Journal of Materials Processing Technology 164–165 (2005) 1479–1486

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Experimental and numerical analysis of natural convection for Al–5.5% Cu alloy

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Abstract

Numerical and experimental investigations have been made for aluminum–5.5% copper (Al–5.5% Cu) binary alloy. During these investigations the effect of natural convection on the solidification process and the alloy structure are studied. No slip condition (stationary liquid metal) is proved to be the applicable condition at top boundaries of liquid metals exposed directly to the ambient (room temperature).

Experimental and numerical results show good agreement. The results present, as the temperature increases the temperature gradient increases and so the natural convection currents. Natural convection flow is quantified and proved to work as a stirrer for temperatures higher or equal to 1100 K, i.e., eddy currents of the metal flow are strong enough to break the weak nuclei. So coarse grains are obtained in the solidified structure.

Keywords: Solidification; Natural convection; No-slip condition

1. Introduction

Fluid flow in metals plays an important role in nucleation, growth, and coarsening phenomena. It affects microsegregation and macrosegregation in metallic alloys. The most common structure for a solid crystal or grain is dendrite that can exist in either columnar or equiaxed form. Free equiaxed dendrites in an alloy, generated by nucleation or fragmentation of existing crystals, grow in a melt that is constitutionally under-cooled. Movement of free equiaxed grains is generally a result of gravitational forces. This includes movement due to sedimentation or floating of the solid and movement due to convection patterns in the melt. Sedimentation or floating of grains is a result of density differences between the grains and the bulk liquid that arise from the rejection or incorporation of solute during the solidification process, and solidification shrinkage. Convection in the melt is due to a combination of density differences resulting from temperature and composition variations in the liquid, typically referred to as thermosolutal convection [1].

Literally, hundreds of papers have been written on melting and solidification for pure substances, including applications. Relevant reviews of the technical literature are documented in the papers by Refs. [2–8]. Natural convection is very important as it not only affects the rate of solidification, the shape of the solid liquid interface, and the distribution of impurities, but can also have a large influence on the structure of the solid formed [9–15].

Cole and Bolling, 1965 have showed the effect of convective flow on the structure of the solid formed experimentally [16]. However, Szekely and Stanek, 1970, have made the first attempt at a quantitative treatment of the convective motion and its effect on unidirectional solidification [11]. Recently, natural convection heat transfer has received good attention from researchers to study its effect on the solidification process of liquid metals [17–23].

The current investigations try to find out the boundary conditions that best describes the air-molten metal interface. It also focuses on the effect of natural convection which is caused by the thermosolutal convection on the macrostructure of Al–5.5% Cu alloy (Fig. 1, [24]) in axisymmetric metal-mold cooled in the lab atmosphere. For this purpose, both

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doi:10.1016/j.jmatprotec.2005.02.142

Nomenclature

C	specific heat of the metal
C_l	liquid composition, i.e., Cu mass fraction of the molten alloy with respect to the total mass of the molten alloy
C_s	solid composition, i.e., Cu mass fraction of the solidified alloy with respect to the total mass of the solidified alloy
f_l	liquid fraction (the ratio of the mass of the liquid to the total mass)
f_s	solid fraction (the ratio of the mass of the solid to the total mass)
g	gravity acceleration
Δh_l	latent heat of fusion
k	thermal conductivity
K	distribution coefficient
P	pressure in the molten metal
q'	rate of the internal energy per unit volume
r	local radius
t	instantaneous time
T	instantaneous temperature
T_l	melting temperature of the alloy
T_m	melting temperature of the pure aluminum
T_s	temperature at which the alloy completely solidified
u	velocity component in the radial-direction
w	velocity component in the vertical-direction

Greek letters

ρ	local density of the molten metal
μ	kinematic viscosity

experimental and numerical models have been developed and tested. Comparisons are made between measurements and computer simulation in the superheat region (liquid phase only).

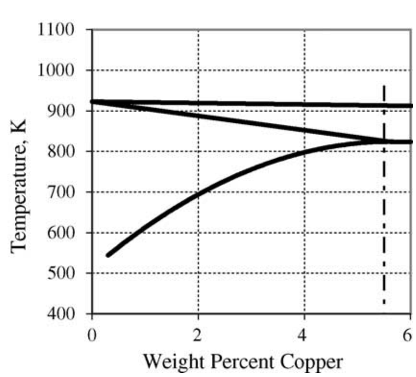

Fig. 1. Aluminum-rich portion of the aluminum–copper alloy phase diagram.

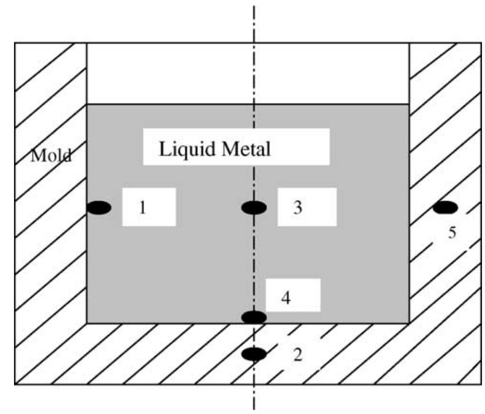

Fig. 2. Longitudinal section of the mold with the positions of thermocouples.

2. Physical and mathematical model

2.1. Physical model

Study of the solidification of binary alloy (AL–5.5% Cu) in a cylindrical mold is made (Fig. 2). The mold with the molten metal is heated to a predetermined superheat temperature and then cooled by natural convection in the lab atmosphere.

The natural convection in the molten metal, i.e., fluid flow caused by thermal convection is studied by changing the initial temperature of the mold and the molten metal. However, the physical theoretical model does not simulate the solidification wave, i.e., the solid-liquid moving interface (mushy zone). The theoretical model simulates the alloy in the liquid phase only. The main variable is the initial temperature, which controls the strength of the natural convection in the system. It is assumed that there is no gradient of temperature or pressure in the angular direction, and this assumption is fit for current study because of the axisymmetric geometry.

The system initial condition is uniform temperature in both the mold and the molten metal. The system is held at a predetermined superheat temperature for long enough time so that the initial system temperature is uniform. The computational system consists of the mold molten metal and the surroundings.

In the formulation of the equations of motion of the molten metal inside the cylindrical mold the following assumptions are used:

- Incompressible homogenous fluid.
- Flow properties are axially symmetric.
- Cu atoms are uniformly distributed through out, i.e., no need to specify species equations.
- Properties of the surrounding fluid (Air) and the mold are assumed to be constant.
- Heat transfer through the air gap that forms between the solidified layer of the liquid and the mold walls at the mold-liquid interface is assumed to be conduction only. This is a justifiable assumption since the gap is less than 1mm. The average thermal resistance of the air gab (for the side-wall