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Influence of Overflow Connecting Channel Cross-Section Design on Selected Parameters of High Pressure Die Casting

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Abstract

High pressure die casting technology (HPDC) is a method enabling the production of shape-complex casts with good mechanical properties, with high repeatability of production within narrow tolerance limits. However, the casts show, to some extent, basic porosity, which may reduce their mechanical and qualitative properties. One of the main areas to focus on in order to reduce the porosity of casts is the correct design and structure of the gating and overflow system. Submitted article is devoted to the assessment of the connecting channel cross-section design for connecting the overflows to the cast on selected parameters of the casting process. Five different cross-section designs of connecting channels are considered, enabling the removal of gases and vapors from the volume during the molding. The connecting channels are designed with a constant width $g = 10\text{mm}$ and variable height $h_1 = 1.50\text{ mm}$, $h_2 = 1.25\text{ mm}$, $h_3 = 1.00\text{ mm}$, $h_4 = 0.75\text{ mm}$ and $h_5 = 0.6\text{ mm}$. The primary monitored parameter is the gas entrapment in selected points of the cast. The following is an evaluation of the pressure conditions change in the mold cavity at the end of the filling mode and local overheating of the mold material just below the surface of the mold face. With regard to the monitored parameters, based on the performed analyzes, the most suitable design solution of the connecting channel is assessed and recommendations for the design and structure of the overflows and their connection to the cast are derived.

Keywords: HPDC, Gas entrapment, Product development, Overflows dimensions, Melt flow

1. Introduction

One of the basic conditions for the economical production is the high pressure die casting casts is a correctly chosen system of overflows of the mold cavity. High quality casts from aluminum alloys are achieved by using pressures with high nominal values. The high value of hydrodynamic pressure allows the penetration of the alloy even into a very narrow gaps between the individual parts of the mold, e.g., into gaps with a width of 0.02 mm. It is most advantageous to design the overflow in the dividing plane of

the mold. Here, a system of round recesses in distance of 3 to 6 mm from the mold cavity is formed within the movable half of the mold. From these recesses – overflows, lead channels from 10 to 30 mm wide and 0.02 to 0.3 mm deep up to the edge of the mold halves [1-4]. The overflows are connected to the mold cavity by a connecting channel 0.6 – 1.5 mm deep and 10 – 30 mm wide [5]. The shape of the overflow is asymmetrical in cross-section. The reason is to allow the cast to be removed from the overflow by shrinking as it cools. In order to make the released overflow safe for the next operation, the designer places a bouncer in the overflow area [3,4].

Overflow can be defined as the volume of metal that is responsible for reducing non-metallic inclusions (porosity) and gas entrapment, located outside the functional part of the cast. The size and dimensions of the overflow depend on the volume of the cast and the characteristic wall thickness of the cast. The location for the overflow placement is identified by the nature and direction of the melt flow through the mold cavity. The overflows are only a narrow area that allows the air to escape from the mold cavity without spraying liquid metal around the mold [6].

It is important to realize the importance of properly venting the air from the mold cavity. Rapid removal of gases and vapors from the mold cavity in conjunction with the reduction of the turbulent melt flow significantly contributes to the elimination of gas pockets and consequently to the reduction of the porosity index [7]. And it is in the high pressure die casting that the porosity is a serious problem because it is difficult to identify by visual inspection and significantly reduces the mechanical and qualitative properties [8]. Porosity is essentially defined as a void in the casting, where the metal in the casting during the filling is missing. Before continuing to solve any problem related to the porosity of castings, it is necessary to correctly identify the type of porosity. Substantially, it is possible to distinguish between the porosity caused by shrinkage of the metal during solidification and the porosity caused by the gas entrapment in the volume of the melt during the filling phase. The main causes of the gas porosity can be found in the gas entrapment of the melt in the filling chamber of the machine, in the poor gate design, in the turbulent flow of the melt in the mold cavity and in incorrect design of the mold overflow system. Some secondary causes are coolant leakage into the mold, excess lubricant and the mold spraying [9–11].

To eliminate the formation of the porosity, it is necessary to correctly estimate the behavior of the melt flow in the mold during the casting cycle. The geometric complexity and often the dimensional diversity of the castings leads to a strong three-dimensional flow of the liquids with significant free surface fragmentation and spatter. The order in which the individual parts of the castings are filled and the location of the overflows are crucial for the formation of homogeneous castings with a minimum proportion of cavities caused by the gas entrapment. Estimating the nature of the melt flow in the mold is challenging. Numerical simulation is a suitable tool for predicting the flow as well as the gas entrapment in the melt volume. This is a powerful and cost-effective way to study different mold designs and filling processes, which ultimately leads to improved casting quality and casting process productivity, including more effective control of the mold filling and casting cycle [12,13].

As mentioned above, the gate and overflow design have the highest share in the formation of gas porosity. The entrapment of gases during passing through gating channels can be reduced by designing suitable cross-sections of the gating channels and the correct design of the branch geometry [6,7,14,15]. The presented article solves the problem of the design of connecting channel between the mold cavity and the casting, where the effect of changing the cross-section design of the connecting channel on gas entrapment in the casting volume, the pressure increases in mold cavity and local overheating of the mold material in the area of connecting channels is investigated. Three hypotheses that correlate with each other are tested:

- a) “As the cross-section of the connecting channels decreases, the rate of gas and vapor removal from the mold cavity is also reduced, so it is possible to anticipate an increase in gas entrapment in the casting volume.” The gas entrapment at the selected critical points of the casting is investigated;
- b) “Reduced cross-section of the connecting channels can cause a local increase in the mold cavity pressure, which can cause a threatening issue of mold opening.” The question whether reducing the cross-section of the connecting channels does not cause an overpressure in the mold cavity, which by its maximum value would exceed the closing force of the machine and thus cause the issue of opening of mold is investigated.
- c) “The local increase in the melt pressure on the mold walls may be accompanied by overheating the mold face, which promotes the degradation of the mold material by erosion and sticking the melt to the mold face.” The temperature of the mold face just below the surface is monitored.

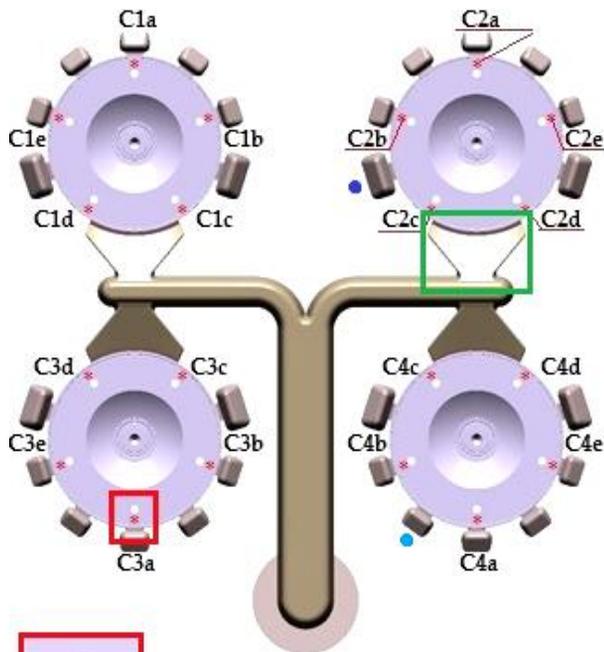
The monitored parameters are evaluated at the end of the filling phase, just before the start of the holding pressure phase, when the mold cavity is filled to 100% of its volume. This time period is chosen due to the fact that the holding pressure greatly reduces the gas entrapment and porosity in the casting volume. The size of the nominal value of the holding pressure is kept constant during the cooling time of the casting in the mold and the calculation of the closing force is derived from it [16]. Measurements are performed using the program Magmasoft 5.3.

2. Experimental details and methodology

Numerical simulation of the casting cycle and evaluation of the monitored parameters are performed on the electric motor flange casting. Since the geometry of the inlet channels has a significant effect on the gas entrapment in the casting volume, the study was performed on a gating system taken from [14] (Figure 1), in which were measured the lowest values of gas entrapment in the casting volume considering the branching of main runner. The measurement of gas entrapment is carried out at points where further mechanical processing of castings takes place (Figure 1). At these points, when filling of the mold cavity, the cores are being flown around, thus creating the structural holes in the casting. While cores are being flown around, two streams of melt are combined and an increased presumption of gas entrapment in the casting volume arises. The measuring points are 2 mm behind the core towards the flow and 2 mm from the surface of the casting to its volume (C1a – C4e). The expected local increase in pressure of the mold cavity and the change in the mold temperature caused by the reduction in the cross-section of the connecting channel are evaluated in the area of the casting just before the connection to the connecting channel (Figure 2).

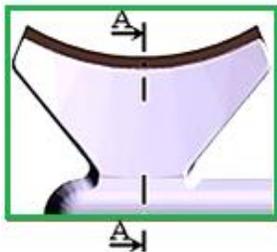
The gas entrapment in the casting volume is monitored and evaluated on the gating systems to which the overflows are connected with a variable height on the connecting channel. The overflows are arranged around the circumference of the casting according to Figure 1 and are made in two size variants. The basic design of the overflow is shown in Figure 2 and Figure 3. The dimensional characteristics of the overflow are given in Table 1.

Since the article is primarily devoted to the assessment of the influence of the cross-section of the connecting channel on selected process parameters, the overflow dimensions are constant for all variants of the tested gating systems, only the cross-section of the connecting channel S_{Cch} is variable. The cross-section of the connecting channel S_{Cch} is a function of its width g and height h that implies the only variable parameter in the design is the height of the connecting channels h_n which is given in Table 2.



Gas Entrapment Monitoring Point

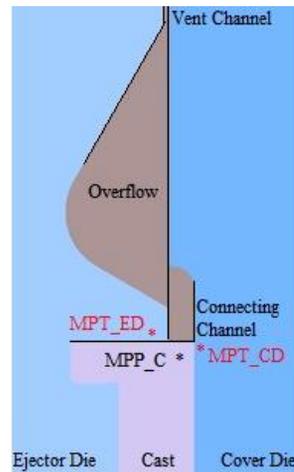
Pressure Monitoring Point in "Gate Zone"



● Overflow Type A

● Overflow Type B

Fig. 1. Gating system and measuring points of gas entrapment



Ejector Die Cast Cover Die
MPP_C - measuring point of pressure_Cast
MPT_ED - measuring point of temperature_Ejector Die
MPT_CD - measuring point of temperature_Cover Die

Fig. 2. Measuring points of pressure and temperature

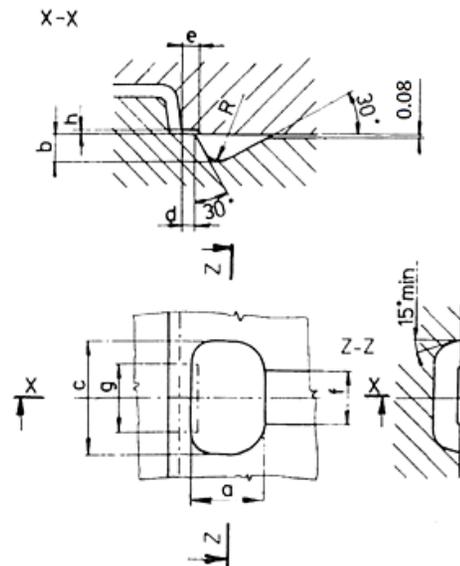


Fig. 3. Design characteristics of overflows [5]

Table 1.

Design characteristics of overflows [5]

Dimension, mm	Overflows Type A	Overflows Type B
a	17	14
b	11	5
c	30	20
f	10	10
R	3	3
d	3	2.5
e	5	4.5
g	12	12
h	Table 2.	Table 2.
Volume, mm ³	2351.08	741.285

Standard ČSN 22 8601 [5] determines the height of the connecting channel $h = 0.6 - 1.5$ mm. Based on this, modifications were made to the design of connecting channel, whose variable parameters are listed in Table 2.

Table 2

Variable design parameters of the connecting channel

Design of Connecting Channel	Height of Connecting Channel, mm	Cross section of Connecting Channel, mm ²
CCh 1	$h_1 = 1.50$	$S_{CCh1} = 18.00$
CCh 2	$h_2 = 1.25$	$S_{CCh2} = 15.00$
CCh 3	$h_3 = 1.00$	$S_{CCh3} = 12.00$
CCh 4	$h_4 = 0.75$	$S_{CCh4} = 9.00$
CCh 5	$h_5 = 0.60$	$S_{CCh5} = 7.20$

Measurements were performed using the simulation program Magmasoft MAGMA5 – HPDC module. The casting is made of EN AC 47 100 alloy (AlSi12Cu1(Fe)). The setting of technological parameters of casting in the simulation is constant for all variants of the gating systems at a variable height of the connecting channels h_n . It is presented in Table 3.

Table 3

Technological parameters of the casting cycle

Parameter	Value	Unit
Melt temperature in filling chamber	617	°C
Die temperature	200	°C
Temperature of the tempering medium	190	°C
Final plunger velocity in 1 st phase	0.8	m.s ⁻¹
Plunger velocity in 2 nd phase	2.8	m.s ⁻¹
Holding pressure	25	MPa
Die cavity filling time	0.017	s

3. Results and Discussion

Using the program MAGMA5 – HPDC module, in the section Result/Air Entrapment the values of gas entrapment at measuring points were determined. The measurement is performed at a time when the entire gating system, including the overflows, is filled to 100% of the volume, just before the start of pressure phase. Table 4 presents the average values of gas entrapment in castings for the considered design solutions of connecting channels.

Table 4

Gas entrapment values in casting volume

Design of Connecting Channel	Gas Entrapment, %
CCh 1, $h_1 = 1.50$	1.687
CCh 2, $h_2 = 1.25$	1.970
CCh 3, $h_3 = 1.00$	2.045
CCh 4, $h_4 = 0.75$	2.124
CCh 5, $h_5 = 0.60$	2.202

As can be seen from Table 4, as the cross-sectional area of the connecting channels decreases, the value of gas entrapment in the cast volume increases.

Based on the performed measurements, the assumption stated in the hypothesis “a) As the cross-section of the connecting channels decreases, the rate of gas and vapor removal from the mold cavity is also reduced, so it is possible to anticipate an increase in gas entrapment in the casting volume.” has been confirmed.

The reduced cross-section of the connecting channel reduces the flow of gases and vapors from the mold cavity, thereby promoting the gas entrapment in the melt volume and the increase in porosity of the castings. The decrease in the cross-section of the connecting channel is accompanied by a local increase in the pressure of the mold cavity, which can lead to a short-term increase in the maximum value of the hydrodynamic pressure exceeding the value of the closing force.

The analysis of the pressure change in the melt was performed using the program MAGMA5 – HPDC module, in the Result/Pressure section. The pressure values were monitored at the MPP_C measuring points, according to Figure 2. The measuring points were placed before connection of each connecting channel to the casting that implies the change in the pressure at the measuring points was evaluated at a total of 27 measuring points. Table 5 shows the average values of the pressure in the melt at the end of the filling phase, determined as the arithmetic mean of the pressure values at the individual measuring points. Since the investigated pressure is understood as the hydrodynamic pressure, which changes over time and depends on the cross-section of the pipeline, the pressure in the melt being active in the area of the gate at the end of the filling phase is also evaluated.

Table 5

Average pressure being active at the end of the filling phase depending on the change in the cross-section of the connecting channel

Design of Connecting Channel	Pressure, MPa		
	Cast MPP_C (average)	Gate zone	
		average	max
CCh 1	6.19	2.82	9.06
CCh 2	6.65	3.64	9.13
CCh 3	6.79	4.85	11.09
CCh 4	6.84	5.08	12.10
CCh 5	9.20	7.09	17.79

As can be seen in a Table 5, as the cross-sectional area of the connecting channels decreases, the value of the hydrodynamic pressure in the volume of the casting increases.

Based on measurement of the pressure conditions in selected points of the gating system, the hypothesis was partially confirmed: “Reduced cross-section of the connecting channels can cause a local increase in the mold cavity pressure, which can cause a threatening issue of mold opening.”

The closing force of the machine must exceed the value of the forces which try to open the mold by its nominal value. The opening forces depend on the projection of the surface of the casting in the dividing plane of the mold, including overflows and runners, and the maximum pressure active on the melt during the pressing cycle. The pressure can be considered as the value of the maximum holding pressure active on the melt. In the performed experiments, the constant value of the holding pressure is set to 25

MPa and the projection of the casting area in the dividing plane is $S_{CAST} = 743,82 \text{ mm}^2$, which is constant for all variants of the gating systems with a variable area of the connecting channel. In simplicity, it is possible to state that if the local increase of hydrodynamic pressure does not exceed the value of the holding pressure, the mold will not open even when the lowest possible closing force of the machine is set [2-4,7,16].

The results of the experiments indicate that at the minimum permissible height of the connecting channel, the maximum pressure in the melt at the end of the filling phase is close to the holding pressure value, which would reduce the number of overflows and possibly exceed the minimum calculated closing force of the machine and thus open the mold. It is therefore appropriate to claim that the increase in hydrodynamic pressure in the mold cavity is conditioned by the sum of the cross-sectional area of all connecting channels.

As has been proven, reducing the cross-section of the connecting channels reduces the gas and vapor removal from the mold cavity and at the same time promotes a local increase in hydrodynamic pressure in gating system. Decreasing the permeability of the connecting channels and at the same time increasing the pressure may promote local short-term accumulation of the melt in front of the orifice of the connecting channel accompanied by an increase in temperature and overheating of the mold face.

The analysis of the change in the temperature of the mold face was performed using the program MAGMA5 – HPDC module, in the Result/Temperature section. The temperature values were monitored at the measuring points MPT_ED/MPT_CD, according to Figure 2. The temperature of the mold face was monitored in the area of connection of all overflows to the casting. In total, the temperature is evaluated at 27 measuring points for the cover die and 27 measuring points for ejector die. Table 6 presents the average values of the mold face temperature after the end of the filling phase of the casting cycle. Since the volume of the overflows was constant for each variant of the gating system, the thermal field of the mold and thus also of the mold face is affected only by a change in the design of the connecting channel.

Table 6

Average values of the mold face temperature depending on the change in cross-section design of the connecting channel

	CCh 1	CCh 2	CCh 3	CCh 4	CCh 5
MPT_ED, °C	158.75	157.95	157.30	158.65	159.73
MPT_CD, °C	177.60	168.55	167.83	168.63	172.25

For better visualization, the change in the temperature of the mold face depending on the change in the cross-section of the connecting channel, a graphical dependence was constructed, visible at Figure 4.

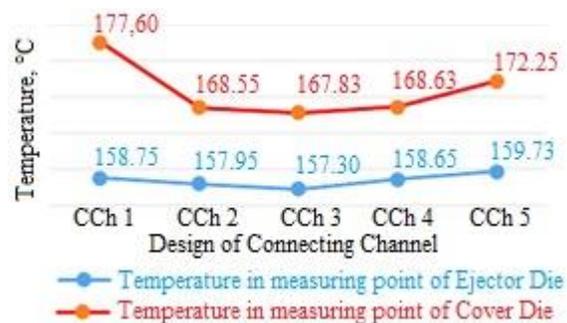


Fig. 4. Temperature change depending on the cross-section design change of the connecting channel

As can be seen at Figure 4 and in Table 6, the temperature of the mold face depends on the change in cross-section design of the connecting channel. The lowest overheating of the mold face is achieved with the design of the connecting channel CCH 3, whose height $h_3 = 1 \text{ mm}$. It can be stated that with a cross-section of the connecting channel $S_{CCH3} = 12.00 \text{ mm}^2$, an advantageous ratio between the hydrodynamic pressure in the melt, the volumetric melt flow through the connecting channel and the heat capacity of the melt volume in the monitored area is achieved.

Although a change in the mold face temperature near the orifice of the connecting channel is evident, a major effect on the function of the mold has not been demonstrated. This partially confirms the hypothesis: “The local increase in the melt pressure on the mold walls may be accompanied by overheating the mold face, which promotes the degradation of the mold material by erosion and sticking the melt to the mold face.” There is no extreme overheating of the mold during the filling phase, on the contrary, according to the simulation results, the mold is partially subcooled. It is therefore appropriate to focus on adjusting the temperature of the tempering medium and the arrangement of the tempering channels in the mold.

4. Conclusions

In presented article, the influence of the cross-section of the connecting channel for overflows on selected parameters of the high pressure die casting is investigated. The gas entrapment in the casting volume at the end of the filling phase, the local increase of the hydrodynamic pressure in the melt and local overheating of the mold face were chosen as the evaluated parameters. Three stated hypotheses were verified, the correctness of which was only partially confirmed. The measurements were performed using the Magmasoft program. Based on the performed measurements, it is possible to draw these main conclusions:

- As the height of the connecting channel decreases, and thus its cross-section decreases, the proportion of the gas entrapment in the casting volume increases, which is caused by reduction in the gas flow during discharge from the mold cavity;
- The change in the cross-section of the connecting channels affects the values of the hydrodynamic pressure in the melt during the filling phase. As the cross-sectional value of the connecting channels decreases, the hydrodynamic pressure in the melt increases, which by its maximum value may

- exceed the nominal value of the holding pressure, which could cause the mold to open slightly during the casting cycle;
- c) The cross-section of the connecting channel influences the local temperature conditions at the casting-die casting mold interface. The performed experiments showed a favorable relation between the hydrodynamic pressure of the melt and the temperature of the mold face associated with the heat capacity of the volume of the melt passing through the connecting channel at the height of the connecting channel $h_3 = 1\text{ mm}$;
 - d) The limit values of the connecting channels height declared by standard ČSN 22 8601 correspond with their values to the demand for gas and vapor removal from the mold cavity without critical influence of the casting cycle parameters;
 - e) The measurements were performed on a gating system taken from the publication [14]. The setting of the technological parameters of casting was identical to the setting of the parameters in the above-mentioned publication, but the difference occurred in the setting of the pressing speed in the first and second pressing phase. In the publication [14] the gas entrapment in the casting volume was found at the height of the connecting channel $h_3 = 1\text{ mm}$, the pressing piston speed in the first phase 0.9 ms^{-1} and the pressing piston speed in the second phase 2.9 ms^{-1} , at an average value of 3.516%. In the presented paper, the value of gas entrapment is 2.045%, with a reduction of pressing speed in the first and second phase. This also demonstrates the effect of the pressing speed on the gas entrapment in the casting volume, where it can be stated that the reduction of the pressing speed has a positive effect on the gas entrapment values in the casting volume, thus reducing the porosity.

With regard to the achieved results summarized in points a) and b), it is possible to evaluate regarding to the removal of the gas from mold cavity and the change of hydrodynamic pressure in the melt, as the most suitable solution of the connecting channel design CCh 1 with connecting channel height $h_1 = 1.5\text{ mm}$. If we take into the account the thermal conditions according to the point c), a solution is outline where it would be appropriate to adjust the height of the connecting channels to $h_3 = 1\text{ mm}$, and keep the total cross-sectional area $S_{CCh} = 126\text{ mm}^2$ (sum of the cross-sectional areas of connecting channels in design CCh 1) by adding other overflows. With regard to the above-mentioned assumption, it is appropriate in the following research to focus on the verification of this solution.

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