Heat flow and heat transfer coefficient during crystallization under the pressure

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Abstract. Estimation of the heat flow at the metal-mold interface is necessary for accurate simulation of the solidification processes. For the numerical simulation, a precise prediction of boundary conditions is required to determine the temperature distribution during solidification, porosity nucleation, microstructure development, and residual stresses. Determination of the heat transfer coefficients at the metal-mold interface is a critical aspect for simulation of the solidification process and the microstructure modeling of the castings. For crystallization under the pressure and for thin-walled castings, HTC evaluation is important due to the very limited freezing time.

Keywords: Squeeze casting, HTC, Heat flow, Pressure.

1 Introduction

All the thermal phenomenons in the casting-mold system are very closely related to the release and transfer of heat during solidification and cooling of the casting. The rate of heat transfer is very important to determine the solidification time and the distribution of temperature fields throughout the system. It also directly and indirectly affects the resulting microstructure, and thus the quality and properties of the future casting [1, 3, 4].

The heat flow between the casting, mold, and surrounding environment is from the initial contact of the melt with the mold up to his complete cooling a non-stationary phenomenon. In non-stationary thermal processes, the thermal content of the solid is changing. The heat content of the casting decreases and the mold rises until the heat contents and temperatures are balanced. The change rate of the thermal content of the solid, the rate of isotherm process and temperature equalization is directly proportional to his thermal conductivity λ and inversely proportional thermal-capacity cabability $c.\rho$. [1, 2, 5, 6].

The heat flow at the interface between the mold and the casting directly influences the solidification process and plays an important role in determining the solidification conditions of the casting metal. In the process of the casting under pressure, the casting quality is directly affected by the transfer of heat to the casting-mold interface, where the amount of heat transferred from the casting to the mold is changing over time. By creating an air gap at the casting-mold interface during solidification, the value of the heat transfer

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coefficient decreases. The change of heat transfer coefficient by the casting time is a key factor for controlling solidification. The value of this coefficient is influenced in particular by the heat-physical properties of the materials, the temperature of the mold, the temperature of the metal, the working pressure, the casting geometry, the roughness of the mold surface and the protective coating of the mold [3, 7, 8, 10].

The squeeze casting technology, which was used in experimental verification of the heat transfer is a relatively unusual method. This is due, in particular, to little experience with practical use combined with the low lifetime of the mold. The pressure value for squeeze casting is from 30 to 150 MPa. The pressure itself prevents the formation of an air gap which normally formed during gravity casting at the interface between the casting and the mold. By eliminating this air gap, there is a significant increase of the heat transfer and the heat flow from the casting into the mold. The melt and later the casting itself is constantly in contact with the walls of the metal mold, which resulting in a significant increase the rate of solidification and cooling of the casting. The result is a change of the structure and mechanical properties of the casting. In The structure, the grains size of the primary structure is reduces and also is change the morphology of eutectic silicon and intermetallic phases, which act less harmful. The resulting structure is finer and more uniform throughout the volume. The concentration of silicon in the eutectic and the volume ratio of the primary α-phase are increased and the volume of the eutectic in the structure is reduced. The result is a change in mechanical properties, where the strength, elongation and fracture toughness are increasing [2, 4, 9, 10].

2 Experimental material and process

For experimental casting, direct squeeze casting method was used. Precisely measured dose of the liquid metal was poured into the mold cavity. The mold was machined from low carbon steel. The surface of the mold cavity and the plunger has been treated with a protective paint type Terracotta. The liquid melt was pressed by using a plunger which section area was 1000 mm2. The onset of action was approximately 8 seconds by filling mold. The sample was under pressure until the cooling of the melt to 200 °C. During the experiment was casted 4 samples at various temperatures and the applied casting pressure. The casting parameters are listed in Tab. 1. The first sample was cast by gravity casting at a temperature of 710 °C. Further samples were cast under pressure by using technology squeeze casting. In both cases the metal mold was preheated to 100 °C. For measuring the temperature of the melt and mold 8 thermocouples type K were used, with a wire Do = 0.25 mm in order to respond rapidly. Position of the thermocouples is shown in Fig. 1.

Table 1. Casting parameters for individual samples

sample	pressure [MPa]	casting temperature [°C]	mold temperature [°C]
1	0.1	710 ± 5	20 ± 3
2	50	710 ± 5	100 ± 3
3	100	710 ± 5	100 ± 3
4	150	710 ± 5	100 ± 3
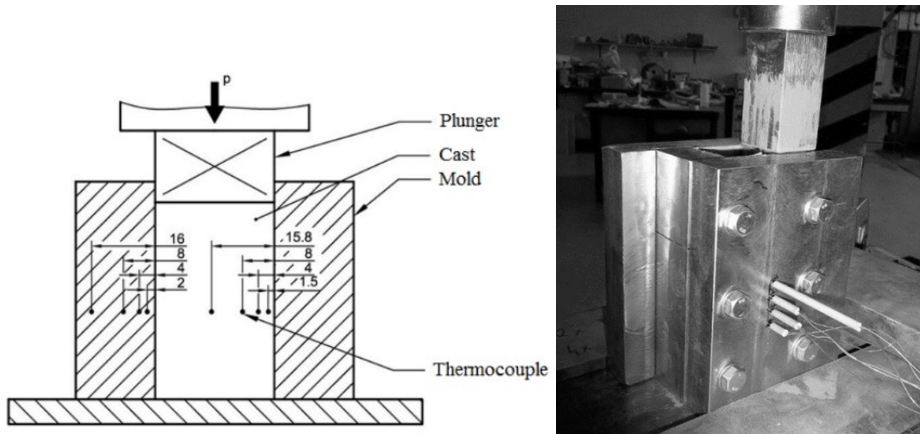
Fig. 1. Principle of thermocouples distribution

The governing heat transfer equation in one-dimensional coordinates is given by equation (1):

$$\rho c_{\text{p}} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) \tag{1}$$

The heat flux on the interface cast-mold can be calculated from the temperature gradient on the surface and the subsurface layer using the equation (2):

$$q = -\lambda \frac{\partial T}{\partial x} 5 = -\lambda \frac{T_1 - T_2}{\Delta x} \tag{2}$$

where λ is thermal conductivity from the casting to the mold. $T_{1,2}$ are temperatures of the measured points and Δx is the distance between these points.

The average heat transfer coefficient HTC at the interphase may be expressed mathematically (3):

$$HTC = \frac{q}{(T_O - T_F)} \tag{3}$$

where T_O is temperature casting surface, T_F is temperature mold surface.

The alloy AlCu4Ti was used for the experiment. Regarding this alloy, a significant solidification front should not occur, and also a wide freezing interval provides a sufficiently long period of time to initiate the pressure action during the time of the alloy crystallization. This alloy was therefore suitable for detecting the heat flow from the cast into the mold. The chemical composition of the AlCu4Ti alloy is shown in Table 2.

Table 2. The chemical composition of the experimental alloy AlCu4Ti

Element	Si	Cu	Mg	Ni	Sn	P	Sb
[at. %]	0.05	4.612	0.005	0.006	0.025	0.0005	0.00463
Element	Ti	Fe	Mn	Na	Zn	Zr	Pb
[at. %]	0.171	0.127	0.456	0.0001	0.008	0.001	0.002

3 Results

The measured values were processed in a tabular processor Microsoft Excel. From the measured curves of temperature in casting and mold, temperature on the surface of the mold and casting was estimated. In individual time points was by using the regression curve determined an identified temperature in the zero distance from the surface. Principle of evaluation is shown in Fig.2-3.
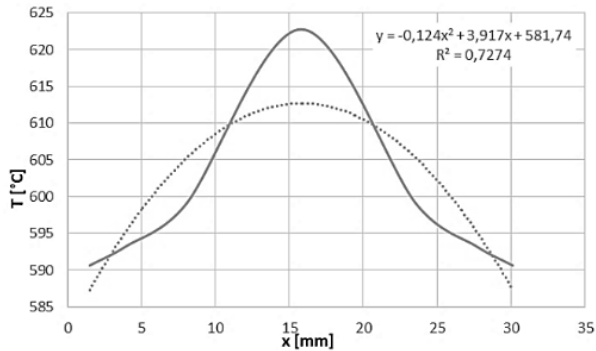

Fig. 2. The fundamentals of determining the surface temperature of the casting by regression curves
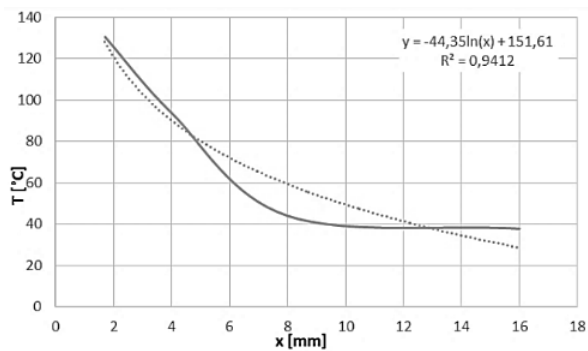
Fig. 3. The fundamentals of determining the surface temperature of the mold by regression curves

In Fig. 4 is shown the course of the temperatures at the casting without pressure.
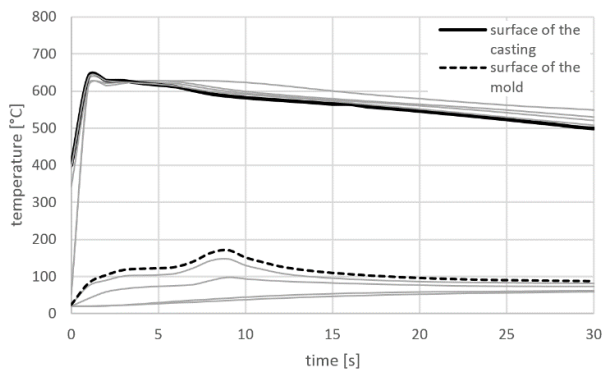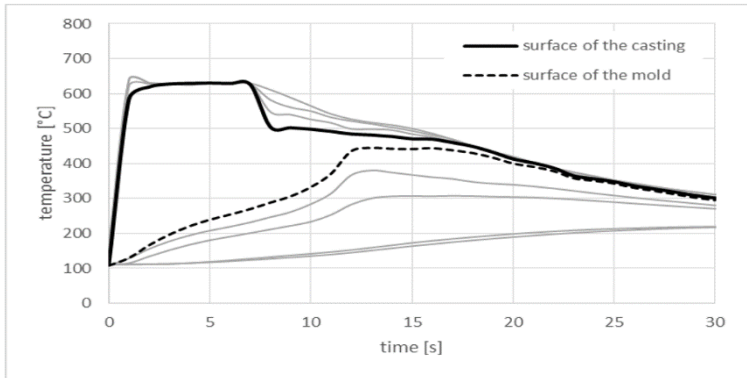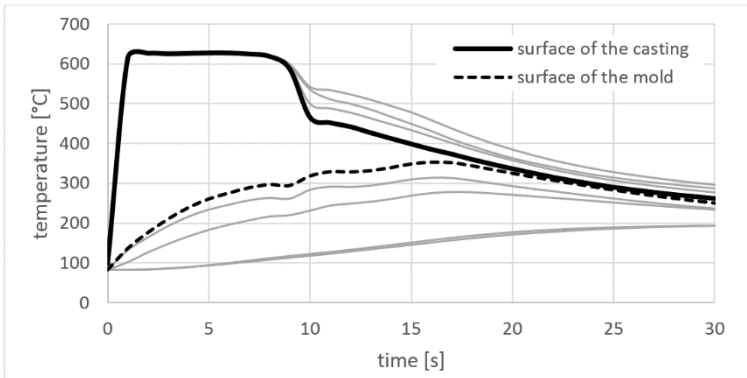

Fig. 4. Temperatures in the casting and in the mold at the gravity casting
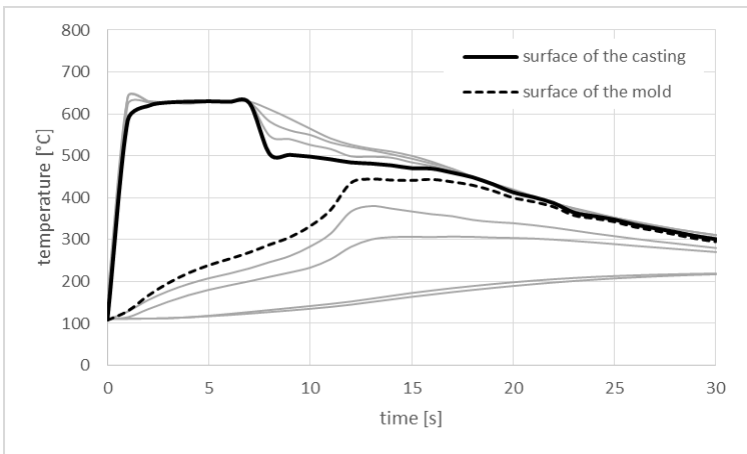
In Fig. 5-7 is shown the course of the temperatures with using squeeze casting technology.

Fig. 5. The temperatures in the casting and in the mold at the operating pressure 50 MPa

Fig. 6. The temperatures in the casting and in the mold at the operating pressure 100 MPa

Fig. 7. The temperatures in the casting and in the mold at the operating pressure 150 MPa

3.1 Heat flux and heat transfer coefficient

The heat flux on the interface between casting and mold was determined from temperatures on the surface of a mold and temperatures 2 mm under the surface by the equation (1). The results of HTC were calculated by the equation (2). The course of heat flux and HTC for each sample is shown on the figures 8-11.
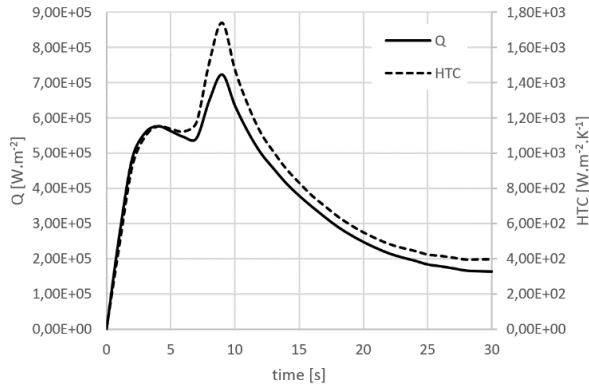

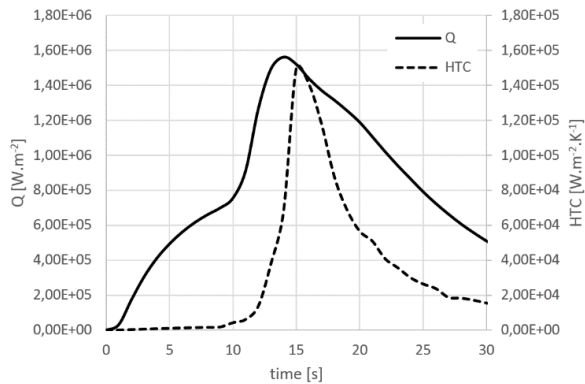**Fig. 8.** Heat flux and HTC in gravity casting at pouring temperature 710 °C

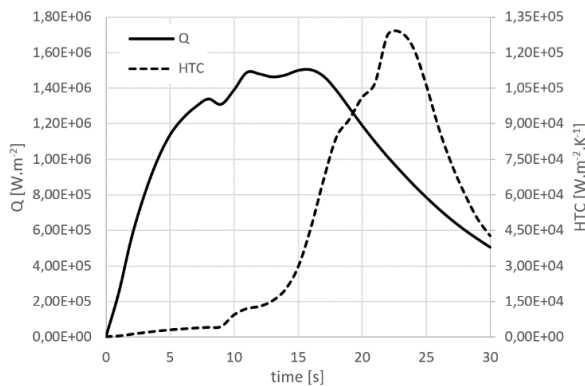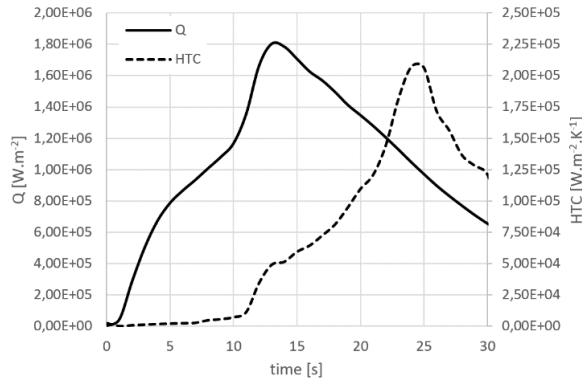**Fig. 9.** Heat flux and HTC at pouring temperature 710 °C and pressure 50 MPa

Fig. 10. Heat flux and HTC at pouring temperature 710 °C and pressure 100 MPa

Fig. 11. Heat flux and HTC at pouring temperature 710 °C and pressure 150 MPa

From the results of the measurements it is clear, that there has been a significant increase of the heat flow and the heat transfer coefficient, which result was in faster cooling of the casting. The amount of heat Q that passes through the isothermal surface S is defined by multiplying the heat flux q and time τ

$$Q = q \cdot S \cdot \tau \tag{4}$$

The amount of heat that has been cast from the cast into the mold for 30 seconds is shown in fig. 12.
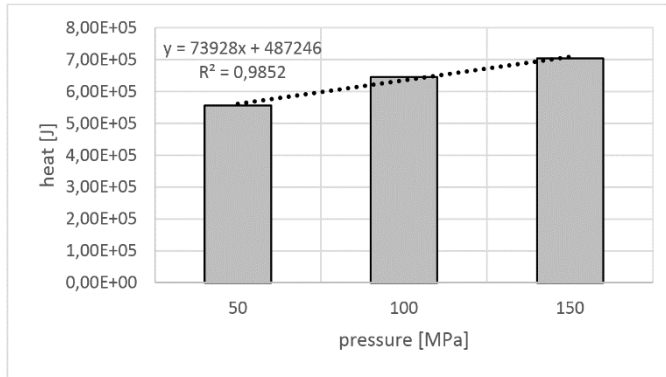
Fig. 12. Amount of heat transmitted to the casting

Conclusions

Heat flux in the gravity cast sample increased within 5 seconds after pouring. Shrinking of the casting resulted in the formation of a gap at the casting-mold interface. The formed gap caused reduced heat flux from the casting. In the unaffected sample, the heat flux at the onset of pouring increased to the value of $5.75.10^5$ W.m^{-2}. At time 7 seconds after pouring, heat flux through the gap started to apply. The heat flux value increased up to $7.22.10^5$ W.m^{-2}. Heat transfer coefficient reached the value of $1.15.10^3$ W.m^{-2}.K^{-1} at the onset of pouring, only to increase to the value of $1.74.10^3$ W.m^{-2}.K^{-1} when applying heat transfer through the gap. For technological reasons, pressure was applied 8 seconds after filling the mold. All samples affected by pressure experienced a significant increase in both the heat flux and heat transfer coefficient at the casting-mold interface. At the casting temperature of 710 °C, the increase in HTC was 187-fold at 50 MPa, 317-fold at 100 MPa,

and 525-fold at 150 MPa. Heat transfer at the casting-mold interface significantly increases with the increasing difference in heat contents of the poured material and the mold, and also with the increasing applied pressure.

It was observed the amount of heat that has passed into the casting mold. A direct relationship between the amount of heat and the applied pressure was observed.

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