Heat transfer analysis during cooling of die with use of water mist

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Abstract

The paper presents the results of the heat transfer area during the cooling process of steel test die with water mist which consist the flow of air in the range 150÷350 l/min and 0.05÷0.24 l/min of water. Temperature change in the thickness of die by means showing with the thermal curves and the temperature gradient and temperature distribution in the space between the nozzle and the cooled surface of the metal mold using a thermal imaging camera and thermocouples measurement. The course of changes in the temperature gradient and the received heat flux from the die while cooling its with the flow of air and water mist stream. It has been shown that the use of water mist with a variable flow of air and water controls the process of heat transfer process between the permanent molds, and a stream of water mist.

Keywords: Innovative Materials And Casting Technologies, Cooling, Water Mist, Die Casting, Heat Flux

1. Introduction

Results shown in this paper are the continuation of research on improving die casting quality and decreasing silumin casting time [1÷3]. The main concern of the work was the usage of water mist as the cooling medium for chosen surface areas of the die in such manner that the temperature is reduced due to evaporation of water mist drops on the die. This way of heat absorption makes the cooling process more efficient than the heat exchange caused by the flow of only water or only air.

The purpose of the examinations that were carried out for this paper was to analyze the heat exchange in the cooling process of a casting die when it is being cooled down with a water mist. The area of particular interest was between the die front/plane and the nozzle that spreads the water mist. It was also important to examine what influence the hot die surface has on the individual water drops and furthermore how the different water – air ratio affects the temperature gradient and portion of heat taken away from the cooled die.

2. Experimental

The examinations were conducted on the station presented in the Figure 1. The water mist was produced in the device (1, 2) in the manner of dosing of certain amounts of compressed air and water and dispersing them with a swirling spray. The proportions were achieved with a use of valves (6) operated by a computer driver and registered with flowmeters connected to a computer system (9).

The test die was made of X37CrMoV51 steel (10) and had an electric heating element installed inside. The die was placed in a termic cover so that the only area where the heat exchange could occurred was the circular front surface, that was cooled in spots with a cylinder nozzle. The temperature was measured with thermocouples of K-type placed in the room between the die and the nozzle as well as on the surface of the die. The entire distribution diagram including the cooled die's surface, water mist emitting nozzle and positions of thermoelements is presented in the
FIGURE 2. The temperature was sampled every second with an accuracy of 0.1°C by temperature recorders: KD7 produced by Lumel and Crystalgraph PC-2T provided by a company Z-tech both computer-assisted. While simultaneously cooling of the die with a water mist and heating it electrically there was an additional electrical energy measurement run using a SilverCrest Energy Monitor gauge from BAT. For the analysis of temperature changes in the area the heat transfer is used infrared camera's Optris PI and for recording an image stream of water mist camera, the Nikon D90.

3. Results

In the paper were analyzed the temperature distribution in the area between the water mist emitting nozzle and the plane of the cooled casting die as well as mutual influence of individual water drops on the hot die surface. It was also determined how a different water – air ratio in the water mist affects the efficiency of the heat absorption from the casting die planes in the air flow of 150÷350 l/min and water 0.05÷0.24 l/min.

3.1. Generating a stream of water mist

A comparison of example water mist streams was shown in the Figure 3. Figure 3a shows an air flow of 150 l/min and water of 0.14 l/min and Figure 3b accordingly 250 and 0.25 l/min. From the observations of the stream of water mist it is apparent that with the increasing of the air flow the geometry and structure of the stream changes. The angle of the stream spread reduces and there emerge two zones: the inner containing fragmented water droplets, probably up to the atomized form. In the outer zone of stream water droplets are significantly larger and move at a slower speed.

Fig. 1. The research station. Modules: 1, 2 - air and water metering, 3 - blending of factors, 4, 5 - solenoid supply of air and water, 6 - computer cooling control, 7, 8 - PC, 9 - cooling circuits, 10 - metal mold research

Fig. 2. Scheme arrangement of thermocouples in the area the heat transfer between the nozzle and the surface of the chilled die
3.2. Analysis of heat transfer between die surface and water mist

The examination of the heat exchange between the casting die and water mist was carried out using a cylindrical die to heat electrically. The view of the heat exchange area taken with a high-speed camera showing the impact of hot metal mold surface and a stream of water mist during the cooling process is presented in Figure 4. The research shows that emerging from the nozzle stream of water mist after a collision with the perpendicular surface of the metal mold melts in the radial direction along the surface of the metal mold with simultaneous evaporation of water droplets.

The example temperature tests conducted in the cooling area for the water mist of a flow of 260 l/min water and 0.05 l/min air are presented in the Figure 5. Thermal curves marked T1 ÷ T5 in accordance with the location thermo-elements (Fig. 2). Research shows that the lowest temperature recorded in the test zone at the point of T1, in which the water mist at a distance of 5 mm from the edge of the nozzle shows little variation of temperature value of 18°C.

The research shows that the cooling of metal die preheated to temperature of 400°C causes it to rapidly cool down (T5). The die's cooling rate is initially about 10 K/s, then decreases, and after 50 seconds at a temperature of 176°C is less than 0.3 K/s. From the analysis of temperature changes in the boundary layer of the die (Fig. 4b: T2, T3, T4) it can be concluded that starting the rapid cooling process reduces the temperature to 24 to 27°C. The highest temperature (27°C) occurs at the point T3 and lowest in T4. The temperature at the point T2 is similar to T3, however, in the whole time of cooling and in the other cooling circumstances its value is lower than at the point T3, although this point is located closer to the surface of the cooled die than the points of T3 and T4.

Probably in the middle area the heat exchange, due to the high water mist flow kinetics the boundary layer thickness at high temperature is lower. With the distance from the axis of the incoming stream in the direction to the die the temperature of the mist increases (T3> T2) and thus the cooling efficiency decreases. A comparison of the temperature at T3 and T4 indicates that within 20 mm from the water mist stream axis increase in the distance from the surface of the die from 3 to 10 mm lowers the temperature in the surface layer only by about 1°C. This means that with the distance from the axis of the incoming stream the boundary layer thickness having an isothermal temperature distribution raises and thus decreases the effectiveness of the cooling die.

Figure 6 presents the area of the heat exchange between the casting die and the nozzle recorded with an infrared camera. Studies of the Figure confirm the results shown in Figures 4 and 5, clearly indicating the presence of a high temperature layer at the surface of chilled casting die which is showed by changes in the values in of both the graphs along the horizontal and vertical lines marked on the thermovision image as well as the color changes below the surface of the casting die. In addition, the research shows that stream of the cooling water mist coming from the surface (streaks of pink color) has the temperature increased in the first few seconds of cooling to 17÷86°C, and then lowered to a value of 24 to 41°C.
Figure 7 illustrates the research outcomes on the influence of the casting die's temperature on the type of the interaction between the water drops and the cooled surface. These Figures were taken with a high speed camera.

The examination of the Figures shows that the change of casting die's temperature in the range 100°C to 500°C will dramatically change the behavior of water droplets on the cooled surface. Depending on the size droplets in the lower temperature range, immediately moisten the surface cooled it vaporize evenly. With the increase in temperatures above 126°C, the process of moistening decreases and then disappears. Droplets of water "jump" on the hot surface bouncing off an emitted cushion of water vapor.

Heat transfer process takes place relatively slowly, mainly due to convection and radiation. Based on these studies there was the dependence of temperature on the average casting die evaporation time of the water droplets developed, as shown in the Figure 8. The equation indicates that the growth in the casting die's temperature to about 170°C reduces the evaporation of water droplets while its further increase re-extends the presence time of droplets on the cooled surface.

This phenomenon was first explained in his theory by Leidenfrost, that claimed that the evaporation time of large drops reaches the minimum (about 1 s) for the heating surface temperature between 150°C and 200°C and then increases with rising temperature up to 150 s [4]. This phenomenon may also help to explain the existence of a temperature difference between the heating surface temperature and saturation temperature of the liquid $\Delta T = 10 + 100$ K, as well as the change of the boiling nature from the bubble to pellicular caused by the formation of an insulating water vapor layer on the surface of the heated die. The phenomenon is accompanied by a multiple change in the density of the heat transfer stream [4].

The conclusions derived from the studies on the casting die's surface's impact on the individual drops of water have been confirmed in observations of the behavior of the stream of water mist on the surface of casting die's depending on temperature and water and air flow in the water mist. When the casting die was cold, the water spray moistens the whole or a part of its surface. A rise in the casting die's temperature and a decrease in the water mist stream causes a reduction and the disappearance of the effect of moistening the surface of the hot casting die's.

In Figures 9 and 10 presents the influence of the cooling stream of air and water mist in the metal mold wall temperature and the size of the incoming heat flux from the chill. Research shows that the cooling of die with air stream 300 l/min flow causes a temperature gradient in the thickness of research die $7.36*10^3$ K/m and can dissipate the die, the surface heat flux is 493 W. However, the use of water mist with air flow 350 l/min and water 0.16 l/min increases the resulting chill in the wall temperature gradient of $11.88*10^3$ K/m and the received heat flux to 1090 W.
Fig. 5. The temperature of the heat transfer area between the nozzle and the surface of metal mold cooled with water mist flow 260 l/min of air and 0.05 l/min of water.

Fig. 6. Thermal view of the temperature field of space research between the surface temperature of metal mold preheated to 300°C and water mist nozzle during cooling with a flow of 280 l/min of air and 0.08 l/min of water.
Fig. 7. Images of the impact surface of the hot metal mold with the individual droplets of water: a) wetting, b) boiling and evaporation, c) without of wetting.

Fig. 8. The average time of drops evaporate from the surface of metal mold.
Fig. 9. The temperature gradient and heat flux received cooling with air flow 300 l/min

<table>
<thead>
<tr>
<th>Air flow, l/min</th>
<th>Water flow, l/min</th>
<th>Temperature gradient, (K/m)*10^3</th>
<th>Heat flux, W</th>
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<tr>
<td>300</td>
<td>0</td>
<td>7.36</td>
<td>493</td>
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</table>

Fig. 10. The temperature gradient and heat flux received with cooling water mist flow: 350 l/min of air and 0.16 l/min of water

<table>
<thead>
<tr>
<th>Air flow, l/min</th>
<th>Water flow, l/min</th>
<th>Temperature gradient, (K/m)*10^3</th>
<th>Heat flux, W</th>
</tr>
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<tbody>
<tr>
<td>350</td>
<td>0.16</td>
<td>11.88</td>
<td>1090</td>
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On the basis of tests were developed describing the statistical dependence of simultaneous effect of the amount of air and water in a stream of water mist on the wall temperature gradient of chilled die:

\[
\frac{dt}{dl} = 10.17 + 0.0067^{*}(\text{air flow} - \text{water flow})
\]

\[
\gamma = 7.36x + 168.28 \quad \text{R}^2 = 0.9845
\]

\[
\gamma = 11.88x + 53.84 \quad \text{R}^2 = 0.9867
\]

<table>
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<tr>
<th>Model</th>
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<th>Mean Square</th>
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<th>P-Value</th>
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<td>1,269</td>
<td>20.24</td>
<td>0.006</td>
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<tr>
<td>Residual</td>
<td>0,3136</td>
<td>5</td>
<td>0,062</td>
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R-squared (adjusted for d.f.) = 86.2%
Standard Error of Est. = 0.25
Mean absolute error = 0.19
4. Conclusions

The research work presented in the following conclusions:
- the volume of air and water flow can control the geometry of the stream of water mist,
- stream of vapor-cooled outflow from the surface has a temperature in the range 17÷86°C,
- die temperature rise reduces the wetting of the surface-cooled die and up to about 170°C reduces the evaporation of individual droplets of water, a further increase in temperature increases again, this time,
- use of water mist with air flow 350 l/min and 0.16 l/min compared to the cooling with 300 l/min of air 2-times increase the heat flux received from the metal mold.

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References