Assessment of the suitability of a gate design modification compared to the change in pressing velocity considering the distribution of gases in the casting volume

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Abstract. The qualitative properties of high pressure die castings are closely correlated with their internal structure, which is directly conditioned by the gas entrapment in the melt volume during the casting cycle. It is known that the gas entrapment in the volume of the melt and their subsequent distribution into the cast can be reduced by changing the technological parameters of the casting cycle or by the modification of the gating system design. The contribution addresses the issue of which variant of the gas content reduction is more efficient regarding the gas entrapment and the nature of the melt flow in the runners. The experiments are based on a real casting process. The established design solution of the gating system and the technological parameters setting are considered as a referential. Different gating system modifications were designed where the design modification is connected with the cross-section of a gate, in which the final acceleration of the melt flow occurs. The observed melt velocity in the gate is considered as a correlation factor, based on which the modification in the piston velocity is determined. The assessed parameter is the gas entrapment in the cast volume at the end of the filling phase. Assessment of the casting cycle and evaluation of experiments is performed using simulation program Magmasoft. Based on the performed analyses, it can be stated that the gate design modification will affect the filling regime of the die cavity by changing the melt velocity in gate, but the nature of the melt flow in runners remains unchanged. Modification of the piston velocity affects the filling regime of the die cavity, and also the nature of the melt flow as it passes through the runners, thereby promoting the gas entrapment in the melt volume. Therefore, it is necessary to pay an increased attention to the design of the gating system and only after debugging the design to proceed to the optimization of technological parameters.

1. Introduction
The high pressure die casting enables the production of thin-walled castings with high dimensional accuracy and low cost. However, the quality properties of the casting are affected by its internal structure, especially by the presence of pores and air bubbles. The inhomogeneity of the casting is caused...
primarily by the entrapment of gases in the melt flow volume as it passes through the gating system, starting with filling chamber and ending in the overflows [1,2]. Reduction of porosity and the associated gas entrapment in the melt volume when passing through the gating system can be achieved by two basic factors. Proper gating system design and setting of casting technological parameters [3].

Technologically, the velocity of a pressing piston is an important factor. The velocity of melt flow in runners is directly dependent of the piston velocity, to which the nature of the melt flow is closely connected. In general, the laminar-planar melt flow in runners is required, which ensures a uniform melt flow with compact stream face. This type of flow is required considering the smooth advancement of the melt flow without splashing and associated gas entrapment in the melt volume. Higher piston velocities shift the nature of the flow to turbulent-non-planar, which splits and opens the stream face, mixes the melt and swirls it, which directly promotes the gas entrapment in the melt volume and its distribution into the die cavity. Last but not least, it should be mentioned that due to the high affinity of aluminum for oxygen and hydrogen, chemical reaction of these elements occurs on the vacant melt surface, thus promoting the formation of oxide inclusions. These are distributed directly to the casting, where they can act as notches and reduce the resistance of the casting to mechanical stress [4-6].

The design parameters of the gating system have a decisive influence on the nature of the flow. Each of the design element, starting with the transition from the filling chamber to the main runner, through the runners, their branching and connection on the gate, the design of the gate and its connection to the casting, the technological casting design and its molding and subsequent degassing and positioning of the overflows a significant effect on the melt flow [7-10]. The melt is required to flow in a straight line in the runners without sudden changes in flow direction at acute angles. Therefore, it is advantageous to solve the transition in the branches of the runners as a radius with circular path of the melt flow [3,11,12].

The gate can be considered as the most critical place of the gating system, and its design must be given an increased attention. It has been shown that the design of the gate has an effect on the filling mode of the die cavity and the final increase of the pressing velocity [2,13]. The high flow velocity of the melt in the gate indicates dispersive character of the die cavity filling which directly supports the gas entrapment in the casting, where it can act as notches and reduce the resistance of the casting to mechanical stress [6,14].

To predict the gas entrapment in the melt flow volume, it is advantageous to directly observe the nature of the melt flow in the die. In operation, this task is difficult, even unrealistic. In the phase of technical preparation of production, it is appropriate to use simulation programs and CAx support in general. Computer simulation has made significant progress in recent years. CAx technologies solve urgent and important problems related to the definition of the cast design, the gating system design and the actual setting of technological parameters of the casting cycle, which is aimed at increasing production efficiency and reducing the amount of rejects [3,11].

As mentioned above, the pressing velocity of a piston and the gate design have a significant effect on determining of the melt flow nature through the runners and the final acceleration of the melt flow before entering the die cavity. The submitted contribution addresses the question of which of these parameters is more advantageous to focus on when designing and optimizing the casting cycle with respect to the distribution of gases in the cast volume, which is directly dependent on the melt flow nature. If we consider the system of the filling chamber – the mold cavity as a closed hydrodynamic system, the velocity of the melt in the gate while maintaining a constant flow is influenced by the cross section of an gate or the piston velocity in the filling chamber. For this reason, for the requirements of the experiments presented in the contribution, it is chosen as a correlation factor between the assessed technological and design parameters. Three variants of gating systems were designed with variable height of a gate with value \( b_1 = 1.25 \text{ mm} \), \( b_2 = 0.92 \text{ mm} \) and \( b_3 = 0.75 \text{ mm} \). Using the simulation program Magmasoft, the average velocity of the melt flow in gate is assessed, based on which the change of pressing piston velocity corresponding with the change of gate design is determined by means of the continuity equation. The design of the gating system with the height of a gate \( b_1 = 1.25 \text{ mm} \) and the pressing piston velocity \( v_{p1} = 2.8 \text{ m s}^{-1} \) is identical with the real gating system and is therefore considered as a reference. If the effect of the gate modifications on the value of gas entrapment in the cast was investigated, the technological parameters of casting were kept at a constant level and the change was
related only with the gate height $b_n$. When examining the influence of the pressing velocity, respectively the pressing piston velocity $v_p$ on the gas entrapment in cast volume, the design of the gating system was constant with the gate height $b_1$ and the change was related only with the setting of the piston velocity. The percentage of the gas entrapment in the casting volume is evaluated just before the start of the holding pressure phase, when the die cavity is 100% filled. This time period of the casting cycle was chosen considering the fact that the holding pressure significantly reduces the gas entrapment and porosity [14].

Based on measurements and observations of the melt flow performed using a simulation program, it is shown that when changing the piston velocity, there is a more significant gas entrapment in the cast volume compared to the change in the gate height. This is due to fact that if the gate height affects the melt flow and the filling mode of the die cavity only during the time when the melt enters the gate, the change of the piston velocity affects the melt flow nature as it passes through the entire gating system.

2. Experimental procedure

The experiments are performed on the gating system of the electric motor flange casting, casted from EN AC 47100 alloy (AlSi12Cu1(Fe)). The gas entrapment in the casting volume is evaluated with the respect to the flow regime and the merging of the melt streams in the area behind the cores, according to the Fig. 1. At these locations the further mechanical machining of the castings occurs and the presence of porosity and cavities localized and revealed by it is unacceptable, therefore it is essential to eliminate it already in the design phase of casting cycle.

![Fig. 1 Location of monitoring points](image)
simulation program Magmasoft MAGMA5 – HPDC module, section Results/Veloci
ty, the average
velocity in gate in monitoring points was determined for each variant of gate design (Figure 1), based
on which with the use of continuity equation the corresponding piston velocity is determined, as a
technological equivalent of gate design modification. Table 1 shows the compared design and
technological parameters determined using the defined correlation factor.

| Design element | Correlation factor | Technological factor |
|----------------|-------------------|---------------------|
| Gate height, mm | v<sub>G1</sub> = 35.00 | v<sub>P1</sub> = 2.80 |
|                 | v<sub>G2</sub> = 50.43 | v<sub>P2</sub> = 3.99 |
|                 | v<sub>G3</sub> = 60.33 | v<sub>P3</sub> = 4.78 |

The gas entrapment in the cast volume at monitoring points C1a – C4e (Figure 1) was evaluated
using the simulation program Magmasoft MAGMA5 – HPDC module, Results – Air Entrapment. The
setting of the input parameters of the casting cycle for simulation purposes is identical to the setting of
the technological parameters in the foundry, and it is documented in Table 2.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Alloy                            | EN AC 47100, AlSi12Cu1(Fe) |
| Melt temperature, °C             | 610                    |
| Mold temperature, °C             | 200                    |
| Pressing piston velocity, ms<sup>-1</sup> | 2.8           |
| Holding pressure, MPa            | 25                     |
| Filling time of the mold cavity, s | 0.015                |

3. Description of achieved results
The gas entrapment in the casting volume is evaluated just before the end of the filling phase, when the
gating system is filled to 100% of its volume. Table 3 presents the gas entrapment results obtained using
the MAGMA5 program. Results present the average value of the gas entrapment in the casting obtained
as the average of the values read from the monitoring points according to Figure 1 (C1a – C4e).

| Gate height, mm | Gas Entrapment, % | Piston velocity, ms<sup>-1</sup> | Gas Entrapment, % |
|----------------|-------------------|---------------------------------|-------------------|
| b₁ = 1.25      | 2.52              | v<sub>P1</sub> = 2.80           | 2.52              |
| b₂ = 0.92      | 4.16              | v<sub>P2</sub> = 3.99           | 4.62              |
| b₃ = 0.75      | 5.16              | v<sub>P3</sub> = 4.78           | 5.74              |

For a better visualization of the gas entrapment development in the casting volume depending
monitored parameters, the graph was designed and it’s shown in Fig. 2.
Fig. 2 Gas entrapment depending on monitored parameters

As arises from Table 3 and Fig. 2, with decreasing gate height $b$ and with increasing piston velocity $v_P$, the gas entrapment value in the cast is increasing. It is evident that the values of gas entrapment observed at the variable gate height show lower values compared to the piston velocity values. Therefore, it was necessary to focus on the melt flow nature in runners to clarify this phenomenon.

The melt flow nature in runners is given by the melt velocity. As the melt flow velocity increases, so does the risk of the melt splashing, disrupting of the melt flow integrity, and thus development of conditions that facilitate the gas entrapment in the melt volume and their distribution to the cast [4,5-8,14]. This is the reason why the velocity in runners was monitored and examined in monitoring points. (Fig. 1).

Table 4 presents the average values of the melt flow velocity at selected monitoring points located on the mean diameter of the runner.

| Table 4 Melt velocity in the runners |
|-------------------------------------|
| Main runner | Melt flow velocity, ms$^{-1}$ | Piston velocity | Melt flow velocity, ms$^{-1}$ |
| Gate height | $v_P$ | $v_P$ |
| $b_1$ | 14.36 | $v_{P1}$ | 14.36 |
| $b_2$ | 14.59 | $v_{P2}$ | 24.47 |
| $b_3$ | 14.48 | $v_{P3}$ | 29.34 |
| Secondary runner | Melt flow velocity, ms$^{-1}$ | Piston velocity | Melt flow velocity, ms$^{-1}$ |
| Gate height | $v_P$ | $v_P$ |
| $b_1$ | 24.08 | $v_{P1}$ | 24.08 |
| $b_2$ | 23.54 | $v_{P2}$ | 34.70 |
| $b_3$ | 23.13 | $v_{P3}$ | 39.35 |

From Table 4 arises, that the values of the melt velocities in the runners are oscillating at a relatively constant level during the modification of gate design. Slight deviations from the constant level can be caused by the differentiation of the melt stream velocity profile in the cross-section of the runner [15,16]. The runners melt velocities increase with increasing the piston velocity. This is associated with a possible change in the melt flow change in runners and thus accompanied by a higher possibility of gas entrapment in melt volume. To confirm this assumption, the flow nature in main runner is monitored.

Fig. 3 show the melt flow nature in the locations where the most significant melt splashing and melt volume gas entrapment occurred.
Fig. 3 A presents the formation of a melt stream as the melt passes from the biscuit to the main runner, in the area between the velocity monitoring points (Figure 1). As its evident from Fig. 3 A, for each equivalent, a wave effect occurs, in which the return wave of melt reflected from the opposite wall of the runner is formed. It traps the gases in the melt and promotes their distribution to the casting. The most significant volume of gases in this section is trapped when the pressing velocity is set to the value \( v_{P3} = 4.78 \text{ m.s}^{-1} \). This setting of the pressing velocity creates yet another extreme. If at lower velocity the effect of the „initially solidified crust“ prevails during the filling, when the melt flow proceeds along
the initially formed crust constituted by the solidifying melt upon contact of the melt with cold face of the die. At the velocity value \( v_{P3} = 4.78 \, \text{m} \cdot \text{s}^{-1} \), this crust is entrained and the filling has a nature of accidental splashing, which creates a larger vacant surface of the melt coming into the contact with the gases in the die cavity (Fig. 3). This creates conditions that promote the oxidation of the melt and the gas entrapment in its volume [4,9, 17].

Fig. 3 B presents the gas entrapment by the melt in the area of main runner branching. It is evident from the simulation that the wave effect and gas entrapment in the wave also occur in here. As mentioned, at a piston velocity \( v_{P3} = 4.78 \, \text{m} \cdot \text{s}^{-1} \), the melt flow in the runners splits and the solid melt stream does not enter the runner branching location. This makes it possible to create a larger space for gas entrapment in the melt (Figure 4). As it can be seen, at the time when the melt is closed at lower velocities and the filling of the secondary runners begins, the variant with piston velocity \( v_{P3} = 4.78 \, \text{m} \cdot \text{s}^{-1} \) still creates „hollow“ gas-containing spots in the melt flow (Fig. 3 B).

The melt flow nature in runners is, as demonstrated by the simulation, dependent on the piston velocity in the filling chamber. It is evident that the final piston velocity in the filling chamber does not increase abruptly, but is conditioned by a smooth acceleration. At Fig. 4 are filling curves showing the dependence of the piston velocity on the instantaneous position of the piston in the filling chamber. The maximum piston velocity in the first filling phase is selected at 0.4 ms\(^{-1}\).

![Fig. 4 Plunger acceleration depending on the position in the filling chamber](image)

The filling velocity of a die cavity is understood as the velocity of the piston movement at the moment when the melt reaches the gate. When the filling velocity of the piston is set to the value \( v_{P1} = 2.8 \, \text{m} \cdot \text{s}^{-1} \), the acceleration of the piston is commenced at the time when the melt is in the area of secondary runners. With increasing piston velocity, a shift in the start of acceleration to the area of main runner is evident. As a result, acceleration is imparted to the melt at a time when a still flow in runners is required, which promotes the change in the flow nature and causes the melt to splash and trap the gases in its volume. With Fig. 4 and the analysis of the piston velocity change in the filling chamber depending on its position, the cause of the change in the flow nature is explained and presented on Fig. 3.
4. Conclusions
As emerge from the results presented in Table 3 and Figure 2, a design modification of the gate and an equivalent change in the piston velocity have a direct effect on the values of gas entrapment in the cast volume.

Table 3 and Fig. 2 show that the gas entrapment in the cast volume is more distinct with the changes in the piston velocity compared to the change in the gate height. As mentioned above [2,6,13], the cross section of the gate and melt velocity in gate determine the filling mode of the die cavity, which makes it possible to predict the development of gas entrapment in the cast volume. With the decreasing height of the gate b, the percentage of the gas entrapment in the cast volume also increases. This fact can be justified based on Table 3. The smaller cross section of the gate allows an increase in the gate melt velocity, which significantly shifts the filling mode of the die cavity from turbulent to dispersive [7,8,11,13].

Although the gate melt velocity selected as a correlation factor is kept at a relatively constant level, based on the measurements presented in Fig. 2 and Table 3, the values of gas entrapment in the cast volume is showing higher values when the pressing velocity is changes, rather than when the gate design is modified. It is clear that with increasing piston velocity the value of gas entrapment in the casting volume increases.

An explanation can be derived from the measurements presented in Table 4. As the value of the piston velocity increases, the value of the velocity in runners also increases. This results in a change in melt flow regime in runners.

The assumption of a flow regime change is confirmed based on the Fig. 3. A wave effect is evident in the observed places, when the impact of the melt on the opposite wall of the runner creates a wave, under which the gas entrapment in the melt volume and distribution in the cast volume occurs. As the piston velocity increases, this effect is more distinct. At the velocity $v_{p3} = 4.78 \text{ m.s}^{-1}$, not only is the swirling of the melt caused by the formation of waves on the impact with the runner wall but also a significant splashing of the melt occurs, which creates a larger vacant surface of the melt promoting the gas entrapment in contact with gases. Based on simulations, it was shown that the melt flow at the pressing piston velocity $v_{p1}$ and $v_{p2}$ maintained a straight face when passing through straight runner without changing the direction and followed the model of the „initially solidified crust “. In case of $v_{p3}$, the melt stream face was incomplete, showing the signs of accidental splashing.

The cause of the higher gas entrapment in the melt volume is thus an increase in the melt velocity in runners. This fact is also confirmed based on Figure 5, where the acceleration of the piston and the increase of the melt flow velocity by increasing the piston velocity shifts from the gate to the biscuit, respectively to the filling chamber.

Based on performed measurements, it is therefore possible to unambiguously state that the design modification of the gating system, respectively of its structural unit is, with regard to the gas entrapment in the cast volume, more advantageous than changing of the pressing system technological parameters. This finding is justified by the fact that if the change of the gate cross section only affects the filling mode of the die cavity (meaning the change only affects the nature of the flow behind the gate), another series of consecutive parameters such as melt velocity in runners and thus the flow nature is bound on the piston velocity.

Based on the achieved results, the following recommendations can be stated:
- when introducing the production of new castings, pay increased attention to the gating system design and the design of castings structural elements,
- eliminate the possibility of gas entrapment in the melt already in the initial gating system design,
- with the proper gating system design, we will achieve more stable casting cycle, with the possibility of partial regulation via technological parameters change,
- when introducing new casting into production, use the CAx systems, which also help to reveal hidden design and technology errors.
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