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Evaluation of the Temperature Distribution of a Die Casting Mold of X38CrMoV5_1 Steel

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Abstract

Relatively cold die material comes into contact with the substantially higher temperature melt during the casting cycle, causing high thermal fluctuations resulting into the cyclic change of thermal field. The presented contribution is devoted to the assessment of the impact of temperature distribution on individual zones in the die volume. The evaluated parameter is the die temperature. It was monitored at two selected locations with the 1 mm, 2 mm, 5 mm, 10 mm and 20 mm spacing from the die cavity surface to the volume of cover die and ejector die. As a comparative parameter, the melt temperature in the middle of the runner above the measuring point and the melt temperature close to the die face were monitored. Overall, the temperature was monitored in 26 evaluation points. The measurement was performed using the Magmasoft simulation software. The input settings of the casting cycle in the simulation were identical to those in real operation. It was found, that the most heavily stressed die zones by temperature were within the 20 mm from the die face. Above this distance, the heat supplied by the melt passes gradually into the entire die mass without significant temperature fluctuations. To verify the impact of the die cooling on the thermal field, a tempering system was designed to ensure different heat dissipation conditions in individual locations. At the end of the contribution, the measures proposals to reduce the high change of thermal field of dies resulting from the design of the tempering channel are presented. These proposals will be experimentally verified in the following research work.

Keywords: Product Development, Casting Process Simulation, Temperature Distribution, Mold Material, Tempering

1. Introduction

The thermal equilibrium of a high pressure die casting mold has a significant impact on casting quality, general reduction of rejects and extension of the die life. The temperature distribution in different locations of the inner die surface as well as in the depth of the die material is difficult to control. This has an unfavorable effect on the die life. The unequal temperature change at different locations in the die cavity has a significant impact on the technological process of the casting, resulting in increased amounts of scrap. Constantly recurring temperature cycles produce thermal stresses, which in connection with high specific pressure within the die result in operating conditions similar to the high dynamic stresses. These conditions include the die cavity and partly its dividing plane [1][2].

The thermal gradient depends on the thermal conductivity of the material from which the die is made, on ratio of the die volume to the cast volume and on the die temperature before casting as well. Better thermal conductivity of the die material has a considerable effect on the rapid dissipation of the heat from the die cavity. Heat dissipation is not only necessary in terms of changes in the volume of the upper layers of the die material, but also for technological reasons when casting. Correct high pressure die casting functionality requires the die to have an optimal temperature at which the most economical operation is guaranteed. Any increase in die temperature above this optimal limit is undesirable and results in many problems, most often of which the cast adheres to the die walls, the deterioration of the casting surface and the variation of the solidification conditions of the cast in die arise. Optimal thermal conductivity of the die material allows for the equalization of temperature the more intensive rhythm without any breaks [2].

Greater ratio of the die material volume to the cast volume facilitates the heat transfer from the top die layers to its entire volume, which contributes to increasing of its life. For example, when casting aluminum alloys under the pressure at a higher ratio of the die to cast volume, the mold life is longer than that of ordinary casting to the metal mold, in which very thin walls predominate. By high pressure die casting, the die works under substantially more difficult conditions, and die cavity is not protected by any means like during the metal mold casting [3][4].

The liquid metals feeds the die with a considerable amount of heat in rapid succession. Despite the heat dissipates continuously to the machine body, to the ambient and to the clamping device, in case of alloys with higher melting point or thick-walled casts, the die is heated in a short time so that the cast solidification would take too long and could damage the die by overheating. Therefore, the heat must be dissipated to the air or refrigerant in a greater extent. In each operation cycle, optimal amount of heat must be dissipated to avoid too much heating, tempering or overheating of the die, and so that the die temperature would be kept as constant as possible. As a refrigerant, the chemically treated water, water mist, oil, glycol or compressed air (low efficiency) are being used. Cooling means high demands on the alternating stress resistance of dies. Proper cooling is intended to reduce the heat gradient between the die cavity temperature and die layer temperature farther away from the die face. In the production of the die from one piece of material, the proper positioning of the tempering channels does not make any problems. For more complex dies composed of different inserts may arise considerable problems with positioning and manufacturing of the tempering channels, since it is necessary to cool every larger insert and core as much as possible while ensuring the perfect tightness in operation so that the refrigerant does not enter the die cavity. Properly designed and functioning tempering must also ensure the increase in work rate that means it must ensure that the time needed to complete solidification of the cast is shortened[3][4][5].

The main objective of the presented contribution is to assess and evaluate the thermal distribution of high pressure die casting die made of steel X38CrMoV5_1, which is commonly chosen, die making material for casting of aluminum alloys. Measurement were realized within the optimization of the die tempering system design. On the basis of the above-described theoretical principles, it has been hypothesized that there is a high changes of temperature in the lower depth of the die cavity, which is gradually diminished with increasing the depth in the volume of the die with the intensive head dissipation through the tempering channels. As the condition of maintaining the thermal equilibrium of the die during the casting cycle is valid, it is necessary to reveal the places most exposed to the heat in the designing phase. In assessing the change of thermal field of the die, an experimental distribution of tempering channels approximating the real form was proposed in order to ensure different heat dissipation conditions. Measurements were carried out using the Magmasoft simulation program. The results presented in the contribution serve as a platform for designing of tempering channels to ensure the thermal equilibrium of the die and rapid heat dissipation from the casting.

2. Experimental procedure

Measurements were carried out on the cast of electric motor flange. In Magmasoft simulation program, the experimental distribution of the tempering system according to Figure 1 was proposed. The measured points were selected at the branch points of the main runner and in gates on the opposite side to the gates (Fig. 1). As the material from which the functional parts of the die were made of, the chromium-molybdenum steel X38CrMoV5_1 was chosen.

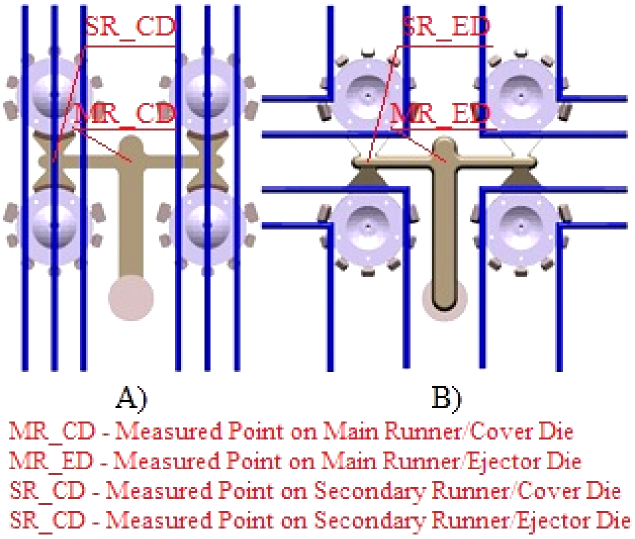

Fig. 1. Gating system of casting and experimental tempering system

Table 1.
Technological parameters of the casting cycle

Parameter	Value
Melt temperature in filling chamber, °C	617
Die temperature, °C	200
Temperature of the tempering medium, °C	190
Piston velocity, $m.s^{-1}$	2.9
Holding pressure, MPa	25
Die cavity filling time, s	0.016

The measured points were placed in a line perpendicular to the dividing plane of the mold. The change in temperature in the cover die and ejector die was monitored. The spacing of the measured points in the die volume was 1 mm, 2 mm, 5 mm, 10 mm and 20 mm from the die cavity face. The setting of the input technological parameters is presented in Table 1. The cross-section of the tempering channels in the cover die is 10 mm, in the ejector die is 9 mm.

To ensure the relative thermal stability of the die material, cycling of five pre-operation heat cycles was defined in Magmasoft simulation program MAGMA5 – HPDC module. The actual monitoring of the temperature change was carried out in the sixth production cycle. The die cavity before sealing was treated with spraying and blowing. The opening and ejection of the cast from die was conditioned by the temperature of the cast. The mold opening will only occur if the maximum temperature in the cast alloy material falls below 400 °C.

3. Research results

Based on measurements carried out on the selected system, the temperature course in the individual measured points was evaluated. Table 2 presents the measured temperature change values.

As presented in Table 2, the die surface layers near the die cavity are subjected to the temperature fluctuations of ΔT above 200°C. The results shown in Table 2 are presented as an absolute temperature values at each measurement point. To understand the course of temperature change, a graphical dependence of temperature change over time was created for each measurement points, presented in Figure 2 and Figure 3.

Table 2.
Temperature change in measured points, °C

Measured Point	Tmax	Tmin	ΔT
MR_CD – 1mm	460.2	219.3	240.9
MR_CD – 2mm	441.3	220.4	220.9
MR_CD – 5mm	393.2	226.9	166.3
MR_CD – 10mm	339.0	241.3	97.7
MR_CD – 20mm	279.9	249.2	30.7
MR_ED – 1mm	461.7	219.1	242.6
MR_ED – 2mm	442.8	220.1	222.7
MR_ED – 5mm	393.9	226.5	167.4
MR_ED – 10mm	336.3	241.9	94.4
MR_ED – 20mm	279.4	249.6	29.8
SR_CD – 1mm	417.5	178.6	238.9
SR_CD – 2mm	389.0	179.5	209.5
SR_CD – 5mm	329.3	184.3	145.0
SR_CD – 10mm	272.8	194.4	78.4
SR_CD – 20mm	217.7	196.6	21.1
SR_ED – 1mm	395.5	191.5	204.4
SR_ED – 2mm	370.7	192.4	178.3
SR_ED – 5mm	317.3	197.7	119.6
SR_ED – 10mm	269.0	208.9	60.1
SR_ED – 20mm	231.8	216.8	15.0
Alloy Temperature			
Center of M. Runner	617	357.6	259.4
Surface of Mold Cavity/CD	612.3	357.4	254.9
Surface of Mold Cavity/ED	612.8	357.3	255.5
Center of S. Runner	615.6	272.0	343.6
Surface of Mold Cavity/CD	612.8	271.6	341.2
Surface of Mold Cavity/CD	615.0	272.3	342.7

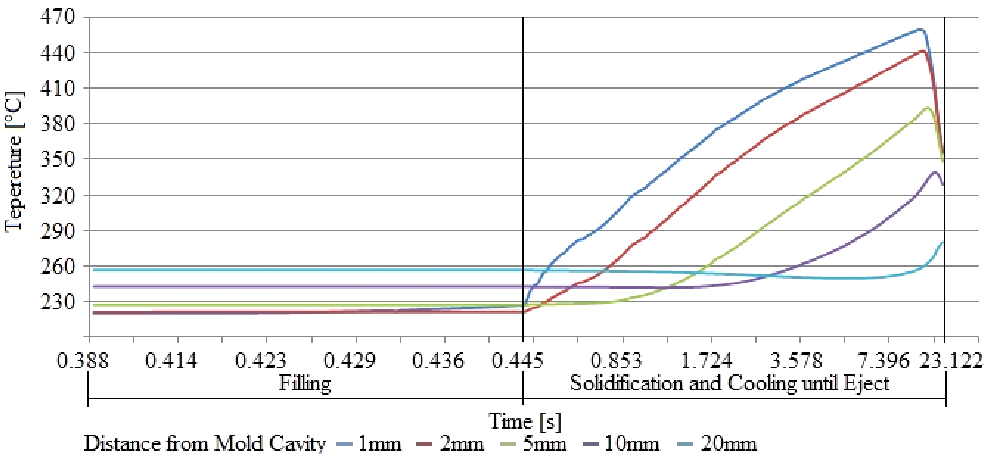

Fig. 2. Temperature course Main Runner/Cover Die

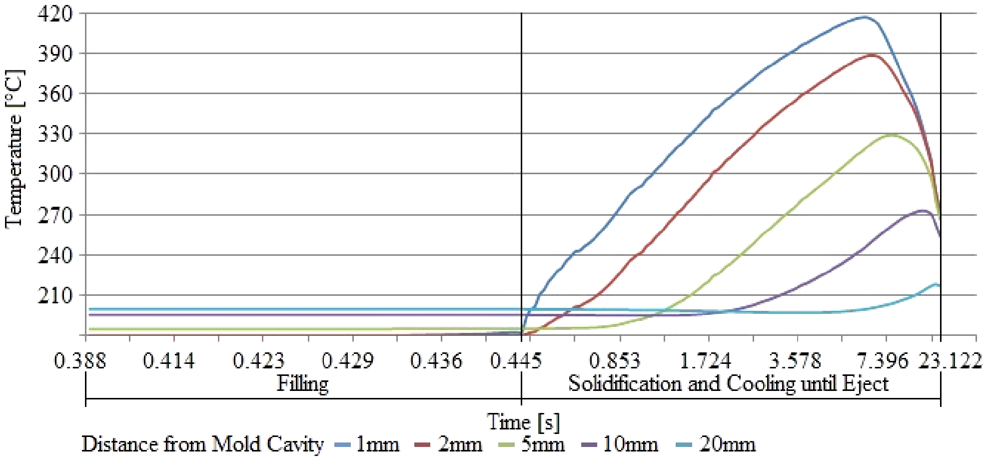

Fig. 3. Temperature course Secondary Runner/Cover Die

As presented in the graphs on Figure 2 and Figure 3, the die temperature during the filling phase is at a constant level, respectively, the layer just below the surface is heated only minimally. The intense increase in the temperature of the die occurs only during the solidification phase. In places where the temperature courses of the individual measurement points intersect, it is possible to determine the progress of the temperature front into the volume of the die reflecting the heat transfer from the die cavity surface to the die mass. The temperature decrease between the end of solidification phase and the beginning of the filling phase takes place at the time the die is open. The cast is being discarded, sprayed and blown. The die face is being cooled at this stage by the influence of the ambient air temperature, due to the temperature medium during spraying and the compressed air during blowing.

The highest temperature gradient between the melt and the die face temperature is at the beginning of the solidification. Figure 4 presents the temperature gradients at 0.445s between the main and secondary runner in cover die.

Arising from the Figure 4, as the distance from the die face increases slightly, so does the temperature. From this fact emerges, that the heat that is transferred to the die by melt is not completely dissipated by tempering channels and partly remains accumulated in the die volume. Therefore is the die volume temperature higher than the temperature at the die cavity surface. Thus, at regular operation cycles, the die volume temperature is at relatively constant level, with an average temperature variation of 15 to 30°C.

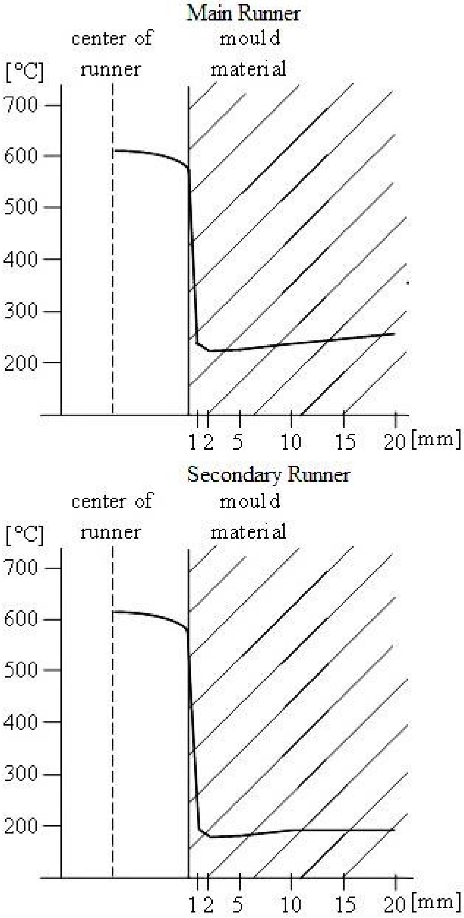

Fig. 4. Temperature gradient in Cover Die

4. Results analysis

The first aspect examined in this contribution was the assessment of the thermal change of the die. As presented in the

Table 2, the amount of the temperature change ΔT decreases with increasing distance from the die cavity wall. Thus, the amount of die material thermal change is indirect to the distance from the die face.

Table 3.
The average temperature change of the mold

The distance from the die face	Increase in temperature within 1 operation cycle, °C
1 mm	204.4 – 241.8 average 231.7
2 mm	178.3 – 222.7 average 207.9
5 mm	119.6 – 167.4 average 149.6
10 mm	60.1 – 97.7 average 82.7
20 mm	15.0 – 30.7 average 24.2

Based on Table 3, it can be stated that alternating heating and cooling during one operation cycle causes a considerable temperature fluctuation in the depth of up to 5mm and less in the depth of 10mm. Of course, this alternating thermal change acts mostly at the die face, whereby the temperature of the die surface layers approximating the melt temperature. At the distance of 20mm from the die cavity, the heat supplied by the melt is transferring gradually into the entire die mass without any significant thermal fluctuations.

The thermal change of the dies is largely influenced not only by the material, but also by the distribution and cross-section of the runners, as well as the flow and temperature of the tempering medium [4]. In the example presented by this contribution, the layout of runners according to the Figure 1 was chosen. As presented on the Figure 1, there is no tempering channel near the measurement points MR_CD and MR_ED. For this reason, the temperature values in the individual measurement points in Table 2 are of relatively equal value. A different situation occurs in the measuring points SR_CD and SR_ED. For measuring points SR_CD, the tempering channel is at a distance of 22mm from the die face, which is 22mm from the measuring point SR_CD 20mm. For this reason, the temperature difference according to Table 2 at measuring points in the place of secondary runner is also more significant.

Figure 2 and Figure 3 present the course of the temperature for each measurement point during the operation cycle. It should be noted that the temperature was recorded only when the die was closed. A significant change in die material temperature occurs during solidification and cooling phase, where the heat transfer from the cast to the die volume is the most intense. At the time when die opening occurs, the average surface temperature of the die at the measurement point MR_CD/MR_ED is 355°C and at the measurement point SR_CD/SR_ED 271°C (considered to the depth of 2mm). The die remains open for 15s, when the cast is dropped from the die and the treatment of die cavity and its closing occurs. Due to the ambient air, spraying and blowing, the temperature of both parts of the die is reduced to the sufficient temperature at which the first contact with the melt occurs.

The intensity of the melt undercooling in contact with the die face determines the structure of the cast. Thus, the temperature gradient between the melt and the die cavity surface affects the grain size of the cast walls. The higher undercooling of the melt, the more fine-grained the cast structure will be, which is reflected in an increase of a surface hardness [7]. In practice, setting the die temperature to 1/3 of the melt temperature is preferred [8]. In this experiment, this condition was maintained. Comparing the temperature gradient according to Figure 4 and the results obtained during the experiment it was found, that the temperature variation between the melt and the surface layer at the die face in the end of a filling phase is an average of 420°C at the place of a secondary runner and 380°C at the place of main runner.

5. Conclusions

The presented contribution is focused at evaluation of the thermal change of the high pressure die casting die using the Magmasoft simulation program.

Monitoring of the thermal course of the operating die, it was found that at varying depths of the die material from the wall of the cavity coming into the contact with the melted metal, the temperature varies considerably over one operating cycle.

When assessing the thermal change of the die, it is not advisable to focus solely on the absolute temperature values at selected measurement points, but also take into account the overall temperature course during the casting cycle, as well as the temperature gradient that will help us to predict the internal structure of the cast.

The distribution and design of the tempering channels has a considerable influence on the change in the temperature field within the volume of the die and the associated heat dissipation. As it has been shown, the smaller the distance between the die cavity wall and the tempering channel is, the smaller is the temperature difference in the die volume. Therefore, it is advisable to dimension the tempering channels as close to the die cavity as possible. In this way, we get a thermally balanced die that produces the same quality casts without large internal stresses in each operation cycle.

The results presented in this contribution serve as a platform for further research. The methodology of thermal change assessment of dies is introduced with the aim to highlight the important aspects affecting the temperature equilibrium of the die. The following research will be aimed to the area of total heat field evaluation depending on the change of the die material, the change and distribution of the tempering channels in the die and their distance from the die cavity.

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