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The impact on the cost of making high pressure die castings with multi-cavity die and vacuum assistance

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ABSTRACT

In view of the increasing prices of energy and charge materials, it is necessary to optimize the costs of making castings. Tests were carried out on the possibility of making castings in a pressure die with an increased number of cavities with the required tightness of the casting. The tests were carried out on castings made in the High Pressure Die Casting process and with the use of the Vacuum System. The research included optimization of the pressure die design through selection of casting parameters and CT tests and microstructure. The results of the tests showed that it is possible to increase the number of pressure die cavities and to obtain the required level of casting porosity, provided that the Vacuum system is used. The amount of gas porosity in castings can be significantly reduced from 4% at atmospheric pressure to 1% at a vacuum of 300 mbar.

High Pressure Die Casting is characterized by very high productivity. It depends on the type of cast alloy, cast size and the type of die casting machine. The number of operations for aluminium alloys cast on cold chamber machines ranges from 15 to 250 per hour. In the case of zinc alloys cast on hot chamber machines, up to 1000 cycles per hour can be achieved [1].

Due to the significant cost of the pressure die, this technology is profitable in the case of large-scale production. The production cost of the product consists of the costs of: material, labor and tooling [2].

$$C = C_M + C_L + \frac{C_D}{P}, \frac{currency}{piece} \tag{1}$$

where.

C_M – material costs (e.g. $, £, €);
C_L – labor costs;
C_D – cost of die and tooling;
P – production volume.

As the production volume (P) increases, the depreciation rate of the C_D/P die decreases. Thus, in small-volume production, the basic impact on the manufacturing cost (C) is the cost of the die (C_D). In high-volume production, the labor cost (C_L) has an impact.

The cost of the material is not only the cost of purchasing the alloy, but also the costs associated with the melting process (energy, non-returnable losses, as well as dross and the indicator of missing castings). These castings can be re-melted, but the cost of providing additional energy to melt them should be taken into account.

Estimating the production costs of pressure die castings is not an easy task due to, among others, the degree of complexity of the casting and die. In a few references [3–7], the authors provided methods of estimating the costs of making pressure die castings.

In order to calculate the total cost of making a die casting, the following costs should be taken into account: utilities (energy, gas, water), materials, pressure die, depreciation of the die casting machine, configuration of equipment and die casting, tests (chemical composition, dimensional accuracy, RTG/CT, strength, tightness, structure, etc.), finishing, storage and packaging, man-hours of employees and overheads and overheads - rent, insurance, environmental fees, medical benefits and remuneration for management and owners.

These costs are largely independent of the foundry, the only parameter that reduces the cost of the casting is the multiplicity of the cavity of the pressure die, which increases the number of castings produced per unit of time. The article analyses only the costs of casting, related to the multiplicity of the pressure die cavity.

It was assumed that the cost of high pressure diecasting (taking into account only the casting process) can be reduced by increasing the number of pressure die cavities. This is not always possible without

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Table 1
Chemical composition of test castings, %.

Si	Fe	Mn	Mg	Cu	Zn	Ti	Al
9.06	0.84	0.21	0.44	1.45	2.02	0.03	85.84

Table 2
Measurements of the second dendrite arm spacing.

	Second dendrite arm spacing - SDAS, μm						
	1/1	1/2	1/3	1/4	1/5	1/6	Arithmetic mean
6 cavity die without VAHPDC	11.8	11.6	11.4	12.0	10.1	11.1	11.33
6-cavity die, with VAHPDC	10.5	9.7	10.0	8.8	11.0	11.6	10.27

changing the die casting machine to a machine with a higher clamping force, and due to the larger volume of the die cavity, it is necessary to use Vacuum systems. This cost can be calculated from the simplified formula [7]:

$$\textit{Casting cost} = \frac{\textit{cycle time}}{\textit{No. of cavities}} \bullet \textit{machine hourly rate} \tag{2}$$

formula (2) is very simplified, it applies only to the casting operation. The total cost of making the casting includes the costs of finishing, the costs of testing the castings and the costs of taxes due. Since the costs of material, energy, labour and taxes are independent of the foundry, the only parameter that reduces the cost of the casting is the multiplicity of the pressure die cavity. In order to reduce the casting costs, the possibility of making a casting in a 6-cavity die instead of a 2-cavity one was considered. The castings made in the 2-cavity die meet the recipient's requirements, but the cost of the casting with increasing energy prices and alloy costs is too high.

Pressure relief systems in the pressure die cavity make it possible to limit the occlusion of the gas phase both in the pressing chamber of the die casting machine and in the die cavity during filling it with liquid alloy. Gas porosity is the basic disadvantage of die castings, limiting the area of their application. In addition to reduced tightness and inadequate quality of the outer surface, it can reduce the strength properties of castings. Although these systems have been known on the market for several years, they are constantly being modernized. Optimization of their work is still subject to numerous studies [8–12].

Typically, the gas content inside die castings is between 10 and 50 cm^3/100 g (at standard temperature and pressure). The use of reduced pressure in the cavity of the pressure die to the level of approx. 20–50

Table 3
The results of density and gas number tests on the test castings.

Sample designation	Measurement results (without Vacuum)			Measurement results (with Vacuum)		
	AVG casting density g/cm^3	AVG casting porosity %	*AVG LG*	AVG casting density g/cm^3	AVG casting porosity %	AVG LG
1.1	2.589	5.511	0.945	2.637	3.237	0.961
1.2	2.594	5.290	0.947	2.633	3.252	0.960
1.3	2.596	5.274	0.947	2.717	1.987	0.990
1.4	2.555	6.752	0.933	2.680	1.745	0.983
1.5	2.567	6.332	0.937	2.692	1.737	0.983
1.6	2.516	8.184	0.918	2.644	3.415	0.966

kPa (200–500 mbar) results in gasification of castings up to 5–20 cm^3/100 g [9]. Further reduction of the pressure to a value below 10 kPa (100 mbar) reduces the gasification of castings below 5 cm^3/100 g. With such a low level of gasification, conventional heat treatment and welded castings are possible [9,10].

By the use of vacuum die-casting, gas contents below 10 cm^3/100 g and even as low as 1 cm^3/100 g may be achievable, facilitating conventional heat treatment and allowing parts to be welded [12].

The tests were carried out on starter head castings made on the IDRA 900 die casting machine in a 6-cavity die using the classical method and the Vacuum system. In order to compare the results, tests were also carried out on castings made in a 2-cavity die. CT analysis of the entire cast was carried out using a Bosello X-ray computed tomography, SRE HEX 50-70 CNC.

Castings were made of EN AC-46000 alloy (EN AC-Al Si9Cu3(Fe)). The chemical composition of the castings was made on the Minilab 300 spectrometer (Table 1).

The AxioVision image analysis system was used to assess the porosity of the tested objects. For each sample (on non-etched sections) 7 microphotographs were taken at 500x magnification. The measurement results are presented in Table 2.

On the photographs of microstructures (Fig. 1) is visible that the use of the Vacuum system significantly reduces the porosity of castings in the analysed castings.

In addition to reducing porosity, the use of pressure-reducing systems in the cavity of the die also resulted in fragmentation of the structure, which was revealed by the SDAS study. Measurements of the distance between of the second dendrites arm were made on non-etched sections at a microscope magnification of 500x by 50 oriented secant sections. The obtained results are presented in Table 2.

Fragmentation of the structure and reduction of porosity should have a positive effect on increasing the mechanical properties of castings. The pores with sharp corner easily produce stress concentration and damage

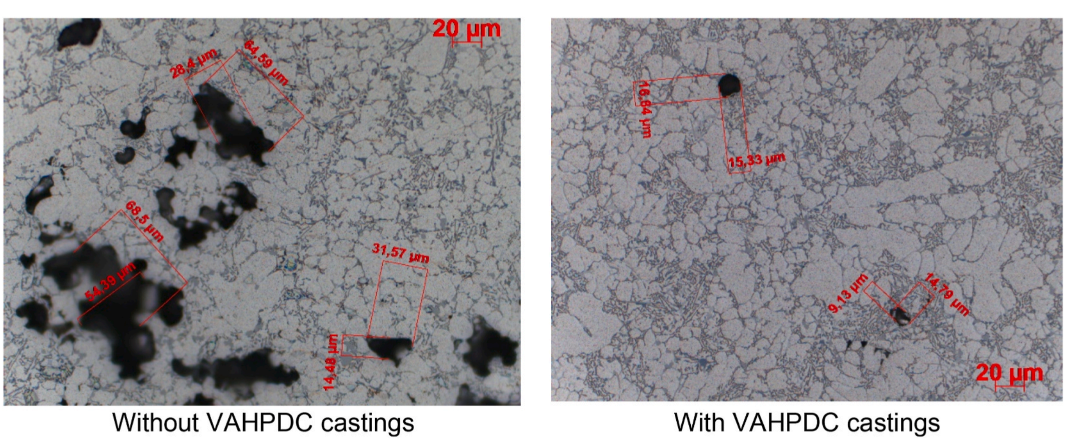
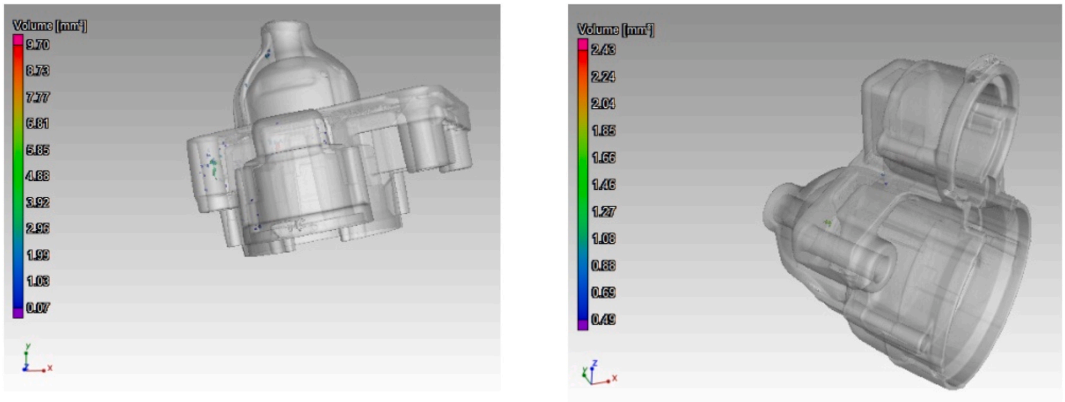


Fig. 1. Porosity in selected castings.



a) Defect volume 77.42 mm^3, defect volume ratio 0.04%

b) Defect volume 8.27 mm^3, defect volume ratio 0.00%

Fig. 2. CT examinations. Cast without Vacuum (a) and with Vacuum (b).

mechanical properties [13–15].

The Archimedes test is commonly used as a non-destructive method to measure the density of castings. The average density is a good measure of the pore volume fraction, but it does not accurately reflect the amount of gas in the casting. Gas pores usually combine with shrinkage porosity and their relative proportion is difficult to separate. Therefore, density measurement is considered insufficient for accurate estimation of gas content in castings [13]. It is a cheap, indicative method and other methods (e.g. X-ray) should also be used to accurately determine porosity. The method of determining the density is described in numerous publications (e.g. 13-15).

The results of density and gas number tests on the test castings are presented in Table 3. Measurements were made on the entire casting (3 measurements each) and the arithmetic mean was calculated.

In order to determine the distribution of porosity in the volume of the casting, CT tests were carried out. Fig. 2 presents selected photographs from the study.

Due to the quality requirements for the acceptance of die-cast, leak tightness tests are required in specific applications. The increased tightness of die-cast allows them to be used for housing elements of pumps, air conditioning elements, etc. Leakage means an unintentional crack, hole or porosity in the surrounding wall of the casting, i.e. where liquid or gas escapes.

Castings obtained using the Vacuum system were subjected to a gas leakage test on a specially constructed test stand. A specific air pressure was applied to a tank of known volume. The tested casting was the closure of the tank. The decrease in pressure (loss over time) was measured with a manometer.

The tests were carried out for the following data: test temperature: 20 °C, tank volume: 200 ml, air weight in the tank: 0.24 g, compressed air density: 1.2 kg/m^3, initial pressure in the tank: 2.18 bar, tank reading pressure after 4 h: 2.18 bar and tank reading pressure after 24 h: 1.90 bar. The leakage of the casting was determined by calculating the amount of gas flow that escapes through the walls of the vessel according to the methodology described in Ref. [16]. After applying pressure in the tank, its value was read using the mounted manometer immediately after closing the valve supplying air to the tank and after 24 h. The air leakage (leakage rate) was 2.33 mbar dm^3/h, so the gas leakage was 0.0028 g/h.

The results can be summarised as the following.

1. The use of the Vacuum system allowed to reduce the total porosity of die-cast from 4% to below 1%.
2. Gas leakage on the test casting was 0.0028 g/h. A value below 1 g/h is considered by the majority of customers in the automotive industry as an acceptable value.
3. Increasing the number of pressure die cavities from 2 to 6 allowed for the following savings:
   a. Die cost - 125% increase,
   b. The number of castings per hour more by 413%,
   c. Cast price - 23% less,
   d. Die cost per 1 casting - 25% less.

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CRediT authorship contribution statement

Piotr Dudek: Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Joanna Białoń:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Justyna Piwowońska:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Wiesław Walczak:** Methodology. **Konrad Wrzała:** Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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