

ADVANCED METHODOLOGY OF DETERMINATION WATER JET COOLING INTENSITY DURING THE CASTING PROCESS

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ABSTRACT

Companies which produce aluminum alloy ingots seek a final product without structural defects. One crucial factor is the cooling during the semi continual casting process. In the beginning of the process, most cracks are made with lengths up to 300 mm, and then, by selecting a suitable method of water cooling, the cracks are closed. A major influence on defect generation is the superheat extraction from the incoming liquid metal by the secondary water-cooling system due to direct water impingement on the ingot surface. The temperature distribution during the casting process can be simulated numerically with known boundary conditions (cooling intensity along the surface). Boundary conditions are obtained by experimental investigation and subsequent evaluation.

A special experimental device was designed for measurement. The device's main function is to ensure that the position of the mold and the sample during measurement is as it would be during the real casting process. The aluminum sample was equipped with a set of thermocouples placed along the cooling surface. The hot vertical surface was cooled down during the experiments by a flat water jet. The impact area is located in the upper part of the cooling surface. The rest of surface is cooled by water flow down along the surface. This article deals with the evaluation of this type of experiment. The boundary conditions (heat transfer coefficients) are estimated as a function of temperature and vertical position. Unfortunately, the results obtained by standard methods for solving the inverse heat conduction problem (for example, using the 2D sequential function specification method) are blurred. This is caused by the Leidenfrost effect and this special type of cooling. A sharp border between the transient and film boiling modes is created and moves down during the experiment.

This article illustrates an applicable solution based on shifting computation element borders during the inverse computations. The method was tested on measured data.

INTRODUCTION

Various simulations for thermal processes such as cooling and hardening are commonly used. The temperature distribution or gradient history inside the material are used in order to determine the influence on the final structure, residual stress and potential for defect formation.

Numerical simulations are based on solving the direct heat conduction problem using the finite element [1], difference [2]

or volume [3] methods. These methods are well known and they are included in the solvers of all standard commercial software, including ANSYS and COMSOL.

For each thermal simulation it is necessary to know the following inputs:

- Geometry
- Material properties – thermal conductivity, density and specific heat capacity
- Initial conditions – initial temperature distribution
- Boundary conditions – heat flux or heat transfer coefficients

Most of these points are not difficult to obtain. For example, the geometry is usually determined by assignment of a studied problem. Material properties can be obtained from material databases or can be measured using standardized measuring equipment. The initial condition is usually reduced to a homogenous temperature.

The last point is much more complicated. Boundary conditions can be express using empirical formulas [4], [5] in some trivial cases simply with geometry, and a special type of cooling with a short temperature range. However, common industrial applications such as spray cooling are not trivial so it is necessary to obtain boundary conditions by measurement.

Cooling experiments are usually designed to be transient. A test sample with built in thermocouples is heated to an initial temperature. Then, the temperature history is recorded during the cooling process. Boundary conditions can be evaluated using the Inverse Heat Conduction Problem (IHCP) from measured temperatures.

This article deals with the 2D IHCP for a highly heat-conductive sample made from aluminum. The sample was cooled using a flat water jet in the impact area and by water flowing along the surface below. This configuration is common for the continuous casting of aluminum. Solving the IHCP is made more difficult by the Leidenfrost effect combined with a special type of cooling conditions.

DESCRIPTION OF EXPERIMENTS

Experimental measurements were designed to reproduce real aluminium casting conditions with a realistic sample material, temperature range, water flow rate and cooling

regime. The test sample was made from a small block of aluminium and was cooled in the vertical position by flat water jets. Temperatures were recorded by a set of thermocouples placed close to the cooling surface.

The area where the water jet impacted the surface is called the impingement zone, and it is located in the upper part of sample. The rest of the sample (below the impingement zone) is cooled by water flow downwards and around the surface (see figure 1).

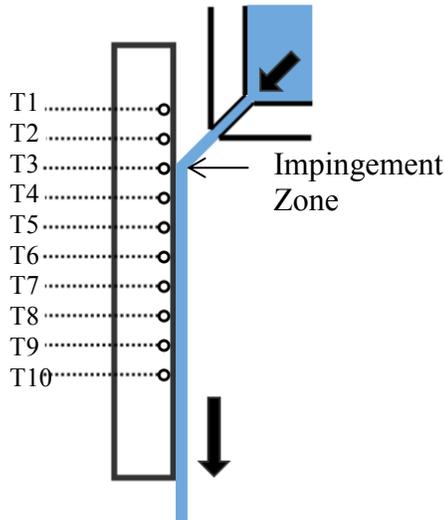


Figure 1 Cross section of test sample

These two zones have different cooling intensities and different distributions of cooling intensity over time. The impingement zone is exposed to intense cooling from the beginning of the experiment, while the bottom of the sample experiences a cooling intensity strongly dependent on the surface temperature. The bottom of the sample is cooled by this lower intensity until the Leidenfrost temperature is reached on the surface.

Experimental Device

The experiment device includes a furnace to heat up the test sample to an initial temperature at approximately 475°C. The sample is placed on a rotatable arm which allows heating in the vertical position and then setting the exact position of the sample for rapid cooling (see figure 2).

The experiments are performed according to the following procedure:

- Heating the sample to a starting temperature (figure 2)
- Setting the water flow rate
- Starting the temperature recording
- Placing the sample in the cooling position (figure 3)
- Begin cooling by removing the deflector (figure 4)

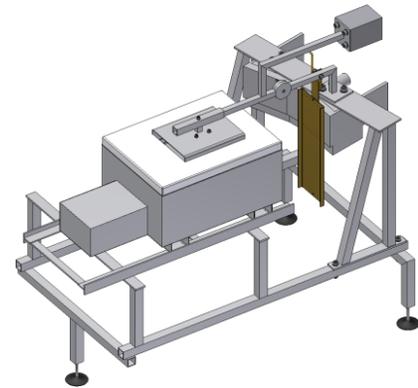


Figure 2 Heating position

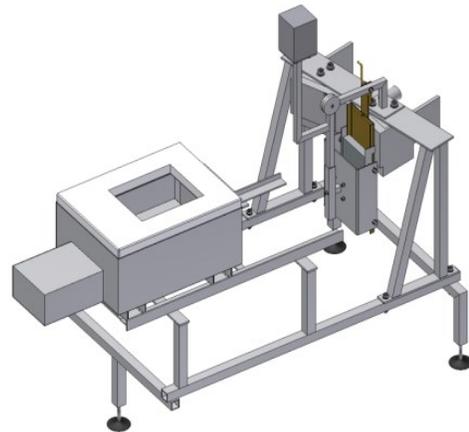


Figure 3 Preparation position before cooling

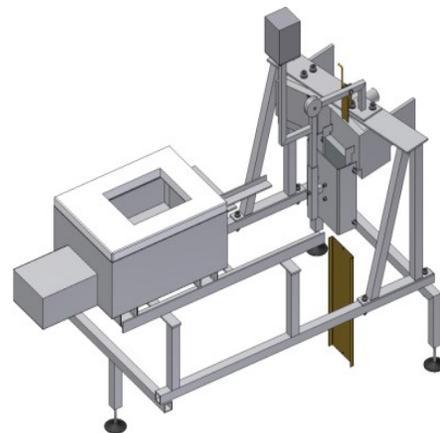


Figure 4 Cooling position

Leidenfrost effect

The Leidenfrost effect is clearly visible on the shape of heat flux function depending on temperature difference (surface temperature minus ambient temperature). Figure 5 is a plot example of the boiling curve for water at 1 atmosphere pressure. The local minimum of this function placed between the transient and film boiling ad is called the Leidenfrost point, and the correspond temperature is called the Leidenfrost temperature. [4]

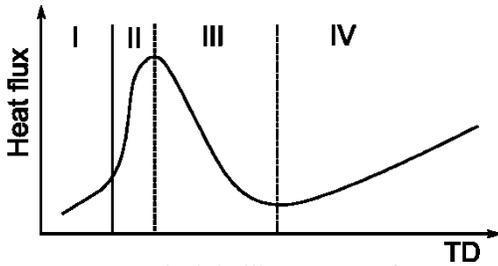


Figure 5 Typical boiling curves for water at 1 atm., I-Convection, II-Nucleate boiling, III-Transient boiling, IV-Film boiling

INVERSE HEAT CONDUCTION PROBLEM

Tasks to find effects from known causes are called direct tasks, while tasks for observed (known) effects but unknown causes are called inverse tasks [6].

Specifically, for the heat conduction problem the causes are initial temperature and boundary conditions. The effects are temperature distribution over time. Solving direct heat conduction problems are not as complicated as inverse tasks. Well-known numerical methods such as FDM [2], FVM [3], or FEM [1] are usually used. Even an analytical solution can be used, in some special, simple cases.

Inverse heat conduction problems are usually poorly conditioned. This means that the small change of inputs (measured temperatures) can cause large differences in results. A linear inverse heat conduction problem (a problem with constant material properties) with a relatively low number of samples (several thousands) can be solved using the full domain method [6], Tikhonov's regularization [7], or other methods. Other tasks can be solved using a sequential method which allows the use of temperature-dependent material properties during the computation. One commonly used method is the sequential Beck's method [6]. The basic idea of this method is described in the next chapter.

Basic of sequential Beck's method

The basic idea of the 1D sequential approach is to solve the entire task step by step in time. The heat flux Q_n corresponding to the time t_n is calculated based on N_f measured temperatures at times $t_n, t_{n+1}, \dots, t_{n+N_f}$. Each of these temperatures is measured at the same interior point of the test sample. N_f is the number of forward time steps and it operates as a regularization parameter.

Q_n is obtained by solving the minimization problem (1):

$$\min_{Q_n} \sum_{i=1}^{N_f} (Y_{n+i} - T_{n+i}|_{Q_n})^2, \quad (1)$$

Where Y_i are measured temperatures, and $T_i|_{Q_n}$ are temperatures calculated using a direct calculation for constant heat flux $Q_i = Q_n$. This task can be solved using a standard optimization method (for example, Brent's optimization [8]).

The minimization problem (1) can be simplified to equation (2) in a linear problem.

$$Q_{t_n} = \frac{\sum_{i=1}^{N_f} (Y_{n+i} - T_{n+i}|_{Q=0}) \Phi_i}{\sum_i^{N_f} \Phi_{n+i}^2} \quad (2)$$

Where T_i are temperatures calculated for zero heat flux and Φ_i are sensitivity coefficients. [9]

Application to real cooling process

The surface of the experimental sample is divided into N sections. Temperatures are recorded by thermocouples placed close to the surface at each section. The solution is found in the form of the N heat flux function of time $Q_1(t_n), Q_2(t_n), \dots, Q_M(t_n)$ (see figure 6). The 2D modification of the previously described sequential method can be used.

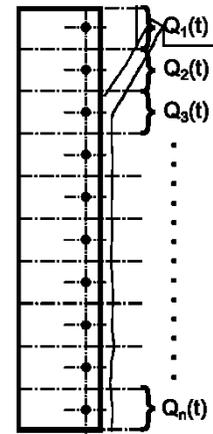


Figure 6 Heat flux function allocation to the surface area

The issue of vertical surface cooling by flat water jet

An extremely inhomogeneous surface temperature in the vertical direction can be observed in the temperature record during the experiment. Therefore, the heat fluxes are extremely inhomogeneous too, because heat fluxes are strongly dependent on surface temperature (due to LF effect figure 5).

For this reason it is important to ensure that the temperature inhomogeneity inside each section (around the thermocouple) is small enough. This can be achieved by increasing the number of thermocouples or by shifting the borders of the control section.

However, increasing the number of thermocouples is possible only up to a certain limit, because each thermocouple causes a small disruption of the natural temperature field in the surrounding material. So the temperature distribution in a sample with too many thermocouples will not match those of a sample without thermocouples.

Shifting borders modification

The basic idea behind this method is to shift the borders of the control section to separate locations with low and high cooling intensities (see figure 7).

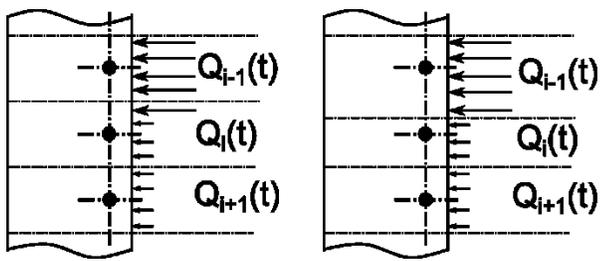


Figure 7 Principle of shifting of the borders

The left side of figure 7 illustrates the situation without border shifting where a small part of the surface (middle area) is exposed to two diametrical different boundary conditions (illustrated by arrow size). The calculated value $Q_i(t)$ is affected by a small part of the high intensity boundary condition in this case. The problem is that this “average” value is applied to the entire middle area in the following computation. This causes overcooling of the surface even at the lower border of this middle section where the cooling intensity should be low. The practical consequence is that the results (boundary conditions) are distorted. The right side of figure 7 illustrates the shifted boundary.

In practice, only the interface between areas with greater/smaller surface temperature than the LF temperature is important to shift. This interface can be called the LF front. The LF front is formed just below the impingement zone and moves down during the experiments. This movement is primarily caused by the gradual undercooling of the surface by heat conduction inside the material. A typical temperature distribution is shown in figure 8.

The speed of this movement can be obtained by image analysis of the video record. The second option is to solve the position of the LF front simultaneously with the rest of the inverse task. This can be done by solving the new problem as a two-stage optimization problem. The standard IHCP is solved in the first stage. The position of the LF front is solved in the second stage based on the results and residuals from the IHCP.

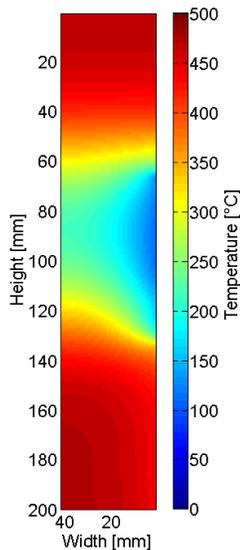


Figure 8 Typical temperature distribution inside the sample. The right side is cooled and other edges are isolated. Impingement zone is approximately 70 mm from the top edge.

CONCLUSION

Cooling by a flat water jet impacting the surface and from water flowing down is a complex and complicated process. At a minimum, a two-dimensional inverse heat conduction problem must be solved to correctly evaluate such an experiment. The issue is moreover complicated by the Leidenfrost phenomenon at high temperatures.

The conventional method leads to a significant distortion of the results. This distortion of results can be minimized by using the described shifting borders modification. A comparison of relative heat transfer coefficients of the standard and modified method is shown in figure 9.

The verification procedure was developed at the Heat Transfer and Fluid Flow Laboratory of BUT.

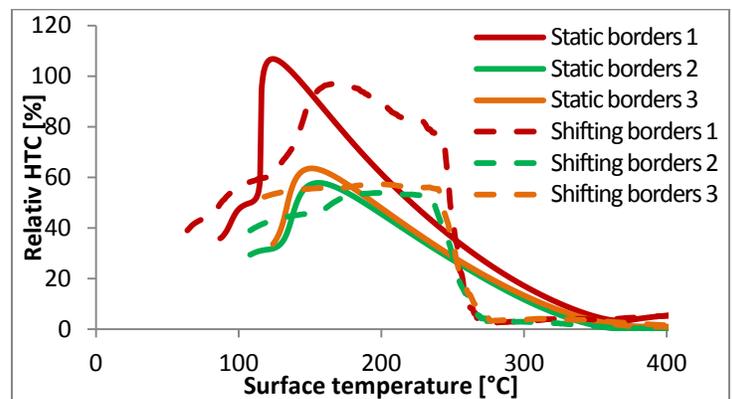


Figure 9 Comparison of relative HTC function with and without shifting of borders

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