# THERMAL EFFECTS OF 99,7% Al MELTS IN ULTRASONIC FIELD

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ABSTRACT. The thermal properties of the liquid aluminium (minimum purity 99,7 wt % Al) have been experimentally investigated at ultrasonic frequency. The thermal conductivity of the molten aluminium has been measured as a function of temperature in the presence and in the absence of power ultrasonic field. It was found that the conductivity of the liquid aluminium decreases in presence of the ultrasonic field. Using the published data on density and heat capacity and the experimental data on thermal conductivity, the thermal diffusivity of the melt under study has also been calculated. The heat transfer coefficient was measured during the solidification of molten aluminum. Heat transfer during solidification is shown to be a complex mechanism controlled by the macro scale of the thermal expansion and contraction of the mold.

## 1. INTRODUCTION

The study of heat flow in high-temperature processes has significantly improved the control of the process solidification, the products quality (macrostructural and microstructural features and hence the mechanical properties in casting) [1]. For reliable results, the temperature distribution in the melt should be accurately known throughout the solidification process. Accurate information on the thermophysical properties of the solidifying metal and the boundary conditions is required, usually expressed as a heat transfer coefficient or heat flux. The heat transfer coefficient is usually calculated from the temperature data measured during the solidification. A lot of methods using these data are reported [2-4].

This work is a study focused on the thermal effects during solidification of 99,7 wt % Al (with commercially purity). Aluminium was found suitable as it has a relatively low melting point, so radiation made a negligible contribution to the heat transfer process.

The thermal conductivity of the liquid metals has not been much studied in terms of the profound effect of heat exchange in presence of the ultrasound. The thermal conductivity $\lambda$ can be calculated by applying Newton's theory of unsteady state method [5]:

$$q = \lambda \frac{T - T_{\infty}}{\Delta x} \qquad (1)$$

where $q$ is the heat transfer to the surrounding medium per unit area, $\frac{T - T_\infty}{\Delta x}$ is temperature gradient between an internal point of the melt and external temperature, $T_\infty$ the surrounding medium temperature and $T$ the temperature at time $t$. The heat transfer is:

$$q = \rho c_p \ell \frac{dT}{dt} \quad (2)$$

where $\rho$ and $c_p$ are density and heat capacity respectively of the sample, $\ell$ is the height of the liquid metal column into crucible. The equation (1) and (2) give the relation:

$$\frac{T - T_\infty}{T_0 - T_\infty} = \exp\left(-\frac{\lambda t}{\rho c_p \ell \Delta x}\right) \quad (3)$$

where $T_0$ is initial temperature.

The thermal diffusivity is one of the important characteristics of the particle thermal motion quiescent liquids. It is directly related to the thermal conductivity ($\kappa$), heat capacity ($c_p$) and density ($\rho$) by expression:

$$\kappa = \frac{\lambda}{c_p \rho} \quad (4)$$

The thermal diffusivity is inherently a measure of the temperature equalization rate in a medium, showing the relation between its heat conducting and heat accumulating power.The present study was undertaken to obtain new data on the thermal conductivity, thermal diffusivity and heat transfer of the molten aluminum and the influence of the ultrasonic field about its. In order to elucidate the effect of ultrasonic waves, the measurements were carried out under similar conditions both with and without sonication. The physical properties used in the calculation are given in Table I. The latent heat evolved during solidification of the casting was incorporated into the effective specific heat capacity [6].

**Table I.** Physical properties used in the calculation of the heat transfer coefficient of 99,7 wt % Al

| Properties (Units) | Value |
|---|---|
| Thermal conductivity $(\mathrm{W \cdot m^{-1} \cdot K^{-1}})$ [7] | |
| -Liquid phase | 98 |
| -Solid phase | 181 |
| -At melting point | 91 |
| Specific heat capacity $(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$ | |
| -Liquid phase | 1289 |
| -Solid phase | 1180 |
| Density $(\mathrm{kg \cdot m^{-3}})$ | 2,399 |
| Effective specific heat capacity [8] $(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$ | $1070{,}4 - 4{,}6168 \cdot 10^{-2} T$ for $T \in (933 - 4000)$K |
| Effective density $(\mathrm{kg \cdot m^{-3}})$ | $2606 - 21 \cdot 10^{-2} T$ for $T \in (933 - 4000)$K |

The heat transfer coefficient, per unit area, is calculated from the slope of the $\ln\frac{T_0}{T_i} = f(t)$ dependence. In the case of aluminum, the radiation heat transfer is generally believed to contribute little to the overall heat transfer coefficient.

## 2. EXPERIMENTAL

Measurements have been made on samples of 99.7% aluminium in the liquid state. The range of temperature is (933-1033) K. The crucible is contained within a concentric stainless steel thermal shield. A temperature gradient is set up along the shield to match that set up along the crucible (about 8K/cm) so that radial heat losses from the crucible are minimized.

The axial temperature gradient in the crucible is detected by a chromel-alumel thermocouple encased in a quartz sheath of 1.7mm (outer diameter). Any errors in the measured absolute temperature will be small and will not affect the measured temperature gradient. The experimental procedure involves a recording of the temperature-time dependence of molten sample under constant radial feat flow through the melt. This study was made under different cooling conditions, which were obtained through external cool air around the crucible. To avoid the formation of any volatile gases during experiment, the mold was preheated to 1200 K.

The ultrasonic field was created with a magnetostrictive transducer and an ultrasound generator, to generate continuous longitudinal waves into the liquid sample. We preferred to introduce the ultrasound waves through the bottom of the crucible. In this arrangement, there is no barrier between the ultrasound source and the melted metal. The stepped stainless steel horn was used to transmit the ultrasound to the molten and it is completely resistant to ultrasonic erosion. Typical operating parameters were frequency f = 20.338 kHz and the nominal input power 600 W. The acoustic power dissipated by ultrasonic probe in 1000 ml deionized water at ambient temperature and pressure as a function of the electrical input power was determined by calorimetry. These data were used to allow selection of the appropriate input power to give constant transmitted power. After the completion of the measurements, the ultrasonic horn was examined microscopically. No attack of the stainless steel by liquid metal samples was observed in either case, so there was no evidence the contamination of the liquid metal by alloying.

## 3. RESULTS AND DISCUSSION

Figure 1 shows the ratio $\ln\left(\frac{T_0}{T_i}\right)$ as a function of time. Within the limits of the experimental error the conductivity of the melt varies linear with temperature. The physical property data used for the evaluation of $\kappa$ are summarized in Table 1. The values calculate for thermal conductivity are presented in Table 2. In presence of the ultrasonic field, in the same range of temperature, the values of the thermal conductivity are decreasing.

Table 2. Estimated $\kappa$ of liquid aluminium.

| | $\overline{c}_p$ $(J/kg \cdot K)$ | $\overline{\rho} \cdot 10^3$ $(kg/m^3)$ | $\lambda(J/m \cdot s \cdot K)$ | | $\kappa \cdot 10^{-6}(m^2/s)$ | |
|---|---|---|---|---|---|---|
| | | | Without ultrasound | With ultrasound | Without ultrasound | With ultrasound |
| 1 | 1037,25 | 2,399 | 207 | 183 | 189,7 | 167,7 |
| 2 | | | 185 | 162 | 169,6 | 148,5 |
| 3 | | | 172 | 149 | 157,6 | 136,5 |
| 4 | | | 151 | 130 | 138,4 | 119,1 |

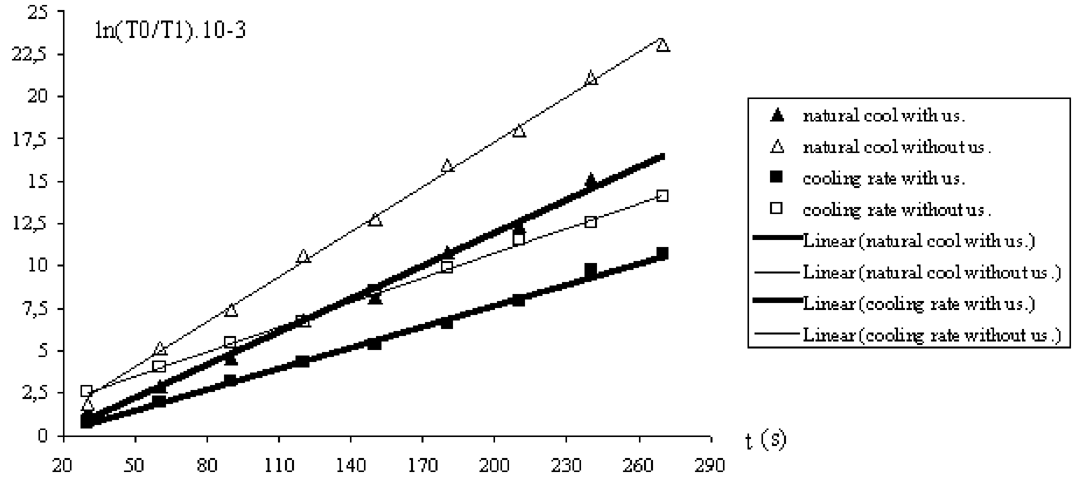


Fig.1 The ratio $\left(\ln \frac{T_0}{T_i}\right) \cdot 10^{-3}$ as a function of the time for Al 99,7%.

It can be noticed that the thermal diffusivity is smaller in presence of the ultrasonic field. A preliminary conclusion indicative the involvement of the acoustic flow in the heat transfers. The presence of the ultrasonic field induces the acoustic flow, which produces a continuous mixing process in the melt. This process can be understood as a decreasing of the axial temperature gradient. However, it is clearly demonstrated [9] that the acoustic flows are to be associated with the ultrasonic absorption, a number of studies showed that the absorption coefficient is quite small for the liquid metals [10]. Consequently, the temperature of the molten in presence of the ultrasonic field has not increasing.

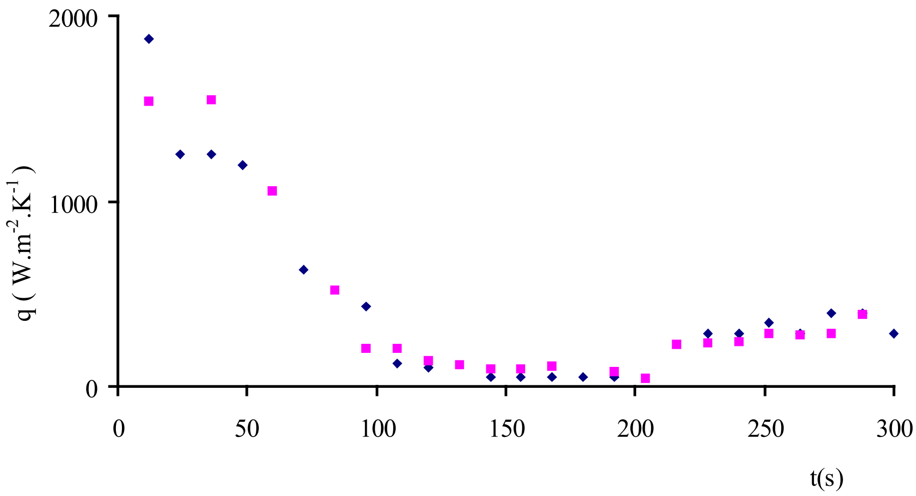


Fig. 2. The heat transfer coefficient as a function of time during solidification.
( ◆ - without us; ■ - with us).

Figure 2 shows the calculated coefficients of heat transfer per unit area obtained during solidification. Since heat transfer by conduction only was assumed, the occurrence of liquid flow in the bulk liquid would reduce the accuracy of the calculated heat transfer coefficient. It can be seen from figure 2 that the heat transfer coefficient determined is maximal at the beginning of the experiments. However, the heat transfer coefficient values display a wide scatter. This spread of the results probably has its origin partly in uncontrolled variable in the solidifying process, but may also be partly due to the assumptions about the thermophysical property data by the help of which the heat transfer coefficients were determined (for example, the temperature independence from the thermophysical properties of the metal).

As it can be seen in the figure 2, an air gap is formed at approximately 70 seconds, characterized by a rapid fall of the heat-transfer coefficient value. At shorter times (around 20 seconds) the heat transfer coefficient data are not significant, probably due to fluid flow in the bulk liquid and convection. In a practical casting situation, distortion of the casting and of the mold due to thermal stress would affect the interface pressure between them and the heat transfer coefficient too. In this work, distortion of the mold wall was neglected for the sake of simplicity. Several other factors are still insufficient known:

- the gases in the interface between the casting and the mold wall (air and maybe hydrogen with a much greater thermal conductivity than air would increase the predicted heat transfer coefficient);
- the need to know the mechanical properties of the metal at temperature close to it solidus temperature (there are only few data in the literature concerning the mechanical properties of metals and alloys at high temperature), these could only be estimated;
- the mechanism of heat transfer during the initial contact stage is unknown, so the heat transfer coefficient in the first seconds of the process was neglected;
- the effect of the oxide film on the surface was not taken into account.

The other two factors that may affect the heat transfer coefficient are the convection and the reflection of the heat flux at the mold wall. The effect of convection arises from a temperature gradient in a liquid sample and brings about overestimation of heat transfer values. The problem of convection becomes much more serious at high temperatures, because a precise temperature control is more and more difficult as the temperature increases. However, in this study we considered that convection was not operative.

The time of the solidification process was considered to be the first 300 seconds of the experiments. The strong decrease of the heat transfer coefficient at the beginning of the experiment (from 1,85 $kW \cdot m^{-2} \cdot K^{-1}$ to about 1 $kW \cdot m^{-2} \cdot K^{-1}$ ) is not significant since the first 50 seconds of data obtained are unreliable due to the occurrence of the fluid flow in the bulk liquid probably due to pouring and convection. The thermocouples in this casting recorded oscillations in the first 100 seconds of the experiment, which indicated that turbulent liquid flow had occurred. Between 100 to 200 seconds, the collection of heat transfer coefficient data did not vary greatly during the period in which the solidification front advanced (values about $130\, W \cdot m^{-2} \cdot K^{-1}$ ). As solidification progressed the relative expansion and contraction of the casting and mold wall altered the amount of the contact and the size of the interface gap between the two surfaces. Eventually this led to their complete separation. The occurrence of an insulating air gap, which formed due to the separation of the solidifying matter and the mold wall due to their relative expansion and contraction, resulted in a marked decrease in the heat transfer coefficient. This decreasing appears after 20 seconds and the heat transfer coefficient declined rapidly down to values of about $130\, W \cdot m^{-2} \cdot K^{-1}$ . This local separation process, which would be influenced by the surface roughness and the pressure between the two surfaces, would strongly affect the value of the heat transfer coefficient.

Heat transfer due to convection involves the energy exchange between a surface and an adjacent fluid. In silent condition, there is natural convection wherein warmer fluid next to the solid boundary causes circulation because of the density difference resulting from the temperature variation throughout a region of the fluid. In presence of ultrasound, there is the situation of turbulent flow. In this case, there is bulk mixing of the fluid particles between regions at different temperatures and the heat transfer rate is increased.

The decrease of the thermal conductivity is caused, also, by acoustic cavitation. Once formed, a bubble in an acoustic field can grow by several processes. At low acoustic pressures, the bubble will grow slowly over many acoustic cycles. In strong acoustic fields, the bubble oscillations can become very large through inertial effects. In general, when a gas is compressed, it heats up. Bubbles growing into resonance size are well coupled to the sound field and can rapidly over-expand. At this point, rapid compression and consequent heating can occur. When the compression is rapid enough, the heating is nearly adiabatic; there is insufficient time for thermal transport occurs effectively. Gas bubbles in a liquid, in absence of ultrasonic field, will slowly dissolve owing to the excess internal gas pressure required balancing the pressure $\frac{2\sigma}{R}$ due to surface tension $\sigma$. Thus, in the absence of an ultrasonic field and any stabilizing mechanisms, all bubbles gradually dissolve. In the presence of the ultrasonic field, the situation is different. During stable cavitation, since evaporation and condensation take place so much more rapidly than the bubble dynamics, the vapor pressure within the bubble remains constant at the equilibrium value. To obtain the stable cavitation there are two contributory elements: an "area effect" and a "shell effect" [11]. The area effect arises through the correlation between the direction of the mass flux and the area of the bubble wall. The shell effect occurs because the diffusion rate of a gas in a liquid is proportional to the concentration gradient of the dissolved gas. In the same time, a sufficiently strong sound field can influence the bubble distribution also by relocating individual bubbles. In the simple situation, the bubbles of larger than resonance size will be accelerate in one direction and the bubbles that are smaller than the resonance size will be accelerate in the opposite direction, in ultrasonic field.The conclusion is therefore that in the ultrasonic field presence, this bubble population may be associated with decreasing of the thermal conductivity mechanism of the liquid metal.

In our experiment, these optimum conditions in cavitation were studied in deionized water at ambient temperature. The ultrasonic treatment of the liquid metals differed essentially from that of aqueous solutions and organic liquids. This is due to the different nature of cavitation nuclei and, hence different conditions required for the origination and development of acoustic cavitation. Only fine solid particles (mainly oxides, e.g. $Al_2O_3$ in aluminium melt) can act as cavitation nuclei in metallic melts [12]. In the same time, the temperature of experimental system is strongly increasing and because the molten metals are light opacity, the cavitation cannot be studied directly. In conclusion, additional experiments at different acoustic power are necessary to check the dependence of thermal conductivity on the acoustic power. The experimental conditions together with the analysis of the acoustic flow and the cavitation effect permit to predict that at high temperature, all these factors are equal contribution to the decreasing of the thermal diffusivity of the liquid aluminium exposed to ultrasound. This decreasing of the thermal diffusivity appear due to the influence of the axial temperature gradient, the acoustic cavitation and the population of the bubbles that are creating in molten mass. All these processes take place only in presence of a dissolved gas and contribute to decrease of the thermal conductivity and also, to decrease of the thermal diffusivity.

## CONCLUSIONS

There is a little information on the investigation of the thermal phenomena in presence of ultrasonic field. The investigation of the ultrasonic melt effects allowed us to establish an essential relationship between both the thermal conductivity and diffusivity and cavitation development. Under optimum condition, the ultrasonic field gives rise to the rich variety of mechanisms and effects which can be observed. It is also important to elucidate the mechanism of elementary processes inside the cavitation bubbles and around them.

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