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A NONDESTRUCTIVE EXPERIMENTAL DETERMINATION OF THE HEAT FLUX DURING COOLING OF DIRECT-CHILL CAST ALUMINUM ALLOY BILLETS

NEPORUŠITVENO EKSPERIMENTALNO DOLOČANJE TOPLOTNEGA TOKA PRI HLAJENJU POLKONTINUIRNO ULIVANIH DROGOV IZ ALUMINIJEVIH ZLITIN

Miha Záložnik[1], Ivan Bajsić[2], Božidar Šarler[3]
[1]Impol d.d., Sektor razvoj, Partizanska 38, 2310 Slovenska Bistrica, Slovenija
[2]Univerza v Ljubljani, Fakulteta za strojništvo, Laboratorij za meritve v procesnem strojništvu, Aškerčeva 6, 1000 Ljubljana, Slovenija
[3]Politehnika Nova Gorica, Laboratorij za večfazne procese, Vipavska 13, 5000 Nova Gorica, Slovenija
miha.zaloznik@p-ng.si, ivan.bajsic@fs.uni-lj-si, bozidar.sarler@p-ng.si

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For the computational modeling of direct-chill (DC) casting we need to know the heat flux on the surface of a billet. This is particularly important in the submold direct-chill region, where the heat flux density is the greatest. In order to gather more information about the convective heat transfer in the DC zone we need experimental data. Until now, expensive, destructive measurement methods have been used for this purpose; however, recently there have been developments of a nondestructive measurement technique for determining the local heat flux based on a measurement of the water film temperature. Experiments using this new technique and a specially designed thermocouple sensor were carried out in a real plant environment. The results were inputted into an existing computational model by a modification of the boundary conditions in the DC zone. Simulations using both the original and the experimentally modified boundary conditions are performed and compared.

Keywords: aluminum alloys, direct-chill casting, temperature measurement, computational modeling, simulation, boundary conditions, heat transfer

Pri numeričnem modeliranju procesa je pomembno poznanje toplotnih tokov s površine droga na hladilo, predvsem v območju tik pod kokilo, kjer so toplotni tokovi največji. Izkaže se, da so za to potrebni eksperimentalni podatki realnega procesa. V ta namen smo do sedaj uporabljali drage destruktivne merilne metode. V tem delu je zasnovana nedestruktivna merilna metoda, ki na temelju merjenja prirastka temperature obtekajočega hladila vzdolž droga daje lokalne vrednosti toplotnega toka s površine droga na hladilo. Nova merilna metoda je uporabljena pri poizkusih, izvedenih v realnem sistemu, pri čemer je uporabljeno večtočkovno termoelektrično temperaturno zaznavalo lastne konstrukcije. Na temelju eksperimentalnih rezultatov so modificirani robni pogoji za sekundarno cono hlajenja v obstoječem numeričnem modelu temperaturnega polja droga. Primerjani so rezultati simulacij s prvotnimi in z modificiranimi robnimi pogoji.

Ključne besede: aluminijeve zlitine, kontinuirno litje, meritve temperature, numerično modeliranje, simuliranje, robni pogoji, prenos toplote

1 INTRODUCTION

Semicontinuous direct-chill (DC) casting is currently the most widely used process in the production of aluminum alloys [1]. Because of the complex interactions of the process parameters, numerical simulation methods are used to better comprehend the process and to improve the process operation. At the Impol aluminum factory a computational model of the DC casting process is used to determine the control algorithm installed in the automated casting control system.

In DC casting (**Figure 1**) the melt is poured from the furnace through a troughing system into a bottomless mold with the cross-sectional shape of the billet. A starter head, mounted on a hydraulic ram, forms a false bottom to the mold. When the metal fills the mold, the starter head begins to lower at a controlled rate. As it lowers, the metal inside the mold partly solidifies to form a solid shell strong enough to support the melt. Below the mold, water jets built into the mold spray water onto the billet surface to cool the billet and complete the solidification. Since heat transfer in the billet determines the progress of solidification and thus influences the crystal structure of the alloy, it has a strong impact on the resulting properties of the product. Most heat is extracted in the secondary cooling zone by cooling water flowing directly over the billet surface in the form of a falling water film. During normal operation, heat is transferred by a combination of forced single-phase convection and subcooled convective boiling. Because of the significant influence of the heat-transfer rate at the billet surface on solidification, proper modeling of the thermal boundary conditions is crucial to the process simulation.

Because of plant-specific conditions, all the correlations used to describe the heat transport in the computational model should be verified experimentally with respect to a wide spectrum of casting formats and

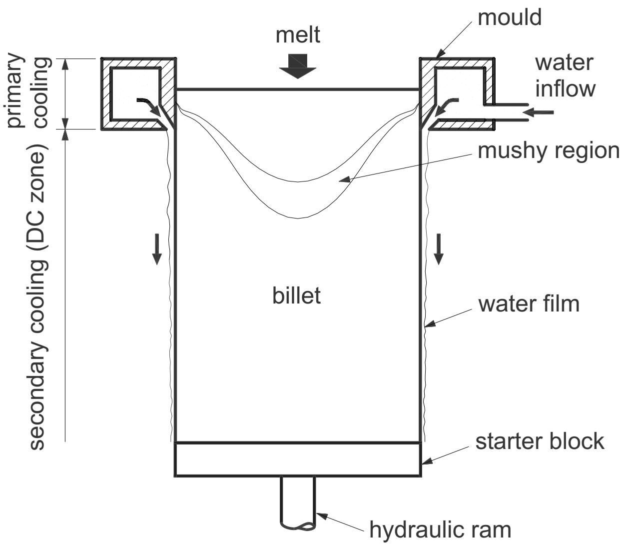

Figure 1: Schematics of the DC casting process
Slika 1: Shematični prikaz procesa polkontinuiranga ulivanja

alloy types. Until now, expensive, destructive measurement methods have been used for this purpose. Liquid-pool depth measurements involving the insertion of steel rods and zinc flooding [2] as well as temperature field measurements with thermocouples immersed in the liquid pool [3] have been performed. To be able to conduct a larger number of experiments in an economical way, the method described in this paper has been designed. This is not meant to be a complete design study, but rather a demonstration of the feasibility of such a measurement technique.

In this study we begin the development of an alternative, nondestructive measurement technique. The average local heat-flux densities at discrete intervals along the billet surface are measured indirectly by measuring the cooling-water temperature increase in the downstream direction. The cooling-water temperature is measured using a specially designed thermocouple sensor, which allows access to the casting machine's interior and immersion of the thermocouple tips in the thin water film. Experiments using the new technique have been performed in a real plant environment at the Impol foundry. The boundary conditions in the computational model are plant-specifically corrected in accordance with the experimental data. The results of the simulations using the original and the modified model are compared.

2 EXPERIMENT

2.1 Experimental setup

All the experiments were conducted in a real plant environment at the Impol foundry in Slovenska Bistrica. The measurements were carried out on a Gautschi VHK 14.700-275/185 model 1988 DC casting machine consisting of 18 molds with a height of 85 mm and an inner diameter of 291 mm for the simultaneous casting of 18 billets with a nominal diameter of 288 mm and a maximum length of 7.5 m.

The cooling-water temperature was measured in the submold DC region at seven consecutive points in the downstream direction of the water flow. Because of the small thickness of the falling water film (approximately 2 mm) and the uneven and rough billet surface, it is experimentally difficult to ensure a proper immersion depth of the thermocouple tips in the film, while at the same time preventing direct contact between the thermocouples and the hot billet surface. Therefore, the thermocouple tips were placed into small plastic cups of 7-mm diameter, which were attached by leaf springs to a specially designed support. The support is mounted on a pivot that was welded to the casting machine's frame allowing it to be rotated toward the billet surface. When placed in the measuring position the cups lean against the billet surface allowing it to slide on them as it moves downwards. Water flowing over the surface of the billet collects inside the cups. A small opening on the bottom of the cups allows the water to flow out of the cup continuously and prevents it from accumulating and disturbing the flow field in the film. This design ensures the proper immersion of the thermocouple tips and reduces unwanted influences on the measurement.

Since the heat flux is highest just below the mold, it is essential that the topmost measurement point be placed as close to the mold edge as possible to obtain useful information from the measurements. The water impingement point is estimated to be ≤5 mm below the lower mold edge. The first thermocouple cup was placed 10 mm below the mold's bottom edge. The relative positions of the sensor, the billet and the mold are shown in **Figure 2**. The vertical positions of the thermocouple

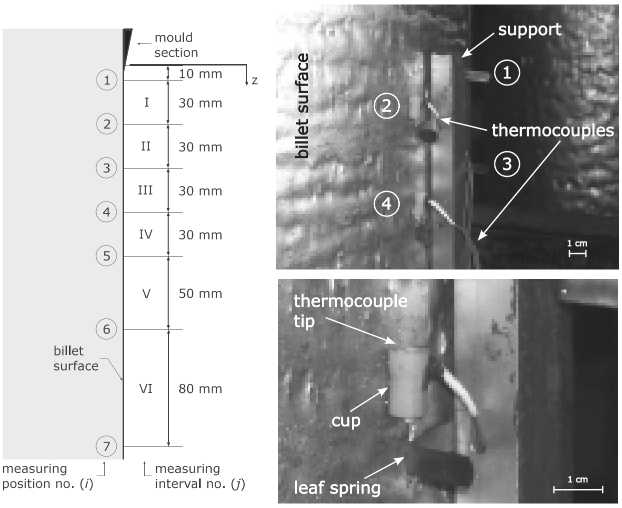

Figure 2: Schematics of the experimental setup geometry showing measurement positions (left), thermocouple sensor (top right), and capturing cup (bottom right)
Slika 2: Shematični prikaz postavitve zaznavala (levo), večtočkovno termoelektrično zaznavalo (desno zgoraj) in zbiralna posodica (desno spodaj)

tips can vary by ±3 mm due to deflection of the leaf springs.

Seven type-K thermocouples with 0.5-mm wire diameter and glass-fiber insulation were used. The welded bare wire tips of 1-mm diameter and 3-mm length were protected by a thin, plastic coating to prevent the ingress of water. The thermocouples were connected to a Yokogawa DR230 multi-channel recorder. They were calibrated in accordance with [4] and the total standard uncertainty of the temperature measurement was ±0.7 °C. The sampling interval was set to 2 s. The total casting table water flow was measured by an orifice flowmeter and recorded by the control-panel instrumentation installed at the casting machine. A uniform distribution of the cooling water among the 18 molds is assumed.

2.2 Experimental procedure

Since the experiments were carried out in a real plant environment, the experimental procedure had to be adapted to the manufacturing process in the casthouse. The casting machine's interior is only accessible during the pre-casting phase. Therefore, the thermocouple sensor had to be placed inside before the casting started. After a cast length of 0.4 m was reached, the temperature sensor was moved into the measurement position and the temperature measurements were started. They were conducted for the entire casting period (about 3 hours). As the interior of the casting machine is not visible during casting, the sensor could not be observed during the measurement. Therefore, it had to be thoroughly inspected after every experiment to identify any possible sources of systematic error due to damage that may have occurred during the experiment. The vertical positions of the sensor, all the cups, and the thermocouple tips were checked before and after every experiment.

Because the principal casting parameters - casting speed, cooling-water flow, melt temperature - are different for every alloy, the experiments were grouped according to alloy type. Measurements were performed on the billets of three different aluminum alloys: AlCuBiPb, AlCuMgPb and AlMgSiPb. Two measurements were made for each alloy. All billets had a diameter of 288 mm.

3 EXPERIMENTAL RESULTS

Typical measured cooling-water temperatures as a function of time are shown in **Figure 3**. The gradual simultaneous increase of all the measured temperatures that can be observed is caused by the increase of the water temperature in the closed cooling-water system. We found that this does not influence the measured temperature differences.

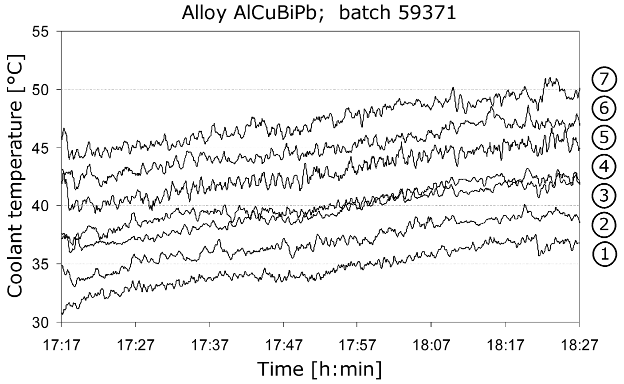

Figure 3: Measured cooling-water temperatures for experiment #2
Slika 3: Izmerjene temperature hladilne vode pri poizkusu #2

Using equation (1) the average heat flux densities on the measuring intervals I through VI (according to **Figure 2**) were obtained from the measured temperatures. They are summarized in **Table 2**.

$$\bar{q}_{\mathrm{s},j} = \frac{q_{m,\mathrm{w}} c_{p,\mathrm{w}} (T_{i+1} - T_i)}{\pi D (x_{i+1} - z_i)} \qquad (1)$$

In equation (1) $\bar{q}_{\mathrm{s},j}$ denotes the average heat flux density on the j-th interval, $q_{m,\mathrm{w}}$ the billet water mass flow, D the billet diameter, T the measured temperature and z the distance from the mold bottom. Subscript j denotes the interval number (in roman numerals) and subscript i the measurement point number, both according to **Figure 2**.

Table 1: Casting parameters
Preglednica 1: Parametri ulivanja

Alloy	**AlCuBiPb**		**AlCuMgPb**		**AlMgSiPb**	
Experiment #	1	2	3	4	5	6
T_{cast}, °C	710	710	705	705	705	705
v_{cast}, m/min	5.0	5.0	4.5	4.5	4.5	4.5
$q_{m,\mathrm{w}}$, kg/s	2.10	1.93	1.48	1.44	1.88	1.87

An uncertainty analysis of the experimental results according to [4] was performed. It was shown that the expanded measurement uncertainty of the measured heat flux typically reaches 50% of the measured value, the principal contribution being the uncertainty of the temperature measurement as a result of limited instrumentation accuracy. The main problem with the obtained results is the large scattering, which can be observed in **Table 2** by comparing experiments on the same material. Because of the fragility of the preliminary sensor design and the limited possibility of monitoring the measurement, systematic errors are likely. Even though they can be identified they are difficult to estimate.

4 COMPUTATIONAL ANALYSIS

4.1 Computational model

The obtained experimental results were used for verifying an existing computational model of DC

Table 2: Average heat flux density on billet surface
Preglednica 2: Povprečna gostota toplotnega toka na površini droga

Distance from mold (mm)		Alloy	**AlCuBiPb**		**AlCuMgPb**		**AlMgSiPb**	
z_i	z_{i+1}	Experiment #	1	2	3	4	5	6
10	40	$\bar{q}_{s,I}$, W/m^2	N/A	700000	900000	880000	560000	1450000
40	70	$\bar{q}_{s,II}$, W/m^2	N/A	770000	830000	800000	1350000	1100000
70	100	$\bar{q}_{s,III}$, W/m^2	840000	230000	680000	1160000	1510000	1420000
100	130	$\bar{q}_{s,IV}$, W/m^2	460000	800000	120000	30000	680000	670000
130	180	$\bar{q}_{s,V}$, W/m^2	440000	380000	150000	360000	360000	N/A
180	260	$\bar{q}_{s,VI}$, W/m^2	70000	260000	360000	410000	N/A	

casting. A detailed description of the model is given in [5]. Briefly, an axisymmetric geometrical model was used; Dirichlet-type boundary conditions were applied at the top boundary, symmetry boundary conditions at the billet center and Robin boundary conditions at the billet surface, in both the primary and secondary cooling zones. An adiabatic bottom boundary was assumed. The single-phase enthalpy conservation model of Bennon and Incropera [6] was used to describe the thermal field. The material properties used were simplified as follows. The densities of the liquid and solid phases (indicated by subscripts L and S, respectively) are assumed to be constant and equal $\rho_L = \rho_S = 2820$ kg/m^3. Specific heats $c_{pL} = c_{pS} = 864$ J/kgK and thermal conductivities $\lambda_L = \lambda_S = 152$ W/mK were modeled in the same way. The solidus temperature is $T_S = 814$ K and the liquidus temperature is $T_L = 911$ K. The liquid fraction f_L is assumed to increase linearly between T_S and T_L. The melting enthalpy is $h_M = 378$ kJ/kg. Casting parameters as shown in **Table 1** were applied. The effective mold height is 70 mm. The solution procedure was based on the dual-reciprocity boundary-element method (DRBEM). The model check was limited to a verification of the boundary conditions used in the DC zone (secondary cooling zone). A modified version of the Weckman-Niessen [7] relation was originally used for the heat-transfer coefficient applied in the Robin-type boundary condition:

$$\alpha_{\text{chill}} = c_\alpha \left[-1.67\cdot 10^5 + 352(T_{\text{wall}} - T_{\text{cool}}) \right] \left(\frac{q_{V,\text{w}}}{\pi D} \right)^{1/3} \qquad (2)$$

where the correction coefficient c_α had a value of 1.2. T_{wall} is the billet's surface temperature, T_{cool} is the water film's bulk temperature and $q_{V,\text{w}}$ is the cooling-water volume flow.

4.2 Verification procedure

Simulations using the original model were performed first. Then the calculated heat flux in the DC zone was compared to the measured heat flux. An estimate of the modification of the heat-transfer coefficient was made and a calculation using the modified model was run. The procedure was repeated iteratively until a good match between the computational and the experimental results was achieved. After two iterations the final expression was found to be:

$$\alpha_{\text{chill}} = c_{\alpha,2}\, c_\alpha \left[\left(-1.67\cdot 10^5 + 352(T_{\text{wall}} - T_{\text{cool}}) \right) \left(\frac{q_{V,\text{w}}}{\pi D} \right)^{1/3} + 20.8(T_{\text{wall}} - T_{\text{sat}})^3 \right] \qquad (3)$$

In equation (3) an additional term taking into account subcooled nucleate boiling, which occurs in the water film at the billet's surface for temperatures above 100 °C, was added. Additionally, another correction factor $c_{\alpha,2}$

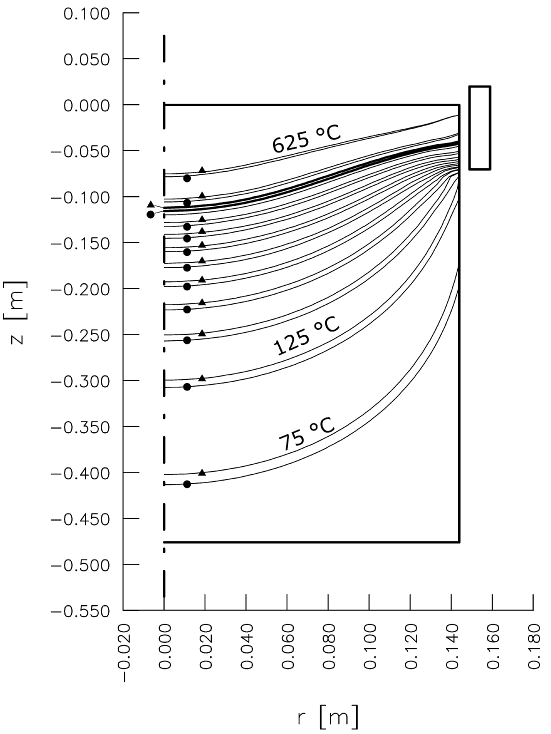

Figure 4: Comparison of the calculated temperature fields. ● denotes isotherms from the original model simulation and ▲ isotherms from the modified model simulation. The temperature difference between the two isotherms is 50 °C. The bold lines represent the solidus.

Slika 4: Primerjava izračunanih temperaturnih polj. Z ● so označene izoterme, izračunane pri simulaciji s prvotnim modelom, z ▲ pa izoterme, izračunane pri simulaciji z modificiranim modelom. Temperaturna razlika med dvema izotermama je 50 °C. Krepki liniji označujeta izotermo solidus.

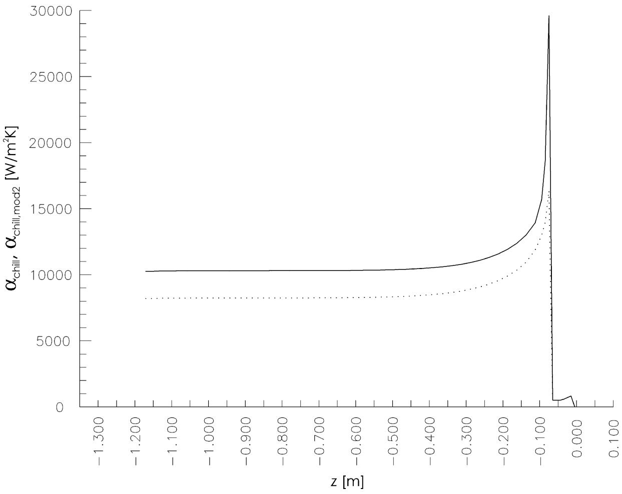

Figure 5: Heat transfer coefficient as a function of the axial coordinate for Experiment #2. The dotted line represents the original (Equation (2)) and the full line the modified (Equation (3)) model.

Slika 5: Toplotna prestopnost kot funkcija vzdolžne koordinate pri poizkusu #2. Črtkana črta označuje prvotni model (Enačba (2)), polna črta pa modificirani model (Enačba(3)).

with a value of 1,25 was added. T_{sat} denotes the water saturation temperature.

The comparison of both simulations showed that the inclusion of the nucleate boiling term causes a high peak in the heat-transfer coefficient at high surface temperatures, which intensifies heat extraction directly below the mold (up to a distance of 20 mm below the mold edge). Thus, the whole heat extraction process shifts upstream, closer to the mold. This causes a slight decrease of the billet's surface temperature. Hence, the heat flux density further downstream decreases (though insignificantly) despite the globally higher heat-transfer coefficient. The simulations with Equation (2) and (3) were compared and they showed that the temperature gradients and the isotherm positions near the mushy region change only slightly. The position of the solidus isotherm changed by approximately 10^{-2} m at the billet center as well as on the surface.

5 DISCUSSION

This paper describes a preliminary study showing all the basic principles of a newly designed nondestructive experimental method. It demonstrates its use and implements the experimentally obtained data. Because the requirements concerning the reproducibility of the measurements were not fully met, further improvements to the measurement technique and the measurement equipment used are under way. They will resolve the difficulties concerning the observation of the experiment and improve the sensor design to make it more robust. This will be done by video observation of the experiment with a mini camera and a more sophisticated design of the leaf springs. This will allow us to get more detailed and reliable information from the measurements, namely the local values of the surface heat flux. Additionally, experimental validation of the computational model will also include measurements of the heat flux at the base of the billet (to the starter block) during the startup phase.

The boundary-condition modifications introduced into the computational model have shown that the temperature field response to the change of the DC heat-transfer coefficient is lower than expected. Further experimentation will investigate the conditions during the startup casting phase, where the sensitivity to cooling conditions is higher, as already shown by Maenner et al.[8].

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