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Temperature Conditions Change in the High Pressure Die Casting mold Volume Depending on the Gating System Volume

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Abstract

The high pressure die casting technology is characterized by high efficiency, which is given by pressing the liquid metal into the die cavity and the subsequent solidification of the cast in a short period of time. The short casting cycle duration and the rapid temperature conditions alternation at the interface cast – die cavity, as well as in the die volume itself, cause cyclic thermal stress of the die material. The submitted article investigates the influence of gating system volume on the temperature conditions change in the high pressure die casting mold volume. Five gating system variants with different runners volume for specific type of low-weight silumin based cast were used to assess the temperature changes in the high pressure die casting mold volume. The temperature was monitored in two selected places of the gating system, with a distribution of 1mm, 2mm, 5mm, 10mm and 20mm in the direction from the working die cavity face to the volume of the fixed and movable part of the die. As a comparison parameter, the melt temperature in the runner center above the measured point and the melt temperature close to the die face were monitored. Monitoring of the temperature change was performed using the Magmasoft simulation program. It has been proven that the gating system volume affects the thermal stress of the die, the temperature drop in the die volume and the casting cycle duration. In conclussions, proposals for measures to reduce the high thermal stress of the die resulting from the gating system volume and design are presented. These proposals will subsequently be verified in the following research activities and compared with the resulting casts quality.

Keywords: Product development, Application of information technology to the foundry industry, Thermal stress, Mould material, tempering

1. Introduction

High pressure die casting (HPDC) is a process that is typically used to produce large series of complex metal parts for multiple industries. Due to its low price, high shape variability of manufactured parts, good production repeatability within narrow tolerance limits and high productivity, it has an important place among the production technologies for the automotive and aerospace industries[1,2].

In this casting method, molten metal is forced into the die cavity at high speed and pressure. In periodic cycles, the processes of filling the chamber, solidifying the casts, opening and closing the die, removing the casts and treating the die with spraying and blowing take place. During these periodically alternating cycles, the die undergoes significant temperature changes, which causes a thermal imbalance. When a molten

HPDC alloy is injected into a relatively cold die cavity, the solidification rate is highly dependent on the heat transfer behavior at the cast-die interface and also within the molten alloy and consequently affects the microstructure and subsequent mechanical properties of the die and cast. In other words, a proper high cooling rate could promote the formation of a fine microstructure in the produced casts. Otherwise, too high cooling rate could cause the molten metal to solidify prematurely before filling is complete. There is a strong correlation between the microstructural characteristics and the mechanical properties, which are strongly dependent on the microstructure[3,4].

Many important quality indicators of components manufactured using permanent die casting, such as the presence of shrinkage porosity, microstructural properties, dimensional stability, cycle time and filling mechanisms, are controlled directly or indirectly by the heat transfer mechanisms connecting the cast to the die[5]. One of the most important factors in this process is the heat transfer during the molten alloys solidification. The resulting microstructure, on which the quality of the cast is based, and the cycle time depends on the heat transfer dynamics[6].

As mentioned above, the alternation of individual casting cycles causes a high imbalance in the die temperature equilibrium. The die thermal balance has significant effect on the casts quality, on the general defects reduction and on the die lifespan extension. The temperature distribution in different places of the inner die face and in the die material depth is difficult to control. This has an adverse effect on the die lifespan. The uneven change in the temperature in different places of the working die cavity has a significant impact on the technological process during casting, which results in increased failure. The constantly repeating temperature cycles induce thermal stresses which, in connection with high specific pressure during die work, lead to operating conditions similar to the high dynamic stress. In these conditions, there is a working die cavity and partly also its dividing plane[7-10].

Thermal drop depends on the thermal conductivity of material from which the die is made, on the ratio of the die mass to the cast mass and on the die temperature before casting. The better thermal conductivity of the die material has a significant effect on the rapid removal of heat from working die cavity. Heat dissipation is not only necessary from the point of view of upper layers die material volume changes, but also for technological reasons during casting. Efficient injection molding requires the die to be at its optimal temperature, at which the most economical operation is guaranteed. Any increase in die temperature above its optimal limit is undesirable and results in many problems, the most comon of which is cast sticking to the die walls, deterioration of the cast face and changing of the cast solidification conditions in the die. Decent die material thermal conductivity allows a more intense rhythm without breaks for temperature equalization[10-13].

A larger ratio of the die material mass to the cast mass facilitates the heat transfer from upper die layers to its entire volume, which contributes to increasing its lifespan. For example. When aluminum alloys are cast by a high pressure die casting technology at a higher ratio of the die mass to the cast mass, the die lifespan is longer than when the same casts are normaly cast in mold in which very thin walls prevail. At the same time, the high pressure die works in significantly more difficult conditions, and its working cavity is not protected by any protective means, as is the case with mold casting[10,14,15].

The main goal of the submitted article is to assess the high pressure die temperature conditions depending on the gating system volume. The submission is based on the conclusions of the previously presented contributions of the author´s team, which addressed the thermal characteristics of the die for the production of a specific high pressure die casts. In publication [16], the overall die heat balance was addressed, where the mechanisms and methods of heat removal from the cast to the die and subsequently to the surrounding environment were described. In the publication [10], it was demonstrated that the die can accumulate a certain heat amount in its volume, and the die layers further from the die face are stressed by a smaller temperature changes. Based on these results, the publication [17] investigated the influence of the tempering channels distribution, or their distance from the die face, to change the die volume temperature. It has been proven that, regardless of the tempering channels distance from the die face, it is possible to mark the zone 5mm from the die face into the die volume as a zone with complete heat transfer without its accumulation. At the same time, it was proven that the tempering channels distance from the die face affects the length of solidification and cooling of the cast, which is reflected in the casting cycle total duration, which is also confirmed by the conclusions of publications[3,5,12,13].

As it follows from the above mentioned knowledge, as the gating system volume increases, heat removal from the die face layers into its volume deteriorates. Which implies that the die thermal stress with regard to the gating system volume should be higher. This hypothesis is verified by the submitted article. When assessing the die thermal stress, five gating systems were designed for a specific type of cast with a variable runners cross-section and thus variable volume. This was aimed to ensure different conditions for heat removal. The die geometry and the tempering channels layout are based on the publication[17]. The measurements were performed using the Magmasoft simulation program.

2. Description of experimental procedure

The assessment of the volume temperature changes of the high pressure die was performed on the die belonging to the cast of the electric motor. The tempering channels diameters as well as geometry of their distribution in the die are taken from the publication [17] as depicted in Figure 1. The measured points and temperature changes evaluation were chosen in branches of the main runner and in the secondary runner opposite to the ingates locations (Figure 1). Chromium-molybdenum steel X38CrMoV5_1 was selected for the functional die parts that will get into a contact with the molten metal. This steel is the commonly selected material for die production intended for casting aluminum alloys.

Measured Points were distributed in a straight line perpendicular to the dividing die plane. The temperature change in the cover die and ejector die was monitored. The spacing of the measured points in the die volume was 1mm, 2mm, 5mm, 10mm and 20mm from the working die cavity face. The melt temperature was monitored in the main runner center and just above the die face. The tempering channels cross-section is 9mm. The tempering channels distribution and their distance from die dividing plane are depicted in Figure 2.

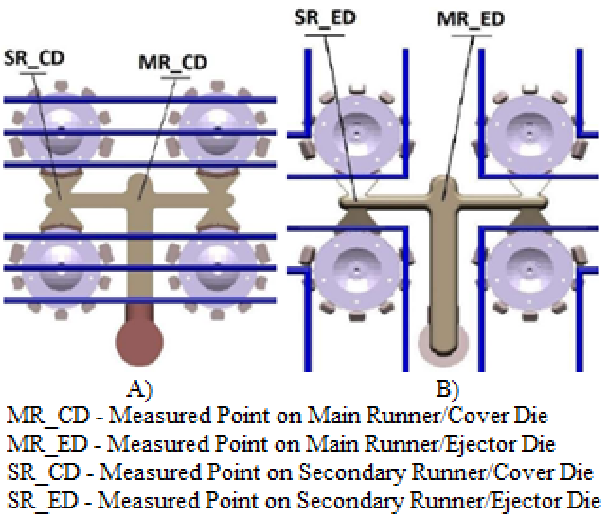

Fig. 1. Gating system of casting and experimental tempering system [17]

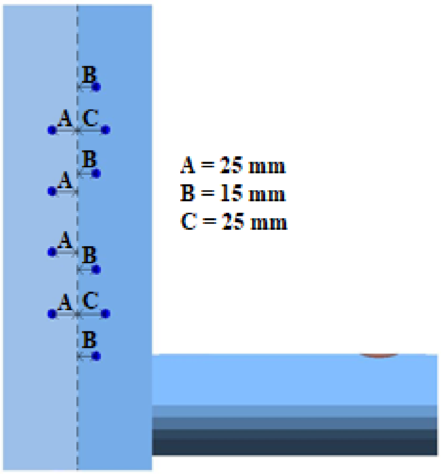

Fig. 2. Distribution of tempering channels in die

The influence of the gating system volume on temperature change in high pressure die volume was investigated on five gating system variants. The basic gating system design, the multiplicity of die and location of casts in die is depicted in Figure 1. The individual variants geometric characteristics of gating system were determined based on the variability of possible numerical designs for ingate and subsequently for the gating system geometric dimensions calculation in accordance with the standard ČSN 22 8601[18] and publications[19,20]. The gating system characteristic dimensions are summarized in Table 1 – Table 4.

Table 1.
Weight and volume characteristics of the cast

Quantity	Value
Alloy	EN AC 47 100 – AlSi12Cu1(Fe)
Alloy density, [kg.m^{-3}]	2650
Cast volume, [m^3]	51697.9 * 10^{-9}
Cast weight, [kg]	0.136
Cast diameter, [m]	0.1165
Characteristic wall thickness, [m]	0.002

Table 2.
Gate dimensions

	Gate area S_G, [mm^2]	Gate length a, [mm]	Gate height b, [mm]
V01	119.50	60.968	1.96
V02	76.06	60.968	1.25
V03	66.05	60.968	1.08
V04	48.32	60.968	0.79
V05	35.03	60.968	0.57

Table 3.
Dimensions of runners

	V01	V02	V03	V04	V05
			Main Runner		
S_{MR}, [mm^2]	788.70	501.99	435.92	318.91	231.20
CT, [mm]	14.39	11.48	10.69	9.15	7.79
CB, [mm]	58.66	46.80	43.64	37.30	31.80
r, [mm]	7	6	5	4.5	4
α, [°]	75	75	75	75	75
			Secondary Runner		
S_{SR}, [mm^2]	358.50	228.18	198.15	144.96	105.09
CT, [mm]	14.39	11.48	10.69	9.15	7.79
CB, [mm]	28.78	22.96	21.38	18.30	15.58
r, [mm]	7	6	5	4.5	4
α, [°]	75	75	75	75	75

S_{MR} – Cross-section of main runner
S_{SR} – Cross-section of secondary runner
CT - Runner's height
CB - Runner's width
r – Radius of side and upper edge connection of channel
α – Inclination angle of the runner side walls

Table 4.
Metal batch volume per one operation

	Volume, [m^3]	
	Coarse cast	Raw cast
V01	206.8 * 10^{-6}	656.11 * 10^{-6}
V02	206.8 * 10^{-6}	554.63 * 10^{-6}
V03	206.8 * 10^{-6}	536.92 * 10^{-6}
V04	206.8 * 10^{-6}	490.12 * 10^{-6}
V05	206.8 * 10^{-6}	456.68 * 10^{-6}

Figure 3 depicts the runners main geometric dimensions (A), and a comparison of the main runners cross-sections (B).

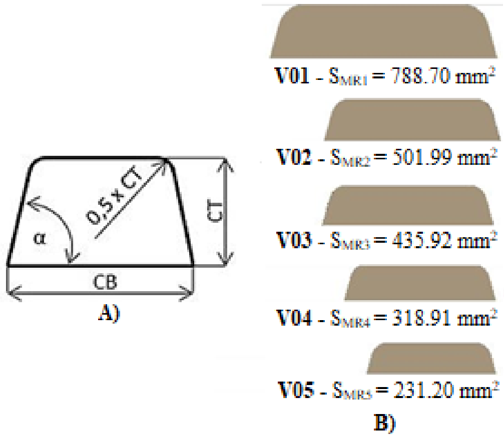

Fig. 3. Comparison of main runners cross-sections

The settings of the technological and process parameters of casting cycle reflects the production of the electric motor flange cast in industrial conditions. These parameters were also used in the settings of the Magmasoft simulation program and are listed in Table 5.

Table 5.
Technological and process parameters of casting cycle

Parameter	Value
Technological parameters	
Initial melt temperature, [°C]	708
Die material	X38CrMoV5_1
Initial die temperature, [°C]	220
Tempering medium	Oil
Tempering medium temperature, [°C]	190
Piston velocity in 1st phase, [m.s^{-1}]	0.2
Piston velocity in 2nd phase, [m.s^{-1}]	V01 – 4.00 V02 – 2.54 V03 – 2.21 V04 – 1.62 V05 – 1.17
Holding pressure, [MPa]	25
Process parameters	
Spraying	Start – 5 s after Begin of Preparation Duration – 3s
Blowing	Start – 2 s after Spraying Duration – 3 s
Die Close Definition	2 s after Blowing
Dosing	Start - 1 s after Die Close Dosing time – 5 s Dwell time – 3 s Dosing volume – see Tab. 4

The pressing piston velocity in the second phase of pressing depends on the required melt velocity in gate. In industrial conditions, the gate velocity is given as v_G = 32.16 m.s^{-1}. The pressing piston velocities in the second phase of pressing listed in Table 5 are determined by calculation using the continuity equation. By changing the pressing piston velocity in second phase of pressing, in addition to the melt velocity in gate, the mass/volume melt flow in runners is also preserved.

To ensure the reltive temperature stability of die material, five pre-production heating cycles were defined in the Magmasoft simulation program. Monitoring of temperature changes was performed in the sixth production cycle. The opening and ejecting of the cast from die was conditioned by the cast temperature. The die opening will only happen as soon as the maximum temperature in Cast Alloy Materials falls below 400 °C.

3. Research results

Based on measured points temperature monitoring according to Figure 1 for individual gating system variants in accordance with Table 1 – Table 4, the temperature change in the high pressure die volume presented in Table 6 was evaluated.

Table 6.
Temperature change in measured points

	V01	V02	V03	V04	V05
			ΔT, [°C]		
MR_CD – 0 mm	298.6	286.5	310.1	310.3	326.2
MR_CD – 1 mm	234.7	222.5	234.9	229.1	228.2
MR_CD – 2 mm	213.5	200.6	208.2	198.5	188.6
MR_CD – 5 mm	166.8	150.8	156.0	138.4	129.5
MR_CD –10 mm	108.3	91.8	94.5	79.9	74.8
MR_CD –20 mm	44.4	35.4	36.0	29.4	27.7
MR_ED – 0 mm	287.0	264.6	302.1	288.2	327.1
MR_ED – 1 mm	232.8	230.4	229.5	228.0	225.3
MR_ED – 2 mm	211.6	208.5	209.2	197.4	196.2
MR_ED – 5 mm	170.7	158.5	155.2	139.7	133.3
MR_ED –10 mm	109.2	102.1	100.9	83.4	77.4
MR_ED –20 mm	45.4	35.1	35.8	29.6	30.9
SR_CD – 0 mm	358.3	362.7	362.4	362.9	368.4
SR_CD – 1 mm	231.2	208.5	222.2	204.3	199.2
SR_CD – 2 mm	198.4	184.8	197.2	173.1	166.8
SR_CD – 5 mm	154.5	130.4	143.0	120.5	122.7
SR_CD – 10 mm	99.8	74.0	80.0	61.2	56.6
SR_CD – 20 mm	33.8	27.1	29.6	20	18.7
SR_ED – 0 mm	356.7	365.0	361.1	354.1	367.1
SR_ED – 1 mm	236.7	193.3	205.5	184.3	159.8
SR_ED – 2 mm	217.4	174.3	177.4	151.7	138.8
SR_ED – 5 mm	171.1	120.9	122.6	102.3	85.6
SR_ED – 10 mm	95.6	74.7	77.2	61.4	52.1
SR_ED – 20 mm	29.7	18.8	21	14.9	14.4

Arising from Table 6, the working die cavity face is stressed by the temperature fluctuation ΔT to the greatest extent.

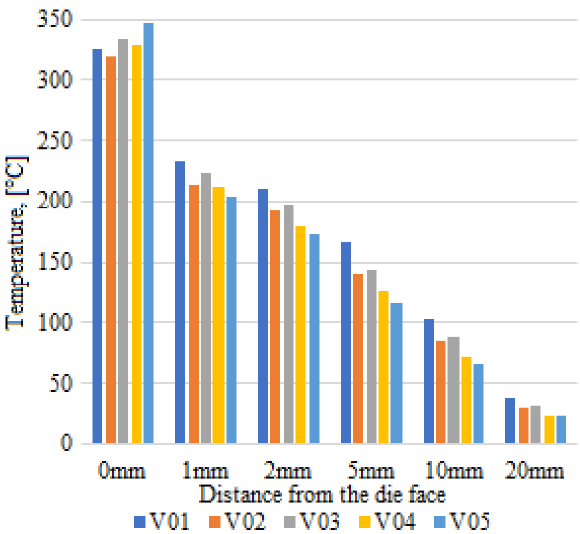

Fig. 4. Average temperature change in die material

Based on Figure 4, it is possible to notice the nature of the temperature change between the die face (point 0mm) and the temperature changes in the high pressure die volume. Comparing the temperature changes in the case V01 and V05, it is clear that the gating system with lowest volume (V05) overheats the die face the most, but the high pressure die volume in this case (V05) shows the smallest temperature changes ΔT. This phenomenon could be related to the melt flow velocity in runners, and with that related filling time of die cavity.

In the case of the melt flow velocity in runners, it is necessary to refer to Table 2 and Table 5. As stated in chapter 2. Description of experimental procedure, when setting the technological parameters, an effort was made to maintain a constant melt velocity in the runners at the value v_G = 32.16 m.s^{-1}. In order to maintain the same melt velocity in gate and simultaneously the mass/volume of melt in runners, the velocity of the pressing piston is variable in the second phase (see Table 5). The melt velocities in the main and secondary runners are therefore at a relatively constant level for all variants of designed and assessed gating systems. The melt flow velocity in the runner does not have a significant effect on the above-described phenomenon resulting from Figure 4.

Therefore, if the melt velocity in gate is maintained and at the same time the mass/volume melt flow and the filling time of the die cavity face should be at a relatively constant level. To verify the effect of time on the temperature change at individual measured points in the volume of high pressure die, Table 7 was constructed.

Table 7.
Filling time and Solidification and Cooling time

	Filling Time, [s]	Solidification and Cooling Time, [s]
V01	2.505	34.841
V02	2.749	28.642
V03	2.792	27.917
V04	2.853	24.055
V05	2.896	22.327

The assumption of a constant die cavity filling time was partially disproved. Although the die cavity filling time is relatively constant for all gating system variants with variable volume, a certain deviation is noticeable. The maximum difference in the die cavity filling times is Δt = 0,391 s. This difference may reflect the actual hydrodynamic conditions in the melt, taking into account hydrodynamic losses and resistances against the theoretical assumptions determined on the basis of the continuity equation. Simultaneously, it is possible to notice a decreasing trend in the die cavity filling time with increasing the gating system volume and thus also with higher hydraulic cross-sections of the runners.

This phenomenon explains the higher overheating of the die face (measured point 0mm) with a lower gating system volume. When the melt remains longer in the runners during the filling phase, the die face is also exposed to a higher temperature.

Solidification and Cooling time (see Table 7) reflects temperature changes in the high pressure die volume. With a higher gating system volume, which also has a higher temperature potential and temperature capacity. During solidification and cooling time, the gating system conducts away the heat into the high pressure die volume for a longer period of time, which allows higher overheating of material in the die volume and thus higher values of temperature change at the measured points.

4. Discussion of the achieved results

The primary aspect to which the research presented in this submission was devoted is the evaluation of the temperature conditions change in the high pressure die volume depending on the gating system volume. These temperature changes in the die volume can also be understood as thermal stress of the die material.

The secondary aim is to verify the conclusion of previous works [10,17] dealing with the issue of thermal stress of the die.

As arises from Table 6 and subsequently from Figure 4, the influence of the gating system volume on the temperature change in the high pressure die volume was proven. At the beginning of the submission, the hypothesis was stated that with increasing gating system volume, the thermal stress of the die material will also be higher. This hypothesis was confirmed, but only in the range of measured points located in the die volume. As it was demonstrated, the die face showed the largest temperature change ΔT with the variant V05 gating system, and thus with the variant with the smallest volume (see Figure 4). This phenomenon is explained on the basis of Table 7, when it is found that due to hydraulic resistances during the melt flow through the runners, the filling phase is extended depending on the decreasing cross-section of the runners. The increased duration of the filling phase gives the possibility of a longer duration of interaction of the flowing metal with the die face, and thus its higher overheating. At this point, there is a new impetus for the direction of further research, when it would be appropriate to focus on the dependence of the melt stream velocity and filling time, as well as the temperature change of the melt stream during its movement in the runners on the gating system volume. Simultaneously, it would be appropriate to determine the deviation between the theoretically calculated and the melt velocity values determined on the basis of simulation, which could clarify the increase in filling time depending on the reduction of the runners cross-section.

A certain extreme in the linearity of the temperature change depending on the volume of the gating system is depicted by variant V03. The causes of this phenomenon will be investigated in the following works.

During examination of the primary aspect of the research, the conclusions of previous works were also confirmed. As follows from Figure 4, and in accordance with the conclusions of the publications [10,17], at different depths of die material from the die face coming into contact with the melt, the temperature changes considerably during one casting cycle. At the same time, confirming the conclusions of publication [17], with a higher gating system volume and thus also the metal batch per operation, the thermal capacity of this volume increases, and this extends the time of heat removal into the die volume, which directly extends the solidification and cooling phase.

5. Conclusions

Understanding the thermal stress of the die material as the value of temperature change at which the die operates during the casting cycle, by monitoring the course of temperature changes in the high pressure die volume depending on the change in the gating system volume, it was found that the gating system volume directly affects the thermal stress of the die material. Simultaneously, it was found that the thermal stress of die face is inversely proportional to the gating system volume.

At the same time, it was proven that the gating system volume, and therefore the heat capacity of the melt with higher volume, directly proportionally influences the length of the solidification and cooling phase, which is reflected in the total duration of the casting cycle.

Even if with regard to the lifespan of the die it would be advisable to select the gating system with the smallest volume, it is necessary to realize that the thermal stress is not a key indicator of the quality and sustainability of production. With this fact in mind, further research will take place, in addition to the topics mentioned in section 4. Discussion of the achieved results, aimed at assessing the impact of the gating system volume change on the process indicators, such as usability of the metal batch per one operation and the size of the closing force, and on qualittive indicators, which are homogeneity of the casts and the gas entrapment by the melt during its passage through the gating system, and thus their transport into the cast volume.

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