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INVESTIGATION OF GAS AND SHRINKAGE POROSITY IN ALSI10MG ALLOY GEARBOX CASTINGS MANUFACTURED BY HPDC

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Abstract
This paper analyses internal defects in aluminium gearbox castings manufactured using the high-pressure casting method. Two defective parts were examined using X-ray imaging, optical and electron microscopy. The results revealed that these defects were a combination of gas and shrinkage porosity. The aim was to identify the causes of these defects and suggest ways to improve the technological process. Analysis of the defects revealed that they were caused by the molten metal's inability to flow freely in the mould cavity.

***Keywords**: high pressure die casting, porosity, casting defects*

1. INTRODUCTION

High-pressure die casting (HPDC) of aluminium alloys represents one of the most advanced and efficient manufacturing technologies for the production of precision metallic castings. This process is characterized by excellent repeatability, short cycle times, and the ability to manufacture geometrically complex components with superior surface quality. HPDC has become particularly important in the automotive and electrical engineering industries, where the demand for lightweight, high-strength, and multifunctional components continues to increase.

In Slovakia, more than ten foundry enterprises are currently engaged in HPDC of aluminium alloys. Among the most prominent are international companies such as Handtmann Slovakia and the newly established Volvo Cars plant in Košice, as well as long-standing domestic firms including MOPS PRESS, ALCAST, and BCB. These foundries supply a broad spectrum of industrial sectors and are strategically located in regions with a well-developed engineering infrastructure and in close proximity to automotive assembly plants, which provides significant advantages in logistics and supply-chain integration [1].

The process predominantly employs aluminium-silicon (Al–Si) based alloys, such as $AlSi_9Cu_3$(Fe), $AlSi_{12}$, and $AlSi_{10}Mg$, along with their modified variants. These alloys combine favourable castability, mechanical strength, and corrosion resistance. The selection of a specific alloy is dictated by the required mechanical properties, machinability, and thermal resistance of the component [2].

Annual production volumes differ substantially depending on the size of the foundry and its degree of automation. Smaller enterprises typically produce between 500 and 1,500 tonnes of castings per year, whereas larger operations, such as Handtmann Slovakia, exceed 5,000 tonnes annually or more than one million individual castings. The newly constructed Volvo Cars facility in Košice is expected to implement megacasting technology using two Giga Press machines (Idra Group) with a clamping force of 9,000 tonnes. This positions Slovakia among the technological leaders in the field of large-scale aluminium die casting [3].

Given the stringent quality requirements for structural components such as chassis, engine, and body parts, strict control of process parameters throughout the entire production chain is essential. This includes alloy selection, optimization of technological settings, subsequent heat treatment, and microstructural evaluation. Typical defects such as porosity, shrinkage cavities, cold shuts, and inclusions can significantly impair the functional performance of cast products. Consequently, their prevention and reduction are subjects of ongoing intensive research and process optimization.

2. EXPERIMENTAL

The High-pressure die casting (HPDC) is a modern manufacturing technology designed for the efficient production of large-series aluminium castings with high dimensional accuracy and superior surface quality. The process takes place in a closed steel die, into which the molten metal is injected under pressure exceeding 100 MPa. The flow behaviour of the melt within the shot chamber significantly influences the final quality of the casting.

Different piston motion profiles, combined with parameters such as piston diameter, melt height, and chamber length, can result in various flow regimes. If the piston moves too slowly (Figure 1a), the rebound of the molten metal from the chamber wall may cause disturbed flow and impaired venting. Conversely, excessively high piston velocity (Figure 1c) results in turbulent metal flow and increased air entrapment, which promotes porosity formation. The optimal condition is achieved through a smooth acceleration phase (Figure 1b), where the metal surface maintains a slight inclination away from the piston without abrupt deformations [4].

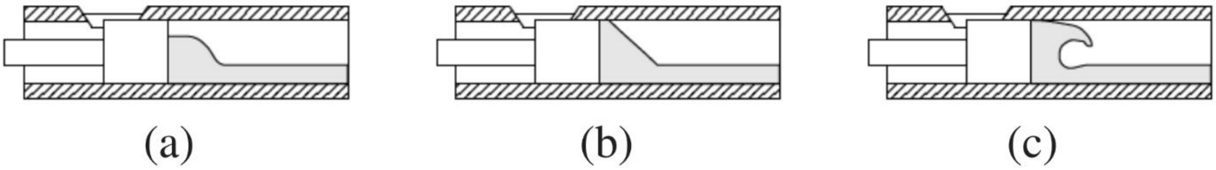

Figure 1. Metal flow in the shot chamber depending on piston velocity in the HPDC process

To minimize air inclusions, the injection process is divided into a slow and a fast phase. During the slow phase, the piston accelerates until the molten metal reaches the end of the shot chamber, after which it moves at a constant velocity until entering the die cavity.

Despite these advantages, one of the major technological challenges of the HPDC process remains the formation of internal defects, with porosity being the most common, either gas porosity or shrinkage porosity. These defects arise as a result of turbulent die filling, insufficient venting, high hydrogen content in the melt, as well as inadequate feeding of solidifying regions in the casting. Their occurrence negatively affects the mechanical properties of the final product [5].

2.1 The formation of gas porosity

Gas porosity arises primarily due to:

- High hydrogen content in the melt (hydrogen is the only gas highly soluble in liquid aluminium),
- Air entrapment during turbulent die filling,
- Degradation of lubricants or wear of piston and cylinder surfaces.

The key mechanism of gas pore formation is associated with the decrease in hydrogen solubility during solidification. As the temperature decreases, hydrogen is released from the liquid phase. When the solubility limit is exceeded, bubbles form, which subsequently expand but may become trapped in the interdendritic regions, where they remain as permanent pores after solidification [6].

The equilibrium condition for pore growth can be expressed as [6]:

$$P_{gas} \geq P_{atm} + P_{met} + P_{retrait} + P_{surface}$$

Where:

P_{gas} – gas pressure inside the pore

P_{atm} – atmospheric pressure

P_{met} – metallostatic pressure

$P_{retrait}$ – pressure induced by metal shrinkage

$P_{surface}$ – pressure of surface tension

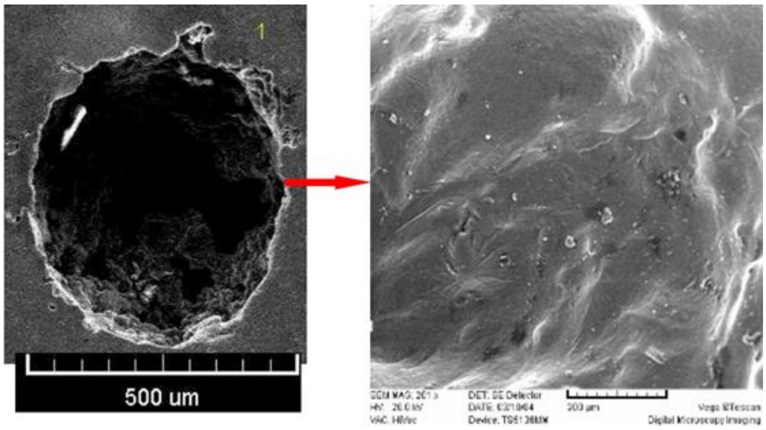

Figure 2. Example of gas porosity [5]

As shown in Figure 2, gas pores are usually round with a smooth or shiny surface and are often found in the upper part of the casting where the gas phase is lighter than the metal. They typically occur in areas of turbulent flow, such as where the metal first makes contact with the mould or in the venting channels [7].

2.2 The formation of shrinkage porosity

Shrinkage pores occur as a result of volume contraction during metal solidification. Microscopic or macroscopic cavities are formed due to the speed of solidification, geometric compression and the limited ability to supply additional liquid to the solidifying area. These cavities most often form in densely cooled or massive parts of the casting, where solidification is slowest [5, 8].

Typical characteristics of shrinkage porosity include [5]:

- Irregular, rough, or jagged morphology (Figure 3),
- Occurrence in internal regions with limited metal feeding,
- Dendritic structures surrounding the pores (observable through SEM analysis).

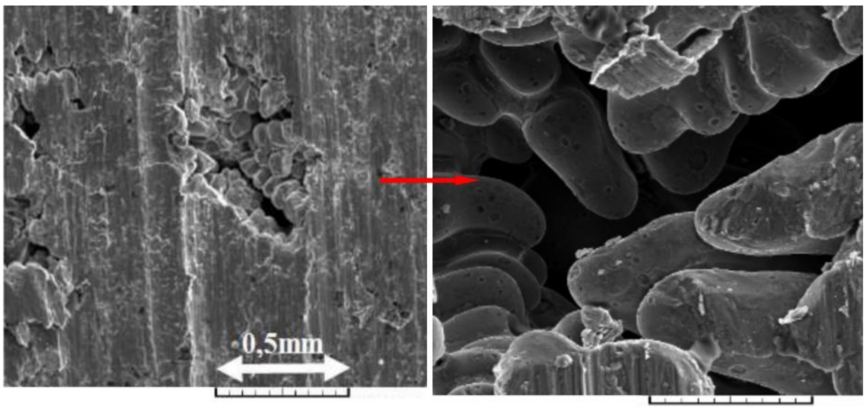

Figure 3. Example of shrinkage porosity [5]

The frequency and size of such pores are influenced by the width of the solidification interval. A wide interval increases the tendency for microporosity formation, whereas a narrow interval (e.g., in eutectic alloys) promotes the development of macroporosity [9].

2.3 Interaction of shrinkage and gas porosity

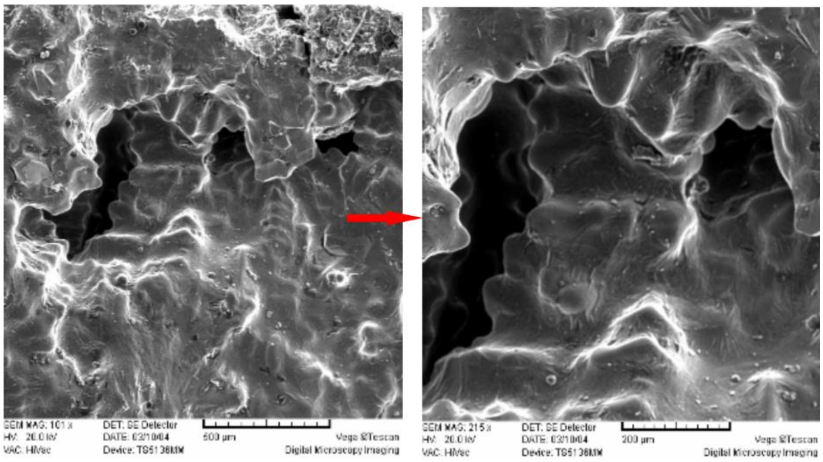

Figure 4. Interaction between shrinkage and gas porosity

High-pressure castings often exhibit combined porosity, where gas trapped in the metal forms bubbles that "branch out" into shrinkage cavities as the metal volume decreases.

Electron microscope images document the connection between gas and shrinkage porosity and indicate their joint evolution during solidification [5,6].

3. RESULTS AND DISCUSSION

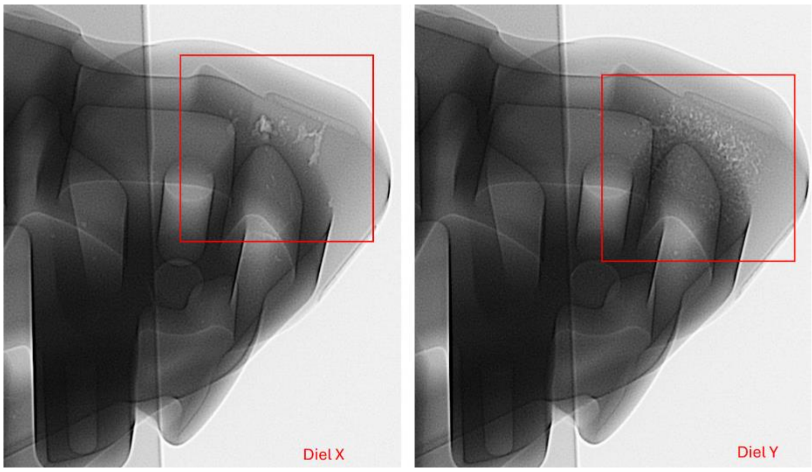

Figure 5. X-ray image of parts X and Y

As part of the analysis of AlSi10Mg aluminum alloy gearbox castings produced by high-pressure die casting (HPDC), two parts were selected in which internal defects occurred during production. These parts were designated as part X and part Y.

Based on visual inspection and quality monitoring, areas with suspected internal porosity were identified on the selected parts. These areas were then subjected to X-ray (RTG) analysis, which confirmed the presence of defects (Figure 5). The X-ray images clearly showed a concentration of porosity in the thicker cross-sections of the parts. Samples of material were then cut from both parts at the examined locations. The samples were cleaned and prepared for metallographic analysis. Special emphasis was placed on maintaining the integrity of the pores and minimizing deformation during cutting to avoid artifacts in further analysis, as shown in Figure 6.

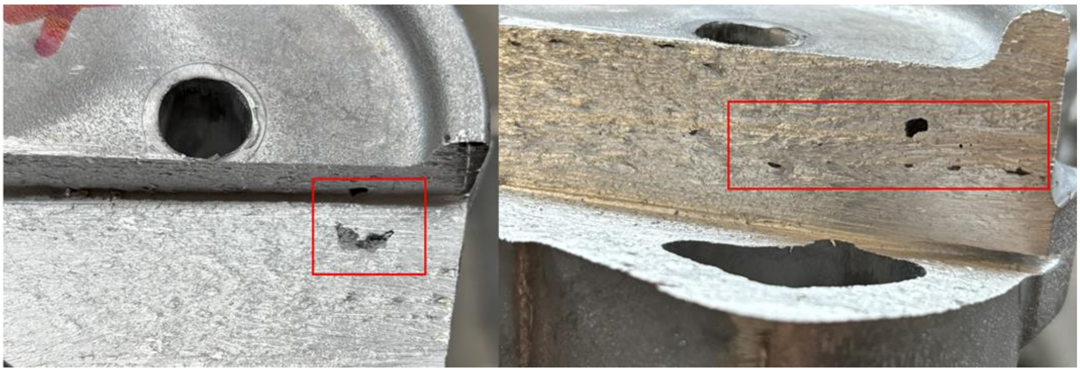

Figure 6. Porosity shown on Sample X after cutting in the examined area

Figure 7. Metallographic samples prepared for analysis

The samples were labeled Sample X and Sample Y, each originating from an identified defect location on the respective casting (Figure 7).

The initial analysis was performed using optical microscopy (Figure 8), which identified the basic characteristics of porosity, their distribution, morphology, and orientation relative to the casting structure. Both samples showed significant deviations in pore distribution. Sample X showed clusters of irregularly shaped pores that corresponded to areas of thicker cross-section. Sample Y contained smaller, evenly distributed pores, but with the occurrence of a larger cavity located centrally, which again supports the hypothesis of combined porosity.

Figure 8. Visible differences in porosity on the examined samples

To determine the type of porosity in more detail, scanning electron microscopy (SEM) with additional energy-dispersive X-ray spectroscopy (EDX) was applied. These methods made it possible to more accurately determine the shape, size, and chemical composition of the areas around the pores.

• **Sample X** – at magnification, distinct spherical pores could be observed, which is a typical sign of gas porosity. EDX analysis also confirmed the presence of oxide inclusions (primarily aluminum oxide – Al_2O_3), which may indicate the introduction of gases into the melt during injection (Figure 10).

• **Sample Y** - larger cavities with irregular shapes and signs of alloy separation were recorded, indicating shrinkage porosity. However, the chemical composition of the cavity surfaces did not contain a significant proportion of oxides, suggesting that gas filling was not a dominant factor in this case.

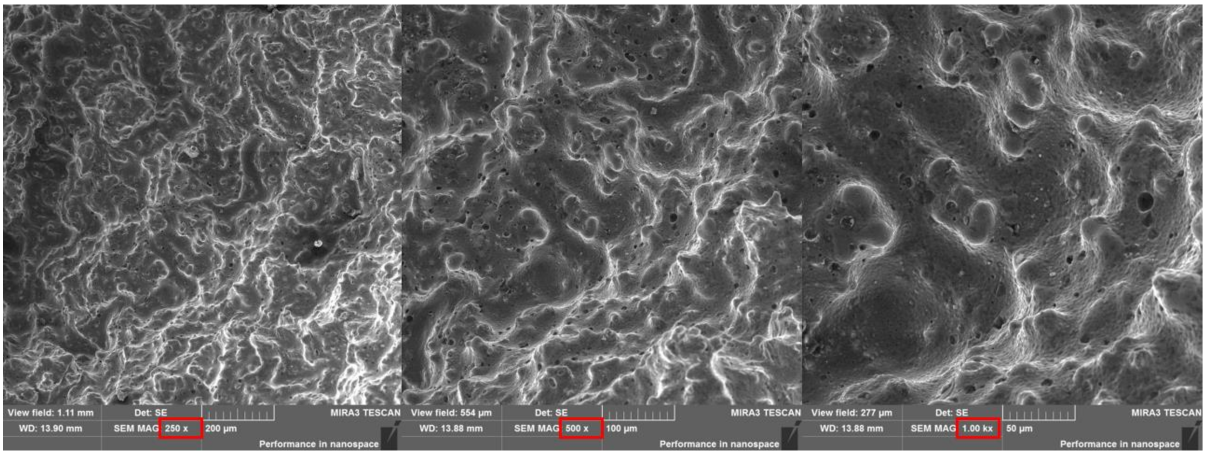

Figure 9. EDX analysis of samples X at magnification 250x, 500x, 1000x

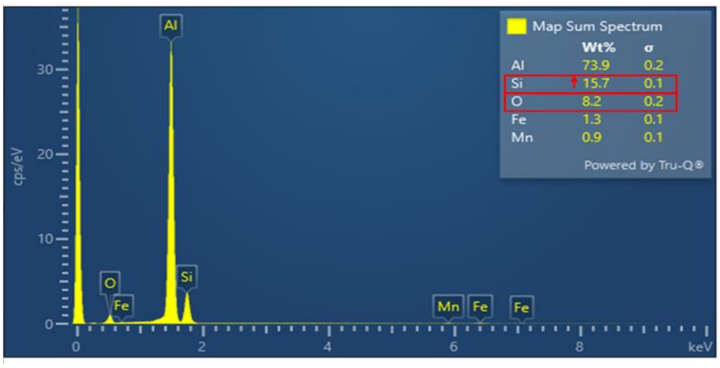

Figure 10. Chemical composition of sample X in the monitored pore

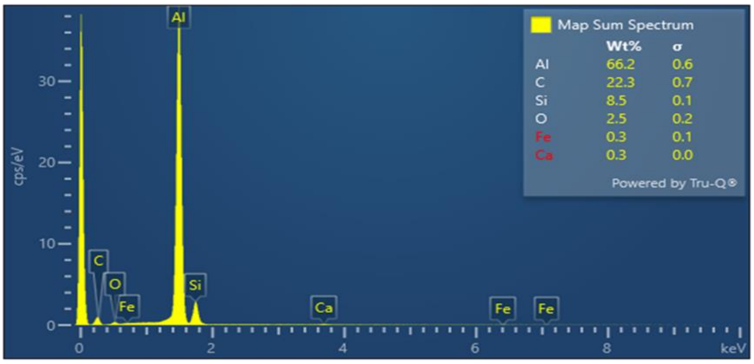

Figure 11. Chemical composition of sample Y in the monitored pore

4. CONCLUSION

Based on the analysis of two problematic parts made of AlSi10Mg aluminum alloy using high-pressure casting, it can be concluded that the cause of internal defects was a combination of gas and shrinkage porosity. X-ray images confirmed the concentration of pores in areas with a thicker cross-section, which correlates with shrinkage defects. SEM analysis together with EDX identified the presence of oxide inclusions and spherical pores, which are typical for gas filling. The results indicate the need for more thorough control of the technological parameters of the casting process, in particular the control of metal temperature, mold temperature, filling phase parameters, and mold venting in order to eliminate combined defects and improve the quality of the resulting castings.

In addition to the adjustment of technological parameters, the elimination of the observed defects was achieved by modifying the size and geometry of the squeeze pin. This optimization improved the feeding of solidifying regions, reduced the risk of interdendritic porosity, and enhanced the overall structural integrity of the castings. The results underline the importance of continuous research focused on the design and efficiency of squeeze pins and related HPDC components, as this field represents a critical factor in defect prevention and in further improvement of casting quality and reliability in industrial practice.

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