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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% Cupper (Al-5.5%Cu) binary alloy. During this investigation 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

Natural convective flow in the melts is due to a combination density differences resulting from temperature and composition variations in the liquid. The most common structure for a solid crystal or grain is the dendrite which can exist in either columnar or equiaxed form. Free equiaxed dendrites in alloy, generated by nucleation or fragmentation of exiting crystals [1]. Literally, hundreds of papers have been written on melting and solidification of metals, including applications. Sample of recent work in this area could be found in references [1] through [4]. This investigation focuses on the effect of natural convection which is caused by the temperature gradient on the macro-structure of Al-5.5% Cu alloy in axisymmetric metal-mold cooled in the lab atmosphere. Comparisons are made between measurements and computer simulation in the superheat region (liquid phase only).

2. PHYSICAL MATHEMATICAL MODEL

Study of the solidification of binary alloy (AL - 5.5 % Cu) in a cylindrical mold is made (Figure 1). 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 a temperature gradient is studied by changing the initial temperature of the mold and the molten metal. 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. The main variable is the initial temperature, which controls the strength of the natural convection in the system. Flow properties are assumed axially symmetric and this assumption is fit for current study because of the axisymmetric geometry. The two-dimensional axisymmetric mathematical model using cylindrical coordinate for incompressible fluid is adopted, i.e., Continuity Equation, Momentum Equation: R-direction and Z-Direction and Energy Equation. No slip condition (i.e., the velocities are zero) is applied at the molten metal-mold interface, at the sidewall, and at the base and at the molten -air interface. The last boundary condition is proved to be valid by this study.

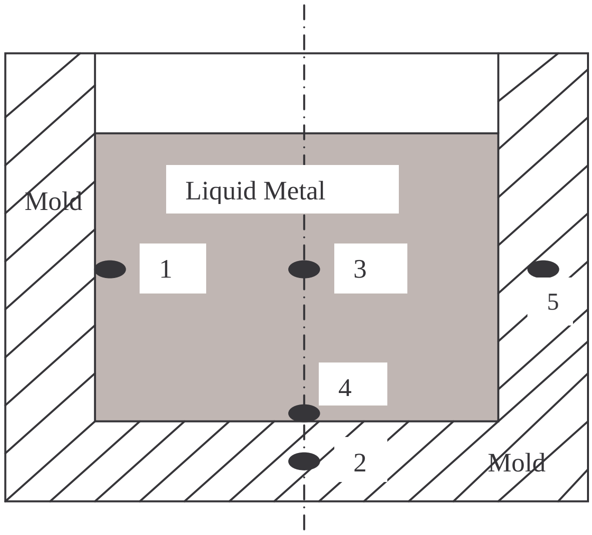

Figure 1: Longitudinal section of the mold with the positions of thermocouples.

3. NUMERICAL SOLUTION METHOD

In order to solve the mathematical model, SIMPELR-algorithm is used, which stands for “Semi-Implicit Method for Pressure-Linked Equation” [4].

4. EXPERIMENTAL PROCEDURES

The experimental setup consists of: Mold made of commercial steel and contains five holes for fixing the thermocouples as shown in the Figure 1, data acquisition system (DAS) installed in PC, furnace with a fine temperature control. The thermocouples connected to the DAS are placed in the spots shown in Figure 1. An uninstrumented mold with the same geometry and parallel manipulation has been used to produce specimen for testing the macro-structure. The filled molds with Al-5.5% Cu alloy are put in the same conditions in the furnace. Then when the temperature reached the predefined one in the superheat region, the molds are moved outside the furnace, seated on a support to cool in the lab atmosphere by free convection. Ingots from the second mold were sectioned in the longitudinal plane, grinded, polished and etched. Then, pictures for macro- structure have been taken. Also the Cu content within the ingot at 2 cm from the top and 2 cm from the bottom is obtained using Atomic Absorption System (AAS).

5. RESULTS AND DISCUSSION

5.1. Theoretical and Experimental Results

The study has been made for initial temperatures of 950°K, 990°K, 1050°K, and 1100°K. Sample result representing a cooling curve and a snap shot of the velocity field at 17 seconds from the start of cooling, for initial temperature 1100°K are shown in Figures 2 and 3 respectively.

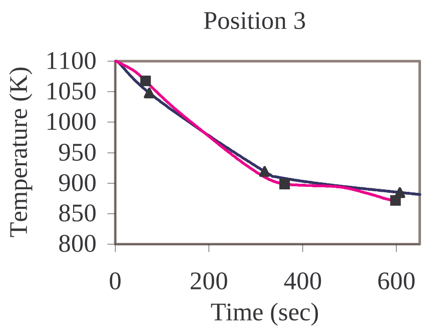

Figure 2. The theoretical (■) and experimental (▲) cooling curves for T=1100°K at different positions (see Figure 1).

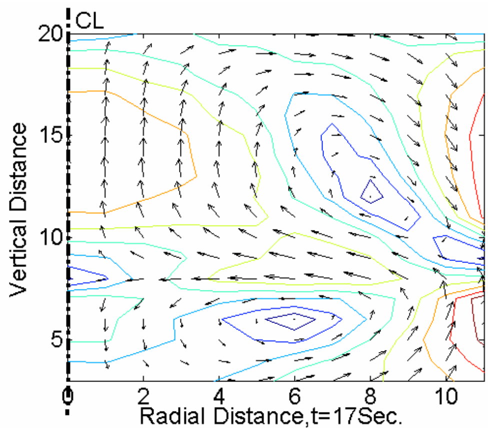

Figure 3. Snap shots of fluid flow for T=1100°K at t=17 sec. Every 1 mm of the vector length represents 0.04 m/sec

5.2. Discussion

In the numerical simulation a no-slip condition for the molten metal-air interface was taken (the top of the molten metal), which is proved experimentally. The macro-structure photos (Figure 4a, b, c, d, e) for the different initial temperatures show an equiaxed grains at the top followed by the columnar zone. This macro-structure exists when chilling effect takes place due to large temperature difference between the molten metal and the lab atmosphere. So this solidified layer is stagnant and no slip condition (i.e., the particles in contact with the layer are not moving or slipping over that layer) in the simulation describes the real experiment best. The photographs of macro-structure show small grains up to the temperature range of 1050 K. The Aluminum used in producing the alloys is not completely pure, i.e., it contains some impurities that work as refinement material. The difference of the macro-structure between Al-5.5%Cu and Al-1%Cu is due to the different grain refinement characteristics of alloys. The dependence of equiaxed growth on alloy content is investigated by Plaskett and Winegrard [3]. They showed that the nucleation occurs ahead of an advancing interface when the temperature gradient divided by the square root of the solidification rate is less than a value roughly proportional to solute content. Explicitly, more Cu content more equiaxed nucleation takes place. The natural convection works as a stirrer for temperatures above 1100°K so that when the nuclei are formed the inertia of the flow breaks those weak crystals that lead to the formation of large grains. Table 1 shows the weight percentage of Cu at the top and the bottom of each case. The differences may be referred to the sedimentation effect that is due to the density difference of Cu and Al.

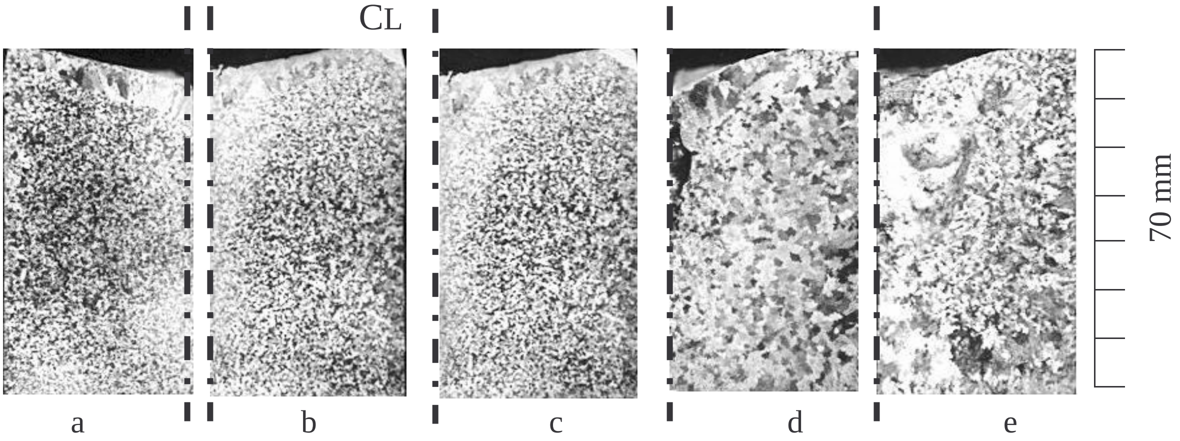

Figure 4: Photographs of macro-structure of Al-5.5% Cu ingot cooled from initial temperature a) T=950°K, b) T=990°K c) T=1050°K, d) T=1100°K, and e) Al-1% Cu for T=990°K.

6. CONCLUSION:

When the molten metal is exposed to the ambient, a thin layer of solidified liquid metal forms at the top surface, so that the boundary condition at the top should be taken as no slip condition. For Al-5.5%Cu alloy where the temperatures higher or equal 1100°K the fluid flow works as stirrer in coarsening the grains, i.e., the fluid flow is strong enough to break the weak nuclei and keep the strong one.

REFERENCES

1. Rodney S. Rerko, Henry C. de Groh and Christoph Beckermann, Effect of Melt Convection and Solid Transport on Macrosegregation and Grain Structure in Equiaxed Al-Cu Alloys, Materials Science and Engineering A247, pp. 186-197, 2003.
2. Hwang, Ki-Young, 1997, “Effects of Density Change and Natural Convection on the Solidification Process of a Pure Metal”, Journal of Materials Processing Technology v 71 n 3 Nov 23 1997. pp. 466-476.
3. T. S. Plaskett, W. C. Winegard, Transactions ASM 51, pp. 222-230, 1959.
4. Suhas V. Patankar, “Numerical Heat Transfer And Fluid Flow”, McGraw-Hill Book Company, 1980.