V_{cast}/\mu$
t	time [s]
T	temperature [K]
T_{amb}	ambient temperature [K]
T_{cast}	casting temperature [K]
T_{melt}	melting temperature [K]
u	x-direction velocity component [m s^{-1}]
U	dimensionless x-direction velocity component
v	y-direction velocity component [m s^{-1}]
V	dimensionless y-direction velocity component
V_{cast}	casting speed [m s^{-1}]
V_0	initial volume of melt per unit length [m^2]
$\mathcal{V}_0$	dimensionless V_0/W^2
W	half-width of the mould region [m]
x	horizontal coordinate [m]
X	dimensionless horizontal coordinate
$\tilde{X}$	scaled dimensionless horizontal coordinate
y	vertical coordinate [m]
Y	dimensionless vertical coordinate
$\bar{Y}$	scaled dimensionless vertical coordinate

Greek symbols

ε	radiation heat transfer emissivity of the molten metal surface
η	transformation variable, $Y/(Y_0+\tau)$
θ	dimensionless temperature
Θ	dimensionless temperature variable in Eq. (80)
λ	dimensionless parameter, $[Q]W/k(T_{cast}-T_{melt})$
μ	dynamic viscosity of molten metal [kg m^{-1} s^{-1}]
ξ	similarity variable, $\tilde{X}/\tau^{1/2}$
ρ	molten metal density [kg m^{-3}]
σ	Stefan–Boltzmann constant, 5.6704×10^{-8} W m^{-2}K^{-4}
γ_{LG}	liquid–gas surface tension coefficient [N m^{-1}]
γ_{SG}	solid–gas surface tension coefficient [N m^{-1}]
γ_{SL}	solid–liquid surface tension coefficient [N m^{-1}]
τ	dimensionless time, $t/(W/V_{cast})$
ϕ_c	contact angle [°]

boundary problem; the numerical method used to solve it is explained in Section 5. The results are presented in Section 6 and conclusions are drawn in Section 7.

2. Model equations

In order to understand the interaction of momentum and heat transfer with the motion of the rising, and possibly deforming, molten metal meniscus, we develop a simplified transient two-dimensional model for the process. We dispense with the full geometrical details of the interior mould space and consider a vertical channel instead. The situation is then as depicted in Fig. 2 where molten metal at a temperature T_{cast}, which is greater than the melting temperature T_{melt}, is confined and initially at rest between the vertical mould walls that are a distance $2W$ apart; the melt forms a meniscus which has the profile $y = h_0(x)$, with x and y

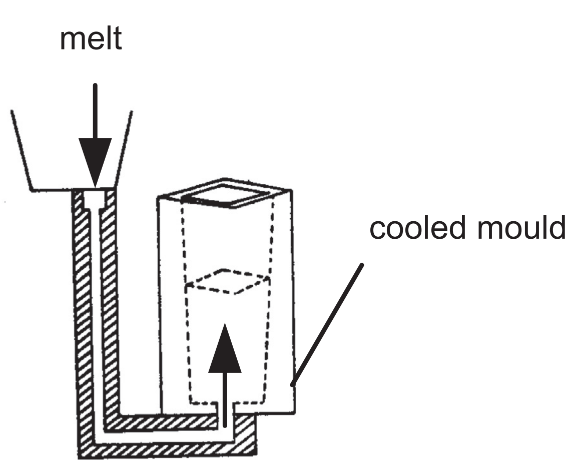

Fig. 1. Schematic for uphill casting.

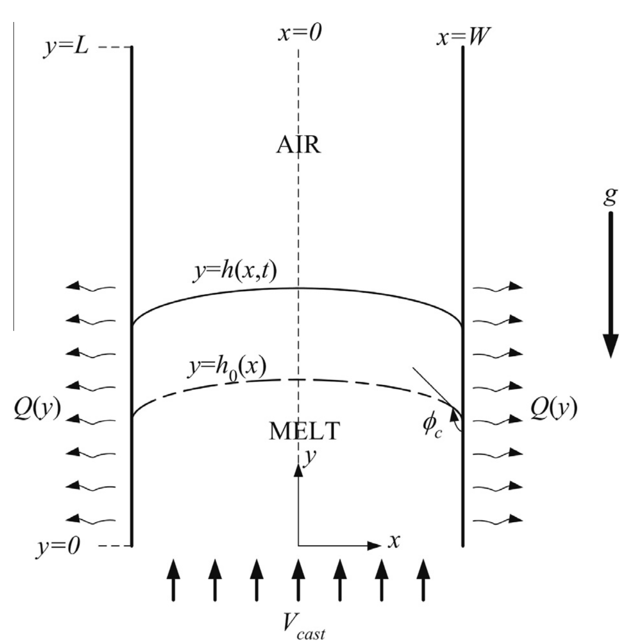

Fig. 2. Schematic of an idealised model for uphill casting.