ISSN 1847-7917

Selection of optimal die casting process parameters based on simulation and genetic algorithms

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Keywords
High-pressure die casting
Mould
Optimization
Simulation
Aluminum alloy

Professional paper

Abstract: High pressure die casting is a common process for manufacturing structural components from non-ferrous metals with a low melting point. Process is particularly suitable for large-scale castings production with complex geometry. There are many features affecting the complexity of the process. It is of great importance for engineers to optimize process parameters and improve casting quality. In this paper, design and implementation of predictive models developed for improving the quality of aluminum die castings are presented. The goal is minimizing material shrinkage and solidification time. Design of experiments were obtained using the Box-Behnken method, and experiments were made in virtual environment, i.e. in NovaFlow&Solid software. Regression analysis and analysis of variance were used for obtaining mathematical models. Optimization of mathematical models was performed using genetic algorithms. Optimal values of input parameters are preheating mould temperature of 150 °C, velocity of piston of 2.5 m/s and injection pressure of 49.2 MPa.

1. Introduction

High pressure die casting (HPDC) is a process of molten metal injecting at high speed and high pressure into permanent mould. The pressure in the mould is maintained until the casting solidification is completely finished. The mould is made of material that is highly resistant to heat and wear, and is designed to allow the production of geometrically complex castings with a high degree of dimensional accuracy. High pressure die casting is used in a serial and mass production of castings. Excellent surface quality and high precision are the main features of castings produced by high pressure die casting. The process is very productive, the price of one casting is acceptable even though the mould is very expensive. Due to the above characteristics, more than 50 % of all castings of aluminium alloys are produced by HPDC. In order to obtain a quality casting, it is necessary to properly design the mould and its components as well as to adjust the technological parameters that affect the final properties of the casting, [1]. Those parameters are: alloy and mould materials, mould preheating temperature, ejection force and time, injection speed in the first phase, injection pressure in second phase, piston diameter etc. The temperature of the mould and the temperature of the molten metal that flows into it have a very important influence on the mould life during the process, [2]. The high temperature of the mould prolongs the solidification process, which prolongs the cycle itself, while the cold mould will cause surface defects. Based on the research in the literature, the optimal preheating temperature of the mould for aluminium alloys is from 180 °C to 300 °C, [3], [4].

If the mould temperature is less than the optimal range, the probability of errors and pore appearance increases. Aghion et al. [5] investigated the relationship between the characteristics of high-pressure die casting and the mechanical properties of casting. They reported about the close connection between microstructure and properties of alloy and process parameters as well. The greater the wall thickness, the lower the tensile strength and yield strength, while the elongation increased proportionally. The wall thickness of the casting also affects the porosity and grain size, the thicker wall reduces the occurrence of porosity and increases the grain, but also prolongs the cooling time. Molten metal flow velocity has a significant influence on the alloy microstructure, and consequently on mechanical properties of the casting, [6], [7]. In order to achieve the best possible properties of high-pressure die castings, it is necessary to adjust the parameters that affect the quality of the casting, namely: casting alloy, die casting machine, pouring temperature, melt pressure, molten metal flow velocity in all stages of the process etc [8], [9].

2. Parameters of high pressure die casting process

In order to obtain a satisfactory quality casting, the proper dimensioning of the gating system was performed in this paper. After investigating the influences of technological parameters and properties of aluminium alloys, three input parameters were selected, the action of which was monitored through the conduction of virtual experiments, i.e. simulations in program NovaFlow&Solid. Simulations were carried out according to the adopted Box-Behnken design of experiments and three input parameters were: mould preheating temperature, velocity of piston in second phase and injection pressure (melt pressure in third phase). NovaFlow&Solid is designed to simulate high pressure die casting process and many others commercial casting method. As output process values, obtained by the simulations, were chosen the material shrinkage and solidification time. Regression analysis was used to achieve mathematical models, and then optimal values of the input parameters that will ensure the production of high-quality castings has been determined. Based on the obtained simulation results, the influence of individual parameters will be explained and the conclusion of the conducted process will be made.

The high pressure die casting process consists of the following operations: closing the mould, filling the pressure chamber with melt, starting the piston, pushing the melt into the mould, opening the mould and ejecting the casting. The HPDC process, in the narrow sense, can be divided into three phases in which the action of the speed and pressure of the molten metal will be described. Their dependence is shown in Figure 1., and all phases will be explained below.

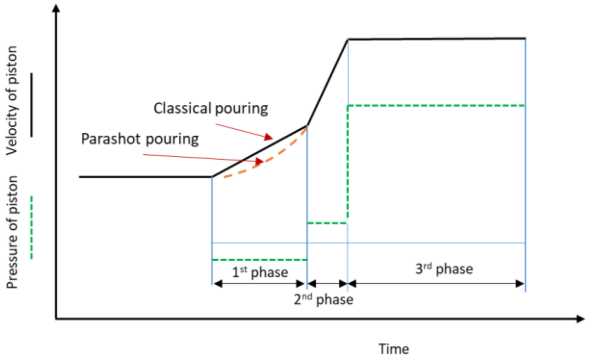

Figure 1. Schematic representation of the piston pressure dependence on the process flow by phases, [10]

In the first phase of HPDC process, it is necessary to expel air from the pressure chamber, so the piston must move at relatively low speeds. The speed in this phase ranges from 0.05 m/s to 0.5 m/s. At higher speeds, there would be a turbulent flow of molten metal that would draw air into the mould causing a danger of the melt splashing through the pouring hole and later the porosity in the casting. In order to avoid this problem, the so-called „parashot pouring“ is applied in which no shock wave is created because the speed of piston gradually increased and followed the speed of the molten metal. In addition to the piston speed, the formation of the wave and the trapping of air inside the pressure chamber are also influenced by the filling of the pressure chamber with melt, and dimensions of the gate cross-section, [11].

The second phase of HPDC process is called the "fast phase" because the molten metal must fill the mould cavity through the gate as soon as possible. In the second phase, it is necessary to determine the maximum speed that will ensure the required properties of the casting. High speeds are mainly used for the production of thin-walled castings to achieve better surface quality and result in less porosity. Increasing the speed increases the dynamic pressure of the melt on the tool, which damages it, and increasing the pressure can cause the mould to open, which leads to the spraying of the molten metal.

When the mould cavity is filled with melt, the third phase of the high-pressure casting process begins. In this phase, a controlled increase in pressure occurs in order to obtain better mechanical properties, lower porosity and better surface quality of the casting. The parameters that affect the pressure at this stage are the type of casting, the closing force of the machine and the type of alloy. In order to avoid undesirable reactions during the process, the beginning of the third phase must be 0.1 to 0.6 seconds after filling the mould with molten metal.

In the HPDC process, one of the main elements is the mould and its temperature is one of the basic parameters that ensure safe operation. The mould temperature for high-pressure die casting depends on the molten temperature and specific heat of the alloy being poured, the productivity of the machine, the ratio of melt mass to mould mass, and the cooling efficiency of the mould.

Ishikawa diagram, showed in figure 2., containing all the features that can lead to the consequence/problem being analysed, all with the aim of improving and enhancing the process in an organization or experiment. Diagram graphically illustrates the relationship between a given output and all the factors that affect the output.

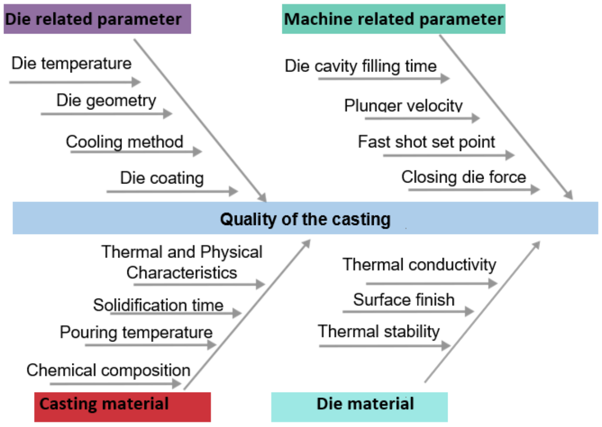

Figure 2 Ishikawa diagram of technological parameters

The visual representation of the causes, which this method provides, facilitates the analysis of their mutual relationship and significance.

3. Virtual experiments and methodology

In this paper importance is given to the parameter design stage. The basic steps to investigate the role of process parameters and mould geometry in level of shrinkage defects and solidification time, are summarized as follows:

- selection of the most significant die casting parameters influencing on the shrinkage and solidification time,
- selection of the appropriate design of experiments,
- performing simulation of the die casting process under the experimental conditions dictated by the chosen design of experiments,
- collection and analysis the data and
- making decisions regarding optimum setting of control parameters.

Solid modelling of the two castings, showed in Figure 3., was conducted by means of CATIA V5, commercial modelling program. The other necessary parts for HPDC process such as biscuit, runners, gates and overflows were also modelled and showed in figure 3. The casting material is aluminium alloy AlSi12 (Fe) or according to the European standard EN AC - 44300. The mentioned alloy is an eutectic alloy with excellent casting properties with high chemical resistance.

Design of experiments is carried out using the Box-Behnken design. The number of required experimental points is given by Equation 1.

$$N = 2k \cdot (k - 1) + n_0 \qquad (1)$$

k - number of different experimental factors,

n_0 - number of repetitions of the experiment at the intermediate level.

The experimental design for three controllable variables with their maximal and minimal values are presented in Table 1, and is organized by the Box-Behneken design of experiments.

Table 1. The experimental factors and their levels

Levels of input variables	Preheating mould temperature [°C] **A**	Velocity of piston, v_{II} [m/s] **B**	Injection pressure, p [MPa] **C**
1	150	2.5	40
2	200	5.25	60
3	250	8	80

Experimental runs with results are given in Table 2. Two process variables were read from the report obtained at the end of the simulation, i.e. after each virtual experiment. Experimental results were inputted into computer software Design-Expert. Statistical processing of data was carried out resulting in mathematical models for shrinkage and solidification time.

Linear mathematical model for material shrinkage, was suggested and analysis of variance (ANOVA) indicated that all three input variables are insignificant model terms. R-Squared, Adj R-Squared, Pred R-Squared and Adeq Precision were obtained as 0.9496, 0.68, 0.51 and 10.2, respectively.

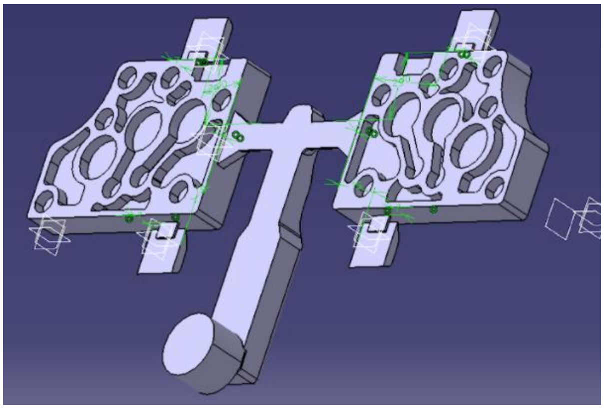

Figure 3. Model of castings made in CATIA V5

Table 2. Design of experiments and experimental results

Nr	**A** [°C]	**B [m/s]**	**C [MPa]**	**MS** [%]	**ST** [s]
1	200	5.25	40	1.98	8.04
2	200	5.25	40	1.98	8.04
3	150	5.25	20	2.35	7.32
4	150	2.5	40	1.82	7.75
5	200	5.25	40	1.97	8.04
6	200	5.25	40	1.97	8.04
7	200	8	60	1.66	8.04
8	250	5.25	20	2.41	9.09
9	200	2.5	20	1.99	8.44
10	150	8	40	2.00	7.18
11	200	5.25	40	1.97	8.04
12	200	8	20	2.39	7.91
13	250	2.5	40	1.91	9.54
14	200	2.5	60	1.51	8.49
15	250	5.25	60	1.64	9.12
16	250	8	40	2.05	9.11
17	150	5.25	60	1.63	7.51

Mathematical model for material shrinkage, MS

Linear mathematical model was adopted in a form:

$$\mathrm{MS} = 2.32648 + 4.97500\mathrm{E}\text{-}004 \cdot \mathrm{A} + 0.039727 \cdot \mathrm{B}\text{-}0.016906 \cdot \mathrm{C} \qquad (2)$$

In Figure 4, it can be noticed that at the lowest values of mould preheating temperature and velocity of piston (in the second phase) is the lowest percentage of material shrinkage. and in proportion to their growth. the percentage of material shrinkage increases, reaching its maximum value of 2.41%.

Figure 5, showed that at the lowest values of the velocity of piston and the highest value of the injection (third phase) pressure results in the lowest percentage of material shrinkage. The lowest injection pressure and the highest velocity of the piston, results in the reaching maximum value of material shrinkage, 2.41%.

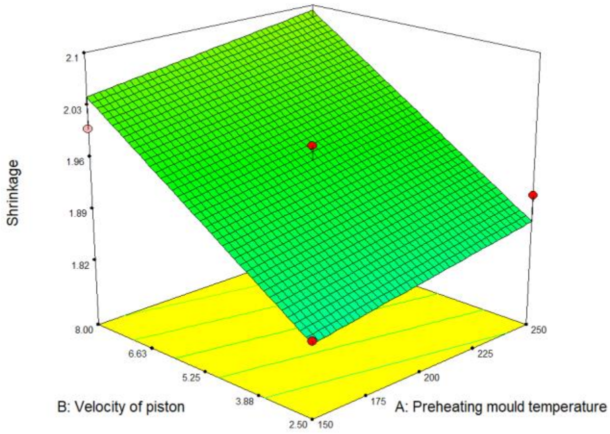

Fig. 4. Influence of velocity of piston in second phase and preheating mould temperature, injection (third phase) pressure constant [40 MPa]

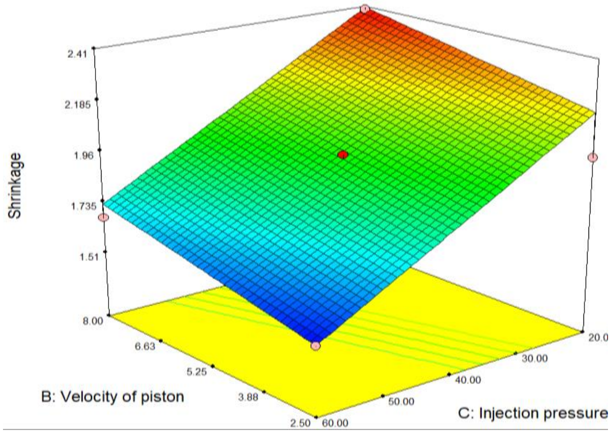

Fig. 5. Influence of velocity of piston in second phase and injection (third phase) pressure, constant preheating mould temperature [200 °C]

In Figure 6, it can be seen that at the lowest values of the injection pressure and the mould preheating temperature is the lowest percentage of material shrinkage, and with their growth, the percentage of material shrinkage increases to its maximum value of 2.41%.

Mathematical model for solidification time, ST

Quadratic mathematical model was suggested for solidification time *ST*, and ANOVA showed that A, B, C, A^2 and B^2 are significant factors model terms.

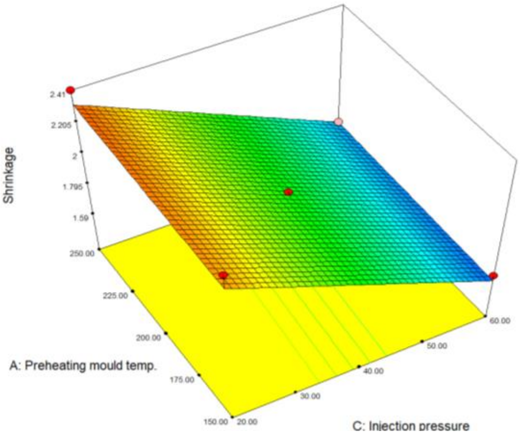

Fig. 6. Influence of preheating mould temperature and injection (third phase) pressure, constant velocity of piston in second phase [5.25 m/s]

After insignificant factors were excluded equation for prediction of solidification time, ST, was adopted in a form:

$$ST = 8.82226 - 0.015550 \cdot A - 0.3511 \cdot B + 5.77330E - 003 \cdot C + 8.47500E - 005 \cdot A^2 + 0.019322 \cdot B^2 \qquad (3)$$

R-Squared. Adj R-Squared. Pred R-Squared and Adeq Precision were obtained as 0.9968. 0.9926. 0.9482 and 51.448. respectively.

Figures 7. 8. and 9. show the dependence of the mathematical model of three input variables.

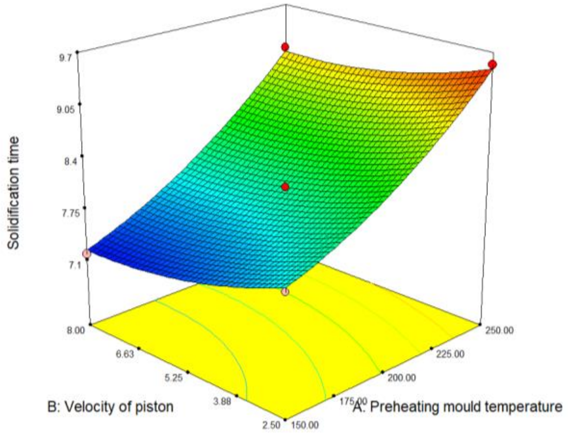

Fig. 7. Influence of velocity of piston in second phase and preheating mould temperature, injection (third phase) pressure constant [40 MPa]

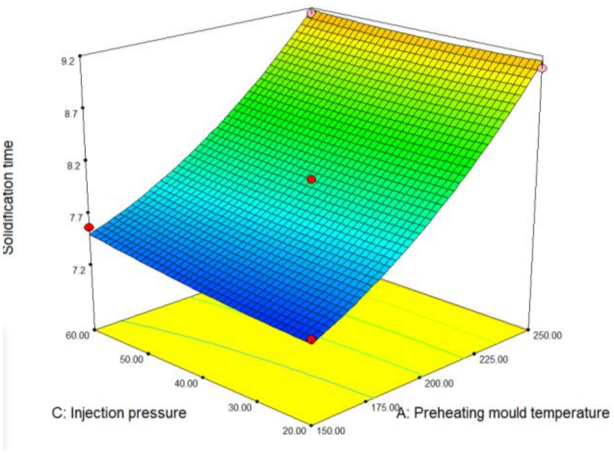

Fig. 8. Influence of preheating mould temperature and injection (third phase) pressure, constant velocity of piston in second phase [5.25 m/s]

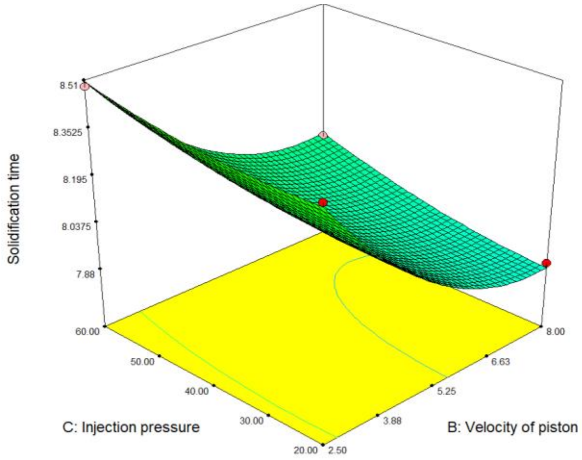

Fig. 9. Influence of velocity of piston in second phase and injection (third phase) pressure, constant preheating mould temperature [200 °C]

After the mathematical models of the observed output quantities have been obtained, it is necessary to optimize and determine the values of the input parameters that will give the smallest material shrinkage and the shortest solidification time.

The objective function for a given problem is shown as follows:

$$\min(fx) = \sum \frac{w_i\sqrt{f_i^2}}{C} \qquad (4)$$

where are:

w_i- weight factor

f(x) - objective function

f_i - i-th mathematical model

C – target value of the i-th mathematical model

The optimization was performed using genetic algorithm in software package MATLAB 2021. The subject of optimization are two mathematical models that describe the dependence of material shrinkage and solidification time on mould temperature, velocity of piston in second phase and injection (third phase) pressure. The goal of optimization is to obtain optimal process input parameters (Table 3) which would provide the smallest shrinkage of material and shortest solidification time.

Table 3. Optimal values input parameters

Optimal values of input parameters	
Preheating mould temperature [°C]	150
Velocity of piston. v_{II} [m/s]	2.5
Injection pressure. p [MPa]	49.2

The simulation provides useful information about the casting process and it is possible to monitor the movement of the melt and check the correctness of the mould construction. After the simulation. performed with the optimal parameters given in Table 3. the values of the output parameters were obtained: material shrinkage 1.60% and solidification time 7.746 s.

In Figure 10. the shrinkage of the material. after filling the mould cavity. is shown. Figure 11. shows the simulation predictions about the places of probable porosity occurrence. It can be seen that both shrinkage and porosities mostly occur in added parts i.e. overflows, (marked in red) which should be removed after the process.

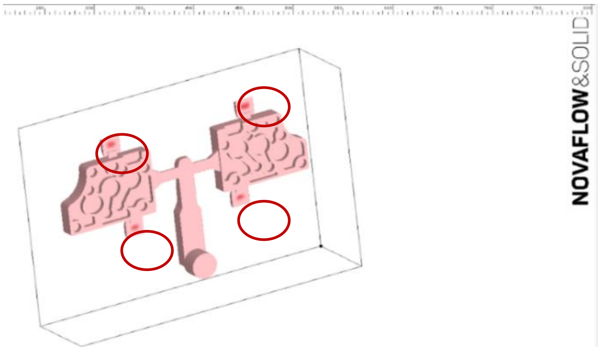

Fig. 10. Shrinkage of material

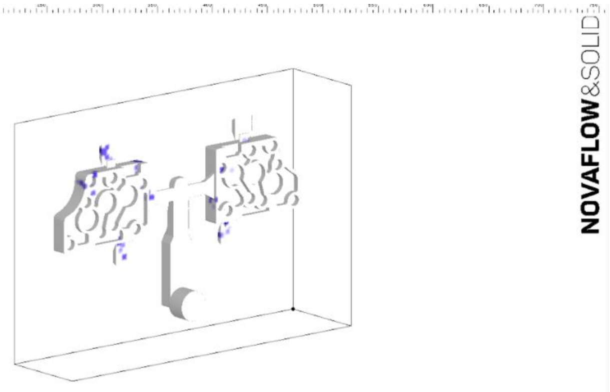

Fig. 11. Porosities in the castings

4. Conclusions

Nowadays, the general requirements are for the products to be as high quality as possible and the production process to be as short as possible. Therefore, optimizing the production process and applying computer simulations is very important to achieve better productivity. To perform the casting process, it was first necessary to model the casting in some 3D modelling software such as CATIA program (V5). Dimensions and geometry of casting, together with the entire inflow system, are determined by calculating. Subsequently, the input parameters of the casting process were selected based on research in the literature, which were considered to have a significant impact on the final properties of the casting. Simulations were then performed to confirm the correctness of the inflow system. The mentioned simulations were performed in the NovaFlow&Solid program. During the simulations, the whole casting process was monitored and the occurrence of errors was monitored, after which two output variables were selected whose values were recorded. The output parameters that were monitored were material shrinkage (MS) and solidification time (ST). Experimental results were processed by regression analysis and mathematical models were obtained to predict the two mentioned output variables.

After that, optimization was performed in order to determine the input parameters that will ensure the lowest material shrinkage and the shortest solidification time. The optimal input parameters were: preheating mould temperature 150 °C, velocity of piston 2.5 m/s and injection pressure 49.2 MPa. The values of the output parameters were obtained by process simulation with mentioned input parameters as: material shrinkage 1.60% and solidification time 7.746 s. According to the simulation results, it was observed that the geometry of the inflow system and the limit values were chosen correctly because most of the errors occurred in the overflows which have to be removed when the process is finished.

REFERENCES

[1] Anglada, E., Meléndez, A., Vicario, I., Arratibel, E., Cangas, G., 2015. Simplified Models for High Pressure Die Casting Simulation. Procedia Eng., 132, 974–981, doi: 10.1016/j.proeng.12.585.

[2] Gunasegaram, D., R., Finnin, B., R., Polivka, F., B., 2007. Melt flow velocity in high pressure die casting: Its effect on microstructure and mechanical properties in an Al-Si alloy. Mater. Sci. Technol., 23(7), 847–856, doi: 10.1179/174328407X176992.

[3] Sadeghi, M., Mahmoudi, J., 2012. Experimental and theoretical studies on the effect of die temperature on the quality of the products in high-pressure die-casting process, Adv. Mater. Sci. Eng., doi: 10.1155/2012/434605.

[4] Suraj, R., Marathe, D., Carmo Quadros, D., R., 2020. Thermal Factor of Aluminium High pressure Die Casting Container (Mould) to achieve Six Sigma Quality of Castings, Int. J. Eng. Res., 9(4), 59–68, doi: 10.17577/ijertv9is040228.

[5] Aghion, E., Moscovitch, N., Arnon, A. 2007. The correlation between wall thickness and properties of HPDC Magnesium alloys, Mater. Sci. Eng. *A*, 447(1–2), 341–346, doi: 10.1016/j.msea.2006.10.065.

[6] Ma, C., Zhang, W., YU., Zhang, Z., Ma, Y., Xiong, S., 2021. The effect of slow shot speed and casting pressure on the 3D microstructure of high pressure die casting AE44 magnesium alloy, J. Magnes. Alloy., doi: 10.1016/j.jma.2021.09.011.

[7] Li., Z., Li., D., Zhou, W., Hu, B., Zhao, X., Wang, J., Qin, M., Xu, J., Zeng, X., 2021. Characterization on the formation of porosity and tensile properties prediction in die casting Mg alloys, J. Magnes. Alloy, doi: 10.1016/j.jma.2020.12.006.

[8] Jadhav, A., R., Hujare, D., P., Hujare, P., P., 2021. Design and optimization of gating system, modification of cooling system position and flow simulation for cold chamber HPDC machine, Mater. Today Proc, 46, 7175–7181, doi: 10.1016/j.matpr.2020.11.346.

[9] Li, H., 2020. Towards intelligent design optimization: Progress and challenge of design optimization theories and technologies for plastic forming, Chinese J. Aeronaut., 34(2), 104–123. doi: 10.1016/j.cja.2020.09.002.

[10] Mikell P. Groover, 2020. *Fundamentals of Modern Manufacturing Materials, Processes, and Systems Seventh Edition,.*

[11] Mehtedi, M. El., Mancia, T., Buonadonna, P., Guzzini, L., Santini, E., Forcellese, A., 2020. Design optimization of gate system on high pressure die casting of AlSi13Fe alloy by means of finite element simulations, Procedia CIRP, 88, 509–514, doi: 10.1016/j.procir.2020.05.088.

Provenance: The article is based on the master’s thesis by Brigita Ljuba (mentor: Sonja Jozić) entitled “Optimization of aluminum alloy high-pressure die casting”. These defended in December/2021. at Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split.