THE ISSUE OF DETERMINING THE LOCKING FORCE OF A HPDC MACHINE

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In the high-pressure die casting machines, the locking force is a parameter that determines the size of the machine. For the safe operation of the machines, it is necessary that the die is locked perfectly, which ensures compliance with the dimensional tolerances of the cast and prevents metal from spraying out of the parting plane. The submitted contribution is devoted to the issue determining the adequate locking force of the machine and describes the recommended methodology for determining its size and the resulting area of application. Based on the dimensions of the gating system, the dimensions of the die frame cavity insert are calculated. By determining the center of the cavity insert and the center of the gating system, the position of the carriers of the opening and locking force are determined. In order to unify the carriers of the opening and locking force, the gating system is modified. It is proven that the unification of the centers eliminates the momentary rotating effect of forces not lying on one carrier, and at the same time, the modification of the gating system contributed to the reduction of the gas entrapment in the volume of the high pressure die cast.

KEYWORDS

HPDC, Locking Force, Moment of Forces, Twisting couple, Gas Entrapment

1 INTRODUCTION

The principle of high-pressure die casting (HPDC) technology is to press a molten alloy into a metal die cavity at high speed, where it subsequently solidifies under high pressure. Under these conditions, it is possible to produce complex casts with relatively small wall thicknesses [Koza 2024]. The use of high pressure die casting enables the mass production of alloy components with high dimensional accuracy and high production efficiency. However, cast defects such as gas entrapment, pits caused by improper filling of the die cavity and shrinkage of the melt during solidification, etc., are commonly and often randomly distributed in the components, which directly reduces the mechanical properties of the casts. The design and arrangement of the gating systems as well as the appropriate configuration of the process parameters are the key factors affecting the melt flow characteristics and solidification process during the HPDC process [Tavodova 2022, Wang 2022].

Gating systems play a very important role in high-pressure die casting. Poor design of the gating system can lead to various cast defects such as gas porosity, shrinkage porosity, map-like surfaces, cold joints and poor surface quality [Hu 2000]. The gating system is located in the high-pressure permanent die. It is one of the most important parts of the entire casting process, as ii is here where the molten metal takes shape and the complete cast is formed. When manufacturing dies for HPDC, the design of the cast layout should be considered based on the relationship between the pressing system, cast conditions, gating and cooling system design [Kwon 2019].

The gating system design methodology and its impact on the process parameters is summarized in the publication [Majernikova 2024]. On of the indicators addressed in this publication is the locking force of the machine directly proportional to the cast surface projection onto the parting plane of the die. With the dimensions of the cast, the demands on the machine size and the size of the clamping and locking forces also increase [Mielke 2025].

The size of the required locking force of the machine can be determined based on relations (1) and (2) [Majernikova 2024, Ruzbarsky 2014]:

$$F_L \geq k * F_O \tag{1}$$

Where:

F_L – locking force [N],

F_O – opening force [N],

k – coefficient of safety; minimum selected k = 1.1 (10%)

$$F_O = S_{Cmax} * p_{max} \tag{2}$$

Where:

F_O – opening force [N],

S_{Cmax} – maximum gating system area projection in parting plane, including the biscuit, runners and overflows [m^2],

p_{max} – maximum pressure on melt (holding pressure) [Pa].

In general, it is advantageous, with regard to eliminating the effect of moment of the forces loading the die body and guide columns, to design the die frame and cavity inserts so that their center and the center of the gating system in the die parting plane have the same coordinates [Majernik 2021, Ragan 2007]. Since the carrier of the resulting opening force caused by the piston pressure on the melt passes through the center of gating system and the carrier of the locking force passes through the center of the die, by projecting the centers of the die and gating system into common coordinates, we will achieve the unification of the opening and locking forces and prevent the rotating effect arising from the moment of forces, or the force pair [Challamel 2021, Gu 2025].

The primary objective of the submitted article is to assess the suitability of the design modification of the gating system with regard to the unification of the position of the carriers of the opening and locking force of the machine. For a specific type and design of the gating system, the appropriate size of the cavity inserts is designed according to the methodology summarized in the standard CSN 22 8601 (still valid) [CSN 22 8601 1984]. Using static methods, the centers of the cavity inserts and the gating system are determined, whereby the submitted article also describes the methodology for determining the centers of the die structural nodes by using the determination of static moments of the surface to the axes of the selected coordinate system. By comparing the coordinates of the centers of the cavity inserts and gating system, the necessary correction of the gating system geometry is determined to achieve the identification of the machine opening and locking force carriers. Using the MagmaSoft simulation program, the suitability of the design modification of the gating system is verified with respect to the selected quality indicators.

2 DESCRIPTION OF EXPERIMENTAL PROCEDURE

2.1 Die size determination method

The size of the die depends primarily on the number of molded casts, the size and principle of the pressure casting machine. The main dimensions of the die are determined by calculation according to the relations (3) to (6). The calculation respects the requirements for location of the overflows and cooling system [CSN 22 8601 1984, Ruzbarsky 2014].

In general, for a multiple die with casts molded into cavity inserts in frames, the calculation of the dimensions of the cavity inserts and the size of the die can be based on Fig. 1.

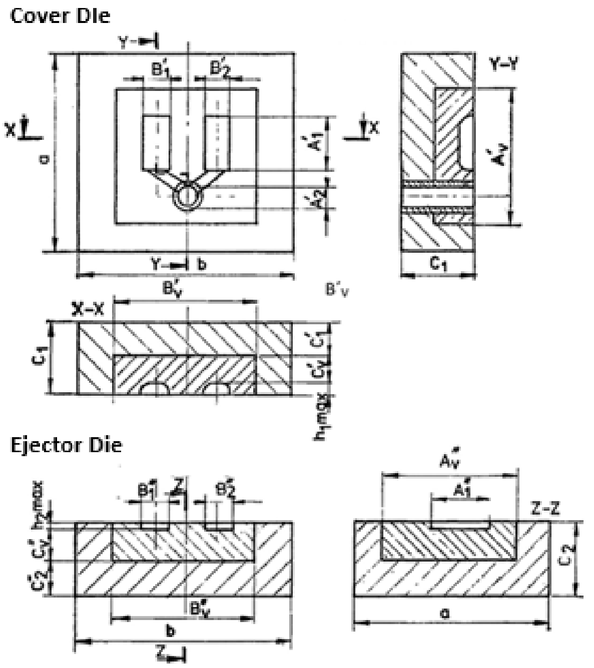

Figure 1. Main dimensions of the multiple die

The dimensions of the inserts A'_V and B'_V in cover die are determined according to relations (3) and (4):

$$A'_V = (3.4 - 3.6) * \left[\sum_{i=1}^{n} A'_i\left(1 + \sum_{i=1}^{n} m_{A'_i}\right)\right]^{0.84} \quad (3)$$

$$B'_V = (3.4 - 3.6) * \left[\sum_{i=1}^{n} B'_i\left(1 + \sum_{i=1}^{n} m_{B'_i}\right)\right]^{0.84} \quad (4)$$

The dimensions of the inserts A''_V and B''_V in ejector die are determined according to relations (5) and (6):

$$A''_V = (3.4 - 3.6) * \left[\sum_{i=1}^{n} A''_i\left(1 + \sum_{i=1}^{n} m_{A''_i}\right)\right]^{0.84} \quad (5)$$

$$B''_V = (3.4 - 3.6) * \left[\sum_{i=1}^{n} B''_i\left(1 + \sum_{i=1}^{n} m_{B''_i}\right)\right]^{0.84} \quad (6)$$

Where:

dimensions A'_V, B'_V, A''_V and B''_V are based on the Fig. 1.

To calculate the frame size, the larger of the values A'_V or A''_V is used (as well as B'_V and B''_V), and is designated as A_V (B_V) in the calculation. The frame sizes are then determined by relations (7) and (8):

$$a = (3.6 - 3.9) * A_V^{0.84} \quad (7)$$

$$b = (3.6 - 3.9) * B_V^{0.84} \quad (8)$$

Where:

dimensions a, b are based on the Fig. 1.

2.2 Method for determination of the die and gating system center of the gravity

The center of a parallel force system, whose forces are tied to the points, is called the point through which the resultant of this force system passes when the system is rotated by an arbitrary angle. When analytically determining the position of the center, knowledge of the mass distribution in the space of the body is a prerequisite [Pasko 2014, Gu 2025].

Based on relation (2), where we use the maximum gating system area projection in parting plane, including the biscuit, runners and overflows - S_{Cmax} to determine the opening force F_O, it is possible to consider this projection of the gating system area into parting plane of the die as a homogeneous body of constant thickness, i.e. a shell, and the coordinates of the center of such a body are determine according to relations (9), (10) and (11) [Pasko 2014]:

$$x_C = \left(\int_S xdS\right)/S \quad (9)$$

$$y_C = \left(\int_S ydS\right)/S \quad (10)$$

$$z_C = \left(\int_S zdS\right)/S \quad (11)$$

Where:

x_C, y_C, z_C – center coordinates in axes [mm],

S – total body surface area [m^2],

If it is possible to divide a body into a finite number of parts whose centers we know or can determine, then in the case of projection of the casts surface onto the dividing plane considered as a homogeneous body, and therefore a shell, we determine the coordinates of the center according to the relations (12), (13), (14) [Pasko 2014]:

$$x_C = (\sum x_i S_i)/(\sum S_i) \quad (12)$$

$$y_C = (\sum y_i S_i)/(\sum S_i) \quad (13)$$

$$z_C = (\sum z_i S_i)/(\sum S_i) \quad (14)$$

Where:

x_C, y_C, z_C – center coordinates in axes [mm],

x_i, y_i, z_i – gravity centers coordinates of the body´s i-th part [mm],

S_i – total body surface area of i-th part [mm^2].

For a surface area or a shell in a plane, in the case of projecting the cast surface area onto the parting plane, it is necessary to understand the parting plane, relations (12) and (13) apply, while $z_C = 0$.

2.3 Cast and gating system characteristics

The size of the cavity inserts, their center and the center of the gating system were determined using the gating system of the electric motor flange cast according to Fig. 2. The cast is made of Alloy EN AC 47 100 (AlSi12Cu1(Fe)).

Figure 2. The electric motor flange cast

For the production of the cast according to Fig. 2, a gating system is used, the model of which is shown in Fig. 3, or Fig. 4. The characteristic dimensions of the cast and the gating system are given in Tab. 1.

Table 1. Cast and gating system characteristics

Quantity	Value
Alloy	EN AC 47 100 – AlSi12Cu(Fe)
Alloy density ρ, kg.m^{-3}	2650
Cast volume V_{cast}, m^3	51697.9*10^{-9}
Cast weight m_C, kg	0.136
Cast diameter, mm	116.5
Characteristic cast wall thickness h_{CH}, m	2
Length of secondary runner,	280
Length of main runner, mm	264
Width of the main runner, mm	38
Width of the secondary runner, mm	20.5
Height of runners, mm	14.59
Total height of the gating system, mm	396.5
Total width of the gating system, mm	346.5

2.4 *Cast volume gas entrapment assessing method*

The assessment of gas entrapment in the cast at the end of the filling phase was assessed using the Magmasoft MAGMA 5.5.1 program – HPDC module. The setting of input parameters of the casting cycle and the parameters of the casting process was essentially identical to the setting of the casting machine when producing casts using the initial gating system. The differences between the real cast and the simulated cast are based on the design of the gating system after unification of the center coordinates.

The parameter settings for the purpose of the numerical simulation are given in Tab. 2.

Table 2. Numerical simulation casting process parameters settings

Technological parameters	
Parameter	Value
Alloy	EN AC 47 100 (AlSi12Cu1(Fe))
Melt temperature	708 °C
Die temperature	220 °C
Max. pressing piston velocity in the first phase	0.2 m.s^{-1}
Max. pressing piston velocity in the second phase	2.7 m.s^{-1}
Holding pressure	25 MPa
Process parameters	
Die treatment - spraying	Start – 5 s after cast removal
	Duration – 3 s
Die treatment - blowing	Start – 2 s after end of spraying
	Duration – 3 s
Die locking	2 s after end of blowing
Dosing	Start – 1 s after mold locking
	Metal batch volume – Variant 1: 446.98*10^{-6} m^3
	– Variant 2: 437.68*10^{-6} m^3
	Duration of batching – 5 s
	Delay time – 3 s

To improve the simulation accuracy and to obtain a better description of the target entity, a mesh with high fineness and generation efficiency was chosen. A fine mesh was chosen for the casting cycle simulations, the parameters of which are stated in Tab. 3 where cells are distributed equidistantly to the geometry of individual volumes.

Table 3. Mesh setting parameters

Element parameters			
	Element size, mm		
	In the x-axis direction	In the y-axis direction	In the z-axis direction
Mold	5	5	5
Runners	2	2	2
Tempering channels	2	2	2
Filling chamber + biscuit	2	2	2
Casts + overflows	0.66	0.33	0.66
Gate	0.38	0.19	0.38

The assessment of gas entrapment in the cast volume was carried out in places where the cast is subsequently chipped and the occurrence of porosity in these places could be problematic during machining, with regard to the possibility of pores being exposed after chip removal. At the same time, these places were assessed as critical with regard to the occurrence of porosity and with regard to the melt flow around the cores, which form the structural opening of the cast. When the melt flows around the cores, two melt streams merge behind it, which rises the potential for gas entrapment in the cast due to swirling and mixing of the melt. The monitored points are shown in Fig. 3. The locations for monitoring of gas entrapment in the melt volume are located 1 mm in the radial direction behind the core and 2 mm from the cast surface into its volume. The monitored points are marked SM1 to SM5 for each cast in the numbering sequence in the direction of rotation from SM1 to the axis of the main runner.

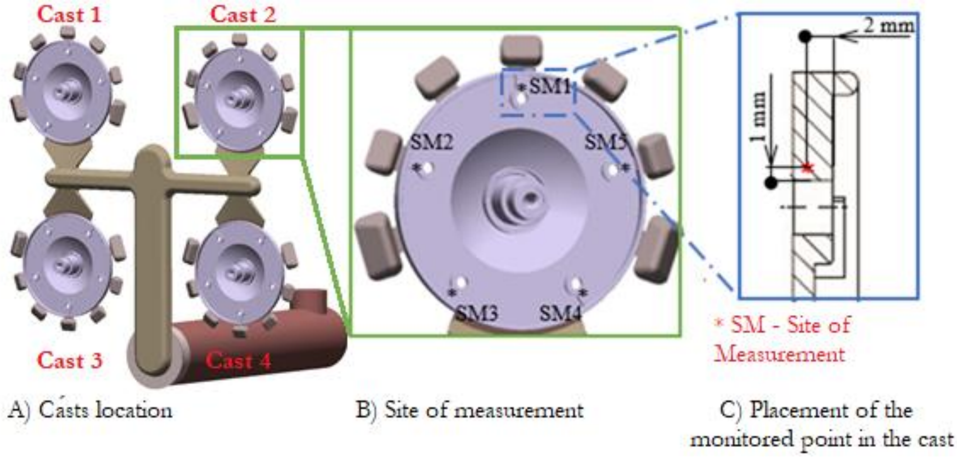

Figure 3. Monitored points for gas entrapment assessment in cast volume

The assessment of gas entrapment was performed using the Air Entrapment submodule at the end of the filling phase, i.e., at the moment when the gating system was filled to 100% of its volume, just before the holding pressure phase. This moment was chosen considering that holding pressure largely eliminates the size and distribution of pores [Gaspar 2016]. Even at this moment, it is possible to assess only the proportion of gases entrapped in cast volume due to the gating system geometry.

3 RESULTS

The problem solution of machine locking force determination and gating system design modification with the aim of unifying the carriers of the locking force and the opening force was performed in the following steps:

- determination of the cavity insert size and its center
- determination of gating system center and performing the design modification of gating system with the aim of unifying the carriers of the resultant forces loading the die,
- determination of the machine locking force,
- casts gas entrapment assessment.

3.1 Determination of the cavity insert size

Based on the dimensions of the gating system given in Tab. 1 and using relations (3) to (6), the dimensions of the cavity insert are determined. Using relations (7) and (8), the size of the machine frame for clamping the cavity inserts is determined. Since the carriers of the locking and opening forces are perpendicular to the parting plane of the die, Tab. 4 shows the cavity insert and the frame dimensions in this plane, i.e., the x-y plane. For relations (3) to (6), the magnification factor, defined in the relations in the range (3.4 – 3.6), is chosen to be 3.5. For relations (7) and (8), this magnification factor in the range of (3.6 – 3.9) is chosen to be 3.8.

Since the frame dimensions are based on the cavity insert dimensions and are increased by the value of the magnification factor 3.8, the frame dimensions are proportionally increased, and therefore the center of the frame and cavity insert lying in the projection onto the parting plane of the die have identical coordinates.

Table 4. Cavity inserts and frame dimensions

Dimension	Value
A'_v, mm	604
B'_v, mm	564
A''_v, mm	604
B''_v, mm	564
a, mm	823.84
b, mm	777.86

According to the relations (12) and (13) it is possible to determine the coordinates of the cavity insert center. If the selected coordinate system is placed on the cavity insert according to Fig. 4, then the coordinates of the cavity insert center are x = 282 mm and y = 302 mm. The position of the cavity insert center and simultaneously the formation of the gating system is shown in Fig. 4. The axis of the main runner is identical to the coordinate in the x axis, namely at a value of 280 mm from the zero point of the selected coordinate system.

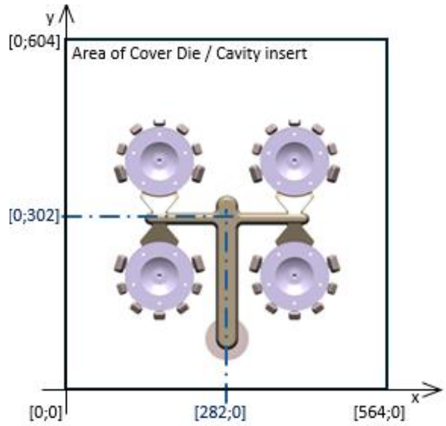

Figure 4. Gating system location in the cavity insert

3.2 Determination of gating system center

To determine the gating system center, the data in Tab. 1 was used. The total area of the gating system projection to the parting plane of the die was divided into unit areas of simple shapes according to Fig. 5. The area of gating system was divided into the main runner area, secondary runner area, biscuit area and the area of casts (understanding the area as the projection to the parting plane).

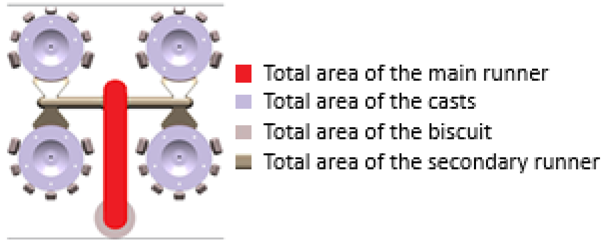

Figure 5. Partial areas of individual gating system sections

The coordinates of the resulting center can be calculated using relations (12) and (13) and by their modification [Pasko 2014, Gu 2025]:

$$x_C = U_y/S = (\sum x_i S_i)/(\sum S_i) \quad (15)$$

$$y_C = U_x/S = (\sum y_i S_i)/(\sum S_i) \quad (16)$$

Where:

U_y – static area moment to the y-axis [mm^3],
U_x – static area moment to the x-axis [mm^3],
S – total resulting area [mm^2].

In the selected coordinate system according to Fig. 4, the coordinates of the individual gravity centers are subsequently determined. The data used to determine the resulting gravity center of gating system are recorded in Tab. 5.

Table 5. Characteristics of gating system partial sections

Partial section of the gating system	x_i	y_i	Si	$U_{yi} = x_i * S_i$	$U_{xi} = y_i * S_i$
Casts	282	308	42616	12017960	13125999
Secondary runner	282	300	4301.2	1212938	1290360
Main runner	280	208	9721.54	2722031	2022080
Biscuit	282	95	3846.5	1084713	365417.5
Σ			60486.12	17037643	16803857

Subsequently, according to relations (15) and (16), it is possible to determine the coordinates of the gating system center as:

$$x_C = U_y/S = 282\ mm$$
$$y_C = U_x/S = 277.81\ mm$$

As follows from the calculations, the difference in the position of the cavity insert center and gating system center is 24.19 mm in the y-axis. The coordinates in the x-axis are identical.

With regard to the die design, the location of the cores, ejectors and other structural parts of the die, the need to maintain the position of the die cavities, and therefore casts, in the original coordinates prevail. To unify the position of the cavity inserts center and gating system center, it is necessary to adjust the design of the main runner by shortening its length by the value Δl = 24.19 mm.

When the main runner is shortened, the area of the gating system projection into parting plane of the die is reduced by the value ΔS = 919.22 mm^2, which is also reflected in the change in the opening ang minimal necessary locking force of the machine.

3.3 Determination of machine locking force

As mentioned above, reducing the area of gating system projection into parting plane causes a change in opening force trying to open the mold halves. Using relation (2), it is possible to determine the magnitude of opening force and subsequently, using relation (1), the value of the designed locking force is determined. Tab. 6 shows the values of the resultant forces loading the die, The magnitude of the opening force can be understood as a minimum possible locking force of the machine. The design modification of the gating system was reflected in the change in the size of minimum and designed locking force of the machine. If the difference in the designed locking force for Variant 1 and Variant 2 is taken into account, the difference is ΔF_L = 29.88 kN. With regard to the sizes of industrially used high pressure casting machines, the size of the required designed force can be neglected or considered minimally.

As follows from Fig. 6, for the original gating system, the point of action of the locking and opening forces, and therefore the distance between their carriers, is shifted by the value p = Δl = 24.19 mm, i.e. the distance p is equal to the difference in the coordinates of the gating system and the cavity insert centers in the direction of the y-axis.

Table 6. Values of forces loading the die

	Variant 1 original	Variant 2 modified
Projection area into the partin plane S_{Cmax}, mm^2	60486.12	59566.90
Holding pressure p_{max}, MPa	25	25
Opening force F_O, kN	1512.15	1489.17
Safety coefficient k	1.3 (30%)	1.3 (30%)
Locking force F_L, kN	1965,80	1935.92

Considering the minimum necessary locking force, for which $F_{Lmin} = F_o$ is valid, the forces F_{Lmin} and F_o are parallel to each other, of equal size, oppositely oriented, and not lying on the same carrier. Such a force pair creates a rotating effect, equal to the sum of one of the forces and the perpendicular distance between the forces. The effect of the force pair is given by its moment, the magnitude of which is determined from the relation (17) [Pasko 2014, Gu 2025]:

$$M = p * F = p * F_{Lmin} = p * F_o \quad (17)$$

For the original gating system, i.e. Variant 1, the magnitude of the moment effect of the force pair is according to relation (17):

$$M = p * F_{Lmin} = p * F_o = 24.19\ mm * 1512.15\ kN = 36578.91\ Nm$$

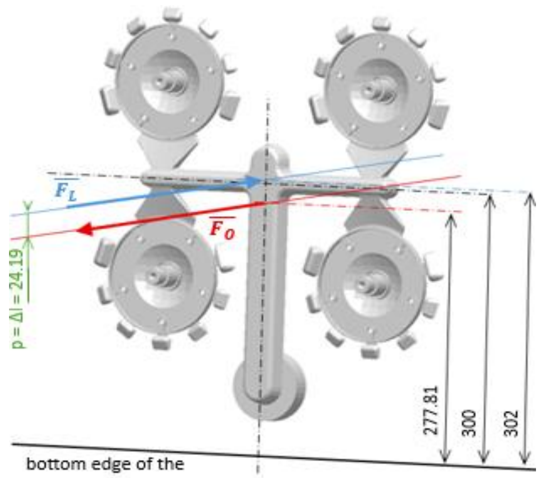

Figure 6. Diagram of the resultant of the opening and locking force in the original gating system

When the coordinates of the cavity insert and gating system centers are unified, the force vectors F_{Lmin} and F_o lie on one straight line and therefore on one carrier, and the moment effect of the force pair is then equal to 0, M = 0 Nm. This significantly reduces the loading of the die body and guide columns from the rotating effects caused by the moment.

3.4 Assessment of casts volume gas entrapment

With regard to the stress of the die body and the design of the high-pressure casting machine, a change in the design is advantageous. To assess the impact of the design modification of the gating system on the casts quality, the gas entrapment by the melt during its passage through the gating system and the subsequent gas entrapment in the cast volume were monitored. The measured values of the gas entrapment in the cast volume at monitored points according to Fig. 3 are presented in Tab. 7 and Tab. 8.

Table 7. Cast volume gas entrapment values in original gating system

	SM1	SM2	SM3	SM4	SM5	Average
Cast 1	0.373%	0.014%	2.812%	2.777%	0.003%	1.1958%
Cast 2	1.850%	0.010%	0.100%	0.061%	0.002%	0.4046%
Cast 3	0.145%	0.001%	0.092%	0.012%	0.004%	0.0508%
Cast 4	3.494%	0.003%	0256%	0.256%	0.001%	0.8540%
					Total Avg.	0.6263%

Table 8. Cast volume gas entrapment values in the modified gating system

	SM1	SM2	SM3	SM4	SM5	Average
Cast 1	1.270%	0.010%	0.107%	0.033%	0.000%	0.2840%
Cast 2	1.064%	0.000%	0.031%	0.053%	0.000%	0.2296%
Cast 3	0.261%	0.051%	0.020%	0.045%	0.004%	0.0762%
Cast 4	2.081%	0.004%	0.000%	0.172%	0.683%	0.5880%
					Total Avg.	0.2945%

4 CONCLUSIONS

The submitted contribution is devoted to the problem of determining the opening and locking forces loading the die. After determination of the opening and locking forces resultants carriers, a design modification of the gating system was performed with the aim of unifying the carriers of forces and examining the impact of this modification on selected indicators. The main impacts of the design modification of the gating system are presented in Fig. 7. As follows from the comparison of the results, the design modification of the gating system with regard to the unification of the opening and locking forces resultants carriers caused a reduction in the stress on the die and the die locking mechanism, as well as a reduction in the gas entrapment values in the casts volume.

By modifying the main runner by reducing its length by the value Δl = 24.19 mm, a reduction in the gating system volume and the metal dose per operation by the value of ΔV = 12033.07 mm^3 is simultaneously achieved, which in terms of material saving s means 0.032 kg per operation. With regard to the size of commercially used high-pressure casting machines, the reduction of the minimum and designed locking force is not of great importance. The unification of the opening and locking force resultants carriers is very important, due to achieving the elimination of the moment of forces according to Fig. 6 and relation (17).

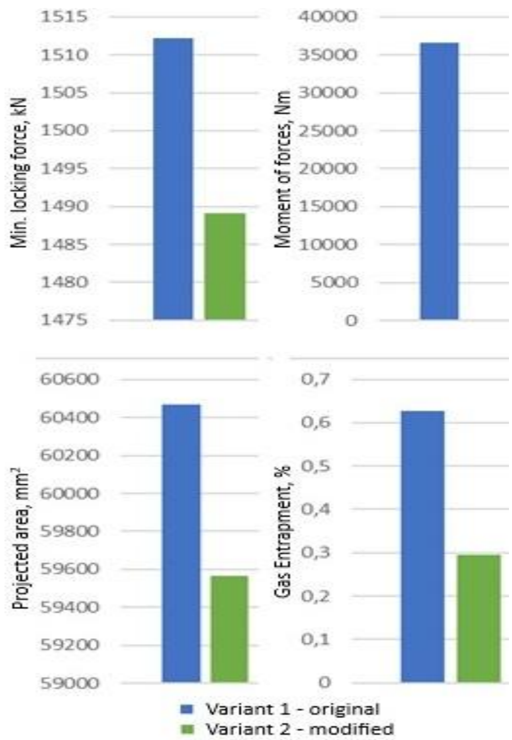

Figure 7. Comparison of monitored parameters

Last but not least, it is necessary to take into account the achieved reduction of gas entrapment values in the cast volume. This reduction can be explained by referring to the basics of the flow hydrodynamics. A melt with highly turbulent flow character passing through the main runner with a shorter length has. Due to the non-planar nature of the front flow and the flow fragmentation, the possibility of shorter contact with the gases contained in the gating system, which also reduces its gas entrapment and subsequent transport of gases into the cast volume.

Aspects of reducing the fragmentation of the melt flow when passing through the gating system by using the design modification of the die and gating systems, as well as the possibilities of reducing the gas entrapment in the high-pressure casts volume will be investigated in the following research activities.

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