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Optimization of the High Pressure Die-Casting Process to Reduce Porosity

J. Piwowońska [a, *], J. Białoń [a], P. Dudek [b]
[a] Łukasiewicz Research Network - Krakow Institute of Technology, Poland
[b] Alpha Technology Llc, Poland
* Corresponding author: E-mail address: justyna.piwowonska@kit.lukasiewicz.gov.pl

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Abstract

The main problem with the use of pressure castings from aluminium alloys for, among others, critical parts in the automotive industry is the presence of porosity. Obtaining castings with reduced porosity is a very difficult task, requiring a number of changes in relation to the classic pressure casting process. This basic defect limits the area of application of pressure castings. In addition to reduced tightness and inadequate external surface quality, it can reduce the strength and/or plastic properties of the castings. One of the solutions to avoid problems in the production of high-quality, tight and at the same time thin-walled and durable castings from Al alloys can be the use of a special high-pressure casting solution using the so-called "vacuum". The use of the Vacuum system in high pressure die-casting can significantly reduce the porosity of castings. The amount of gas present in the pressure casting is influenced by the geometry of the part and the process parameters. At standard temperature and pressure, the gas content inside die-cast parts typically ranges from 10 to 50 $cm^3/100$ g. Using vacuum casting, gas content below 10 $cm^3/100$ g, or even 1 $cm^3/100$ g, can be achieved, allowing simplified heat treatment and welding of the parts.
The article presents selected studies on reducing porosity in pressure castings using the Vacuum system. Microstructural tests, density tests, X-ray and CT, and a leak testing of the castings were carried out.

Keywords: Pressure casting, Aluminum alloys, Porosity, Leak testing, Vacuum system

1. Introduction

Die casting of aluminum alloys is an important and developing method of casting, including for the highly demanding automotive industry. There is a growing demand for castings with increasingly higher mechanical properties. It is not possible to meet these requirements using classic die casting technology due to the presence of gas porosity in the casting structure, which reduces mechanical properties, makes it difficult to maintain the tightness of castings, and thus disqualifies them from many applications. Obtaining castings with reduced porosity is a very difficult task, requiring a number of changes to the classic pressure casting process. One of the most important ways to achieve this goal is to use a special method of casting under reduced pressure in the cavity of a pressure mold (Vacuum system). The proper design of the pressure mold, the quality of the liquid metal, and the correctly selected casting parameters are also of considerable importance [1, 2].

Gas phase occlusion occurs directly in the pressure machine chamber and in the mold cavity during filling with liquid alloy. This fundamental disadvantage limits the range of applications for die castings. In addition to reduced tightness and inadequate external surface quality, it can reduce the strength and/or plastic properties of castings. In order to avoid the above-mentioned problems in the production of high-quality, leak-proof, yet thin-walled and durable aluminium alloy castings, a special high-pressure casting solution is used – casting with the use of so-called

"Vacuum" – systems that reduce the pressure in the cavity of the pressure mold. Although these systems have been known on the market for over a dozen years, they are constantly being modernized. Their optimization is still subject to numerous studies [3-5].

The amount of gas present in a die casting depends on the geometry of the part and the process parameters. Typically, the gas content inside die-cast parts ranges from 10 to 50 cm^3/100 g (at standard temperature and pressure). By using vacuum casting, it is possible to achieve a gas content of less than 10 cm^3/100 g, or even 1 cm^3/100 g, which allows for simplified heat treatment and welding of parts [6-9].

This paper presents attempts to reduce the porosity of aluminium alloy die castings using a Vacuum system. The castings obtained were subjected to microstructural, density, non-destructive (X-ray and CT) and leak testing.

2. Experimental Analysis

2.1. Materials

The castings were made of EN AC – 46000 alloy (EN AC – AlSi9Cu3(Fe)). The chemical composition of the castings was determined using a Minilab 300 spectrometer manufactured by GNR. The results of the chemical analysis are presented in Table 1, and the tested castings are shown in Fig. 1.

Table 1.
Chemical composition of sample castings, wt. %

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

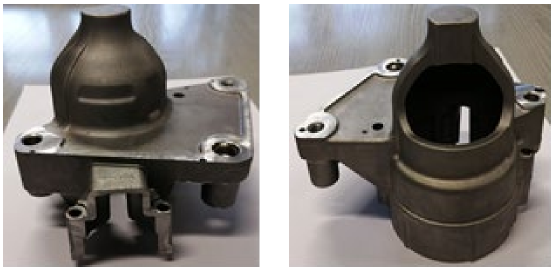

Fig. 1. Photo of the castings – starter motor head

2.2. Measurement Methods

The tests were carried out on starter motor head castings made on an IDRA 900 pressure machine in a 6-cavity mold using the classic method and with the use of a vacuum system. The following parameters were used in the HPDC process: liquid alloy temperature 690°C, pressure:

- classic method – 200, 350, and 500 mbar
- Vacuum system – 180 mbar

Microscopic observations and images were made using the SCIOS-FEG, FEI scanning electron microscope. The following observation conditions were applied: accelerating voltage of 20 kV, BSE detector. Instead, the analysis of local chemical composition EDS in a selected micro area/spot was conducted using the EDS, EDAX X-ray microanalyser.

Porosity tests on selected fragments of the casting were performed using a GE Nanotom X-ray computed tomography scanner. The following exposure parameters were used: 160 kV, 100 µA, voxel size: 30.0 µm/vox. CT analysis of the entire casting was performed using a Bosello SRE HEX 50-70 CNC X-ray computed tomography scanner. Radiographic testing was performed on a Xylon MU2000 device.

The AxioVision image analysis system was used to assess the porosity of the tested objects. For this purpose, seven microphotographs were taken for each sample (on non-etched smears) at microscopic magnification: without the vacuum system at 500x and with the vacuum system at 100x.

Castings obtained using the Vacuum system were subjected to a gas leakage test (Figure 2). A tank of known volume (Vo) was connected on one side to a valve through which a specific air pressure was supplied. The tested casting served as the closure of the tank. The decrease in pressure (loss over time) was measured using a pressure gauge.

Fig. 2. Gas leakage testing station (casting leak testing)

The tests were conducted for the following parameters: test temperature: 21°C, tank volume: 200 ml, air weight in the tank: 0.23 g, compressed air density: 1.2 kg/m^3, initial pressure in the tank: 2.2 bar, pressure reading in the tank after 4 hours: 2.2 bar, reading pressure in the tank after 24 hours: 1.90 bar. After applying pressure in the tank, its value was read using a mounted pressure gauge immediately after closing the valve supplying air to the tank and after 4 and 24 hours.

The leak rate of a casting can be determined by calculating the amount of gas flowing through the walls of the vessel. The leak rate depends on the type of gas. If the gas temperature T and the molar mass M of gas G are known, the mass flow rate of the gas can be calculated from the leak rate qL [10].
Using the equation of state for ideal gases:

$$\frac{\Delta_m}{\Delta_t} = \frac{q_L \cdot M}{R \cdot T}, \text{ g/h} \tag{1}$$

where:
R = 83,14 (mbar·l)/(mol·K),
T = gas temperature, 293 K,
M = molar mass, for air 29 g/mol,
Δm = gas mass, g,
Δt = time interval, h.
Based on formula (1), you can calculate:

a) mass flow Δ_m/Δ_t at a known leak rate q_L,

b) leakage rate q_L at a known gas mass flow rate Δ_m/Δ_t

The leakage rate as a function of time is calculated according to the following equation:

$$q_L = V \cdot \left(\frac{\Delta_p}{\Delta_t}\right), \text{ mbar l/s} \quad (2)$$

where:
q_L - leakage rate, mbar l/s
V - tank capacity, l
Δ_p/Δ_t - change in pressure in the tank Δp as a function of measurement time Δt, mbar/s

3. Test Results and Discussion

3.1. Microstructure

The AxioVision image analysis system was used to assess the porosity of the tested objects. For this purpose, seven microphotographs were taken for each sample (on non-etched smears) at a microscopic magnification of 500x. Selected microphotographs are shown in Figures 3 and 4. The total volumetric porosity in the tested castings is summarized in Table 2.

Microphotographs of castings produced using the classic method

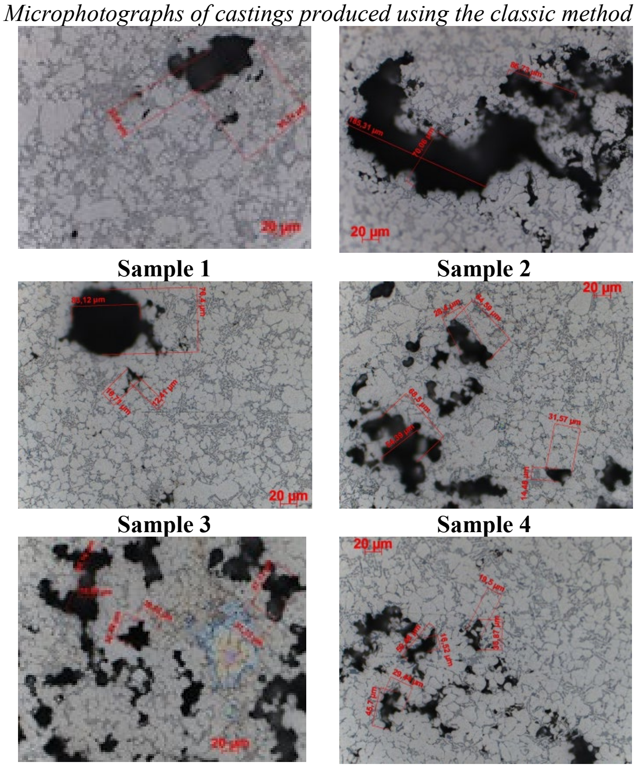

Fig. 3. Selected microphotographs with porosity measurements – classic casting method.

Microphotographs of castings produced using a Vacuum system

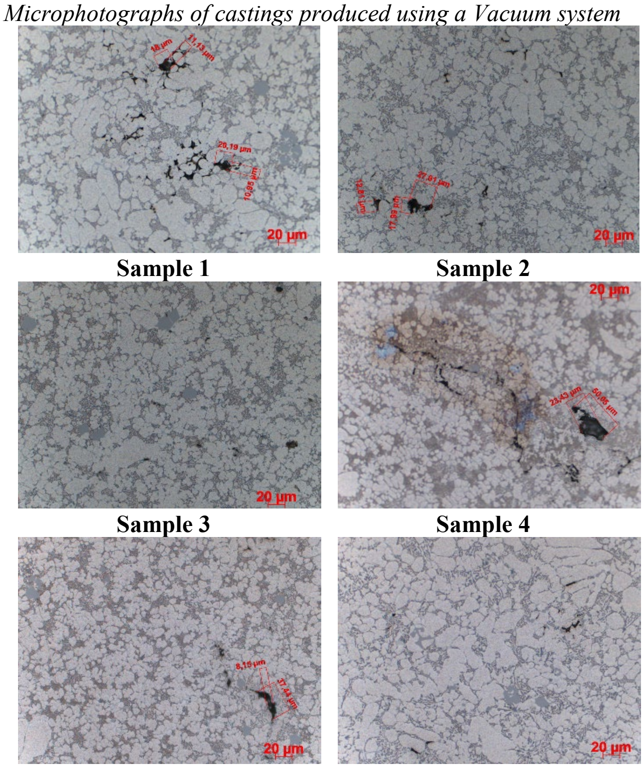

Fig. 4. Selected microphotographs with porosity measurements – Vacuum system

Table 2.
Total volumetric porosity of the castings obtained

Sample	Porosity, %	
	6 cavity die without Vacuum	6 cavity die with Vacuum
1	1.3	0.30
2	6.2	0.20
3	2.1	0.10
4	10.2	2.00
5	4.0	2.20
6	2.0	0.70

Castings obtained using the classic method are characterized by high porosity. However, when using the so-called vacuum system, a significant improvement in the quality of the castings obtained can be observed, with significantly lower porosity.

Comparing the total porosity measured on microphotographs, it can be confirmed that significantly better castings were obtained using the Vacuum system, where the highest porosity is 2.2% and the lowest is 0.1%. In contrast, for the classic method, the highest porosity result is 10.2%, and the lowest porosity is 1.3%.

As is well known, microstructure tests are performed on a very small fragment of the casting (usually in critical areas of the casting), but they do not allow the actual porosity of the casting to be determined. They may suggest areas where, for example, additional overflow or venting should be used to reduce shrinkage and gas porosity. Therefore, the castings obtained were subjected to X-ray and CT examinations, described later in this article.

Total porosity testing of castings using Archimedes' method

The Archimedes test is commonly used as a non-destructive method for measuring the density of castings. The average density is a good measure of the volume fraction of pores, but it does not accurately reflect the amount of gas in the casting. Gas pores are usually associated with shrinkage porosity, and their relative proportions are difficult to separate. Therefore, density measurement is considered insufficient for accurate estimation of gas content in castings [4]. The results of density and porosity tests on test castings obtained by the classical method and using the Vacuum system are presented graphically in Figures 5 and 6. The measurements were taken on the entire casting (3 measurements each) and the arithmetic mean was calculated.

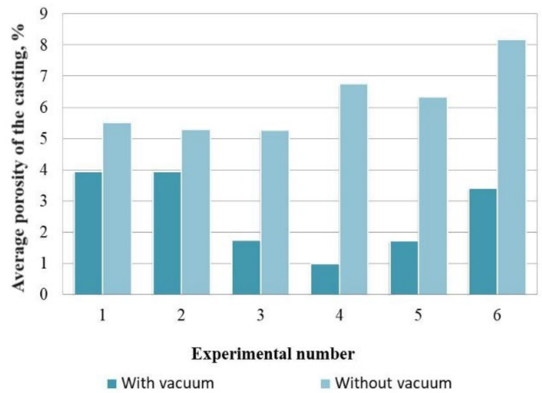

Fig. 5. Average porosity of castings

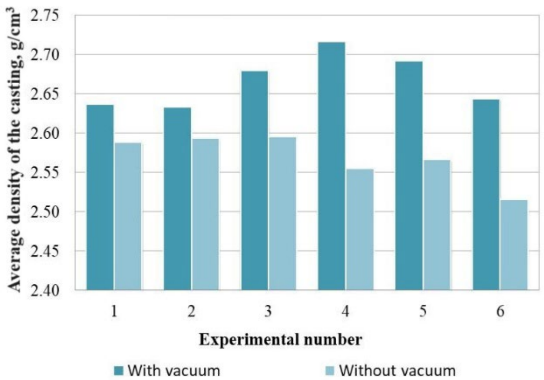

Fig. 6. Average density of castings

When analyzing the results obtained, comparing the average density for the two casting methods tested, it can be seen that castings made using the vacuum system have a slightly higher density, with values ranging from 2.63 g/cm^3 to 2.71 g/cm^3. In contrast, when using the classic method, these values range from 2.51 g/cm^3 to 2.59 g/cm^3.

With regard to average porosity, significantly better results were obtained in tests using a vacuum system, where porosity values ranged from 0.98% to 3.95%. In contrast, for the classic casting method, these values ranged from 5.51% to 8.18%.

3.2. Non-destructive testing

In order to determine the locations of porosity, the test castings were subjected to X-ray testing. Sample photographs from the casting tests are shown in Figures 7 and 8.

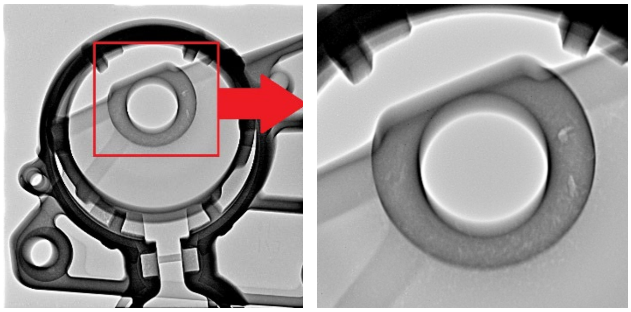

Fig 7. Castings from sample no. 3 without the use of the Vacuum system

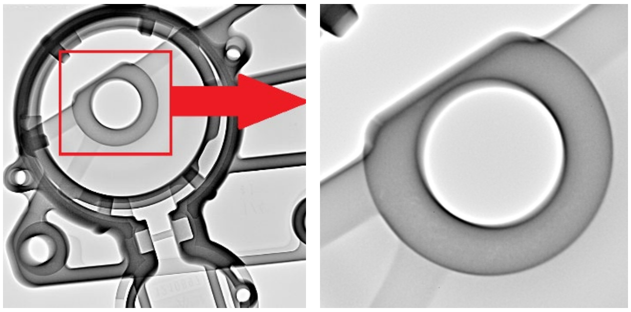

Fig. 8. Castings from sample no. 3 with the use of the Vacuum system

In the case of X-ray analysis, the photographs show significant porosity in castings made without a Vacuum system, i.e., using the classic method. However, no porosity was observed in the detail obtained using the vacuum system. This confirms the conclusions that the use of Vacuum reduces the occurrence of porosity in castings.

CT scans were performed to accurately determine the total porosity in the casting. Sample photographs from the casting tests are shown in Figures 9 and 10.

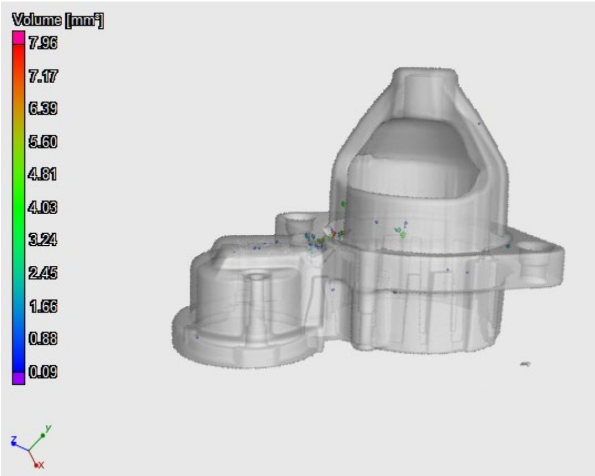

Fig. 9. An example of a cast tomogram made without the Vacuum system

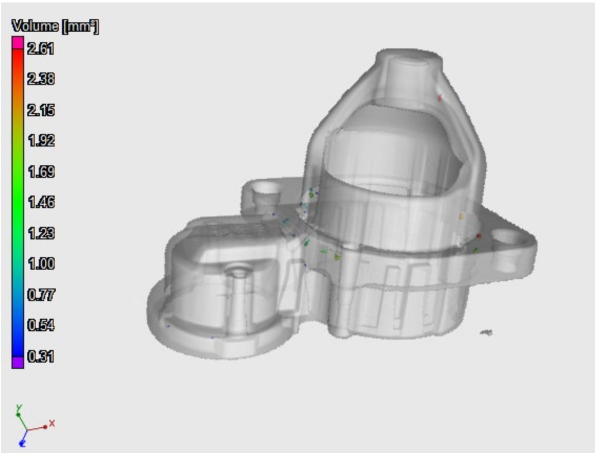

Fig. 10. An example tomogram of a casting made with the Vacuum system

Tomographic tests confirmed the presence of high porosity in castings made without a vacuum system. The photos shown in Fig. 9 show the locations of porosity. In contrast, in castings produced using the Vacuum system, porosity is greatly reduced.

Leak testing of castings

Due to the quality requirements for die-castings in specific applications, leak testing is required. The increased leak tightness of die-castings allows them to be used in pump housings, air conditioning components, etc. – wherever the casting operates in a high-pressure liquid or gas environment. In addition, the aggressive effect of liquids on aluminium alloys, in the case of increased porosity of castings, increases the risk of intergranular and pitting corrosion, thus reducing the durability and operational safety of the component. Increased tightness of castings expands the range of lightweight aluminium alloy castings with high performance properties in vehicle construction.

A leak is an unintended crack, hole or porosity in the surrounding wall of a casting, i.e. a place where liquid flows out or gas escapes.

The basic functions of leak detection are to locate and measure the size of leaks in sealed products and systems. In most cases, the leak test procedure is a quality control step and is a one-time non-destructive test.

In order to determine whether a component or system meets the relevant standards for tightness, it is necessary to specify:

– is there a leak,
– the size of the leak,
– leak locations.

In the tested castings obtained by both methods (classical and vacuum), the leakage (leakage rate) for air according to equation (2) was 2.3 mbar·l/h, therefore the gas leakage (calculated according to equation (1)) is 0.003 g/h.

4. Conclusions

Based on the results obtained, the following conclusions can be drawn:

1. The use of the Vacuum system made it possible to reduce the total porosity of castings (tested using Archimedes' method) from a maximum of 8.2% to 3.4%.
2. More accurate X-ray and CT methods confirmed a significant reduction in porosity after using the Vacuum system (even below 2%).
3. The gas leakage rate on the test casting was 0.003 g/h. A value below 1 g/h is considered acceptable by most automotive industry customers.

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