Plunger velocity and intensification pressure effects on porosity and mechanical response of AlSi9Cu3 HPDC castings

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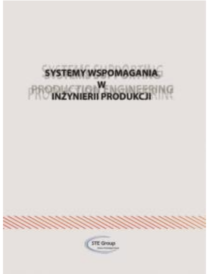

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Abstract: This study investigates the influence of plunger velocity and intensification pressure on porosity formation and permanent deformation of AlSi9Cu3 high-pressure die castings. The objective was to identify process windows that minimize internal defects and improve mechanical response in a geometrically critical region of an automotive component. Experiments were conducted on alternator flange castings under plunger velocities ranging from 2.0 to 3.2 $m \cdot s^{-1}$ and intensification pressures from 13 to 25 MPa. Permanent deformation was evaluated using a two-step loading–unloading procedure, while porosity was quantified on metallographic sections. The results show a non-monotonic dependence of mechanical response on plunger velocity, with an optimal range identified at approximately 2.6–3.0 $m \cdot s^{-1}$, where both porosity and deformation reach minimum values. In contrast, intensification pressure exhibits a near-monotonic beneficial effect, continuously reducing porosity and deformation due to improved compensation of solidification shrinkage. A strong correlation between porosity and permanent deformation was observed, confirming the dominant role of internal defects in controlling the local mechanical performance of HPDC AlSi9Cu3 castings.

Keywords: high-pressure die casting; AlSi9Cu3; plunger velocity; intensification pressure; porosity; permanent deformation; defect formation; mechanical response

INTRODUCTION

High-pressure die casting (HPDC) is one of the dominant technologies for producing aluminium castings characterized by high dimensional accuracy, short production cycles, and the capability to manufacture thin-walled and geometrically complex components. In the automotive industry, this technology is particularly critical for the production of structural components made from Al-Si-Cu alloys, where a combination of low weight and sufficient mechanical integrity is required (Blondheim & Monroe, 2021; Majernik & Ruzbarsky, 2016; Pavlenko and others, 2020).

A critical limitation of HPDC processes is the formation of internal defects, primarily gas and shrinkage porosity, osie inclusions, and cold shuts, which significantly degrade both local and global mechanical properties of the castings (Ružbarský, 2019). Their formation is directly related to the nature of the mold cavity filling and the subsequent solidification stage.

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A key process parameter is the plunger velocity in the second phase of filling, which determines the flow regime of the melt within the gating system. The transition between flow regimes (quasi-laminar → turbulent → dispersed) significantly affects the degree of gas entrapment and oxide film formation, and thus the initiation of porosity (Gaspar & Pasko, 2019; Trudonoshyn and others, 2021). The second crucial parameter is the intensification (injection) pressure, which compensates for volumetric shrinkage during solidification and reduces the formation of shrinkage cavities. However, its effectiveness is limited by the hydraulic connectivity between the mold cavity and the gating system (Ružbarský and others, 2014; Gašpar & Paško, 2016; Ragan, 2007; Majerník and others, 2021).

Despite extensive research on high-pressure die casting processes (Majernik & Ruzbarsky, 2016; Gaspar & Pasko, 2019; Gašpar & Paško, 2016; Majerník and others, 2021), the mutual interaction between plunger velocity and intensification pressure in relation to internal defect formation and the local mechanical response of castings remains insufficiently understood. Most published studies focus on the isolated evaluation of individual process parameters or on global mechanical properties of castings, whereas experimental work analyzing their combined effect in critical regions of real industrial components is still limited. This gap is particularly relevant for structural automotive parts, where local porosity governs component reliability.

The contribution of this study lies in the experimental assessment of the combined effect of plunger velocity and intensification pressure on porosity and permanent deformation of a real automotive casting made of AlSi9Cu3 alloy. Unlike most published studies (Blondheim & Monroe, 2021; Pavlenko and others, 2020; Gaspar & Pasko, 2019; Ragan, 2007), which evaluate individual parameters separately or use simple-geometry test specimens, this work analyzes the interrelationships between process parameters, internal defects, and local mechanical response in a critical region of an industrial component.

MATERIALS AND METHODS

Material and Casting Geometry

The experiments were performed on high-pressure die castings made of AlSi9Cu3 alloy (EN 1706), which is widely used for structural applications in the automotive industry. An alternator housing flange was selected as the experimental component, representing a real industrial part. The choice of this component was motivated by its practical application, the presence of local wall thickness variations, and critical regions with an increased probability of porosity formation. The geometry of the experimental casting is shown in Fig. 1.

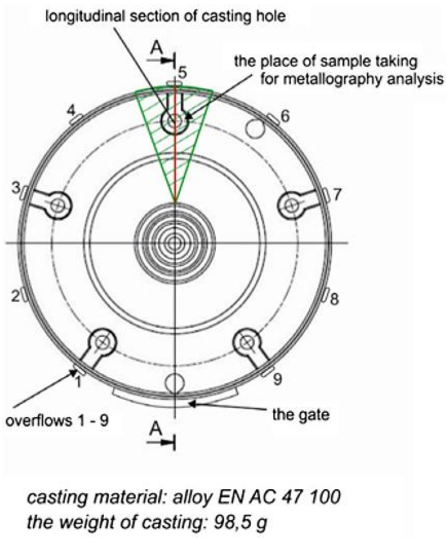

Figure 1 Experimental casting

The chemical composition of the AlSi9Cu3 alloy complied with the EN 1706 standard. The content of individual alloying elements was kept constant throughout the experiments to eliminate their influence on the evaluated casting properties. The compositional ranges according to the standard are given in Table 1.

Table 1 Chemical composition of AlSi9Cu3 alloy according to EN 1706 (wt. %)

Si	Cu	Fe	Mn	Mg	Zn	Ni	Cr	Pb	Sn	Ti	Al
8–11	2–4	0.6–1.3	max. 0.55	0.15–0.55	max. 1.2	max. 0.55	max. 0.15	max. 0.35	max. 0.15	max. 0.25	balance

Process Parameters and Melt Flow

The experiment was designed as a single-factor study, in which plunger velocity and subsequently intensification pressure were varied independently while all other parameters were kept constant. This approach enabled isolation of the influence of individual technological parameters on the evaluated casting characteristics.

Constant conditions:

- Melt temperature: 705°C
- Die temperature: 200°C
- Plunger diameter: 70 mm

Variable parameters:

- Plunger velocity: 2.0-3.2 $m \cdot s^{-1}$
- Intensification pressure: 13-25 MPa

The plunger velocity range was selected to cover the transition between different mold cavity filling regimes. The intensification pressure range corresponds to values commonly used in industrial HPDC practice.

The melt flow velocity in the gating system was determined using a governing equation. Based on the geometry of the plunger and gating system, flow velocities were calculated for each plunger speed level (Table 2). These data were subsequently used to evaluate the influence of filling dynamics on porosity formation and permanent deformation of the castings.

Table 2 Melt velocity in the gating system

Plunger velocity(m/s)	2.0	2.2	2.4	2.6	2.8	3.0	3.2
Melt velocity in gating system (m/s)	38.5	42.2	46.2	50.1	53.9	57.8	61.6

Evaluation of Properties

Mechanical response was evaluated using permanent deformation tests performed on a TIRA test 28200 testing machine in accordance with GME 06007 and GME 60156 standards. The critical testing location was selected in a region of stress concentration near the core of the casting (Fig. 2).

Fig. 2 Selected critical testing location

Loading was applied up to a maximum force of 14 kN, followed by unloading to 7 kN (50% of Fmax). Permanent deformation (s) was defined as the difference between the deformation measured at these two load levels (Fig. 3).

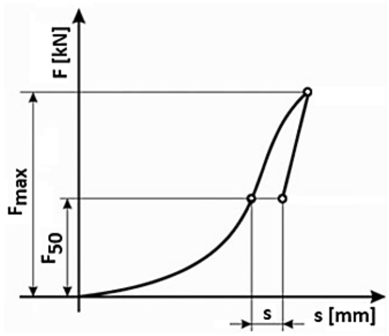

Fig. 3 Principle of permanent deformation evaluation

Permanent deformation was evaluated as a function of process parameters. In the first experimental series, plunger velocity was varied at a constant intensification pressure of 25 MPa, while in the second series the intensification pressure was varied at a constant plunger velocity of 2.6 $m \cdot s^{-1}$.

For each process parameter combination, three independent specimens were analyzed. Reported values represent the arithmetic mean of three measurements. Based on mechanical testing results, a specimen whose permanent deformation value was closest to the series mean was selected for metallographic analysis.

The influence of plunger velocity and intensification pressure was assessed by comparing arithmetic means across individual experimental levels. Result interpretation was based on identifying trends in permanent deformation and porosity evolution. This selection procedure ensured the representativeness of microstructural analysis with respect to the average mechanical response within each experimental series.

RESUITS

Influence of Process Parameters on Deformation

The results showed that plunger velocity has a significant effect on the magnitude of permanent deformation. The highest average value was recorded at a plunger velocity of 2.0 m·s^{-1}. With increasing velocity, the deformation gradually decreased, reaching a minimum at 2.8 m·s^{-1}. A further increase in velocity to 3.0 m·s^{-1} and 3.2 m·s^{-1} led to a renewed increase in permanent deformation. The results of this part of the experiment are presented in Fig. 4A.

The second part of the experiment focused on the influence of intensification pressure at a constant plunger velocity. The highest average permanent deformation was observed at an intensification pressure of 13 MPa, while increasing the pressure led to a gradual decrease in deformation. The lowest average deformation was measured at 25 MPa, indicating a beneficial effect of higher intensification pressure in reducing permanent deformation of the castings. This trend is also evident from the graphical representation in Fig. 4B.

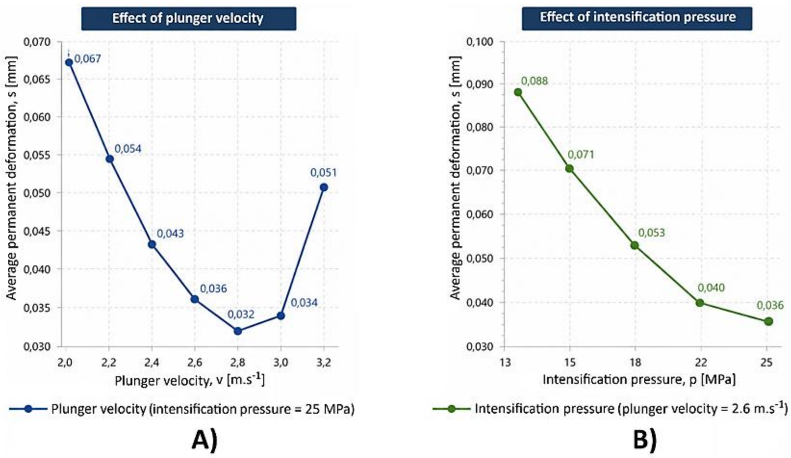

Fig. 4 Dependence of average permanent deformation on plunger velocity (A) and intensification pressure (B)

Influence of Plunger Velocity and Intensification Pressure on Porosity

Porosity was evaluated on specimens corresponding to the arithmetic mean of each experimental series. The analysis was performed at different plunger velocities while keeping the intensification pressure constant at 25 MPa.

The results indicate that the highest porosity was observed at the lowest plunger velocity of 2.0 m·s^{-1}. With increasing plunger velocity, porosity gradually decreased, reaching a minimum at 3.0 m·s^{-1}. At 3.2 m·s^{-1}, the values stabilized without any significant change. This trend is shown in Fig. 5A.

The second part of the experiment focused on the effect of intensification pressure at a constant plunger velocity of 2.6 m·s^{-1}. The results demonstrate a pronounced decrease in porosity with increasing pressure. The highest porosity was recorded at 13 MPa, while further increases in pressure led to a gradual reduction down to a minimum at 25 MPa. This trend is also evident in Fig. 5B.

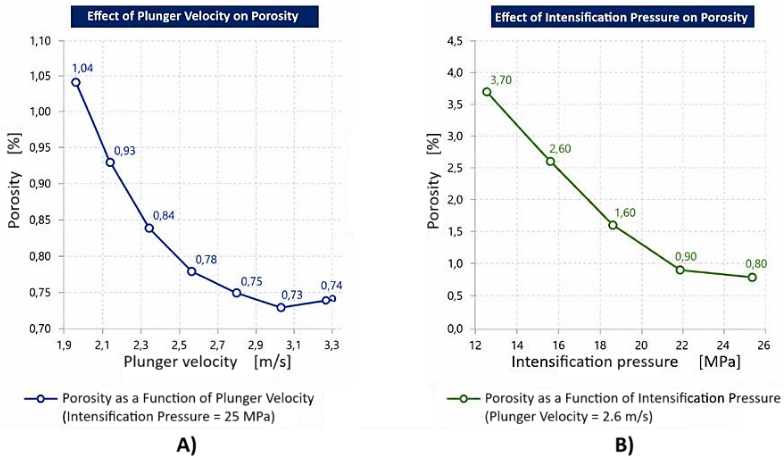

Fig. 4 Effect of plunger velocity (A) and intensification pressure (B) on porosity

DISCUSSION

The experimental results confirm a pronounced sensitivity of the mechanical response and internal integrity of high-pressure die cast AlSi9Cu3 components to variations in plunger velocity and intensification pressure. The observed dependencies indicate that the final casting quality is governed by a complex interaction between the hydrodynamics of mold cavity filling and the effectiveness of pressure intensification during solidification, with both mechanisms acting simultaneously and in a non-linear manner.

Influence of Plunger Velocity on Filling Behaviour and Defect Formation

The dependence of permanent deformation and porosity on plunger velocity exhibits a non-linear character, suggesting the presence of multiple competing mechanisms during the filling stage.

At low plunger velocity (2.0 m·s^{-1}), increased porosity and permanent deformation were observed. This condition is associated with insufficient kinetic energy of the flowing melt, leading to incomplete filling of the mold cavity, premature solidification in thin sections, and reduced venting efficiency. As a result, the probability of gas entrapment and internal void formation increases. Compared to the optimal range of 2.6–3.0 m·s^{-1}, an increase in permanent deformation of approximately 47% and porosity of 36% was observed at 2.0 m·s^{-1}. Percentage differences were calculated relative to the optimal interval as the reference state.

With increasing plunger velocity into the intermediate range (approximately 2.6-3.0 m·s^{-1}), a significant improvement in casting quality is achieved. In this regime, a more stable flow front is established, filling of geometrically complex regions is

enhanced, and gas evacuation becomes more effective. This regime can therefore be considered technologically optimal with respect to defect minimization.
However, at higher velocities (3.0-3.2 $m \cdot s^{-1}$), casting quality deteriorates again. This can be explained by a transition toward turbulent to dispersed flow regimes, where intensive air entrapment and fragmentation of oxide films occur. These defects act as initiators of porosity and local stress concentrations, resulting in increased permanent deformation.
The observed non-linear trend is consistent with literature (Majerník and others, 2021; Cao and others, 2017), which describes the existence of an optimal filling velocity ensuring a stable flow front and minimal gas entrapment. In contrast to studies (Gašpar & Paško, 2016; Ružbarský & Sitko, 2019; Zhang and others, 2020), which analyze filling velocity in isolation, the present results demonstrate its interaction with intensification pressure, which significantly modifies the resulting mechanical response of the system.

Influence of Intensification Pressure on Porosity and Permanent Deformation

Intensification pressure exhibits a clearly monotonic beneficial effect on casting quality. At low pressure (13 MPa), the highest porosity was observed, indicating insufficient compensation of solidification shrinkage.
With increasing pressure, both porosity and permanent deformation gradually decrease. This effect is associated with improved feeding of interdendritic regions and more effective compensation of volumetric shrinkage. At the microstructural level, this leads to a reduction of interdendritic voids and improved feeding of the solidifying phase, thereby decreasing the likelihood of shrinkage microcavity formation in the final stages of solidification. The lowest values were achieved at 25 MPa, confirming the importance of intensification pressure for improving material density and structural integrity.
It should be emphasized that the effectiveness of pressure is limited by the maintenance of hydraulic connectivity between the gating system and the cavity. Once flow is cut off due to advanced solidification, the efficiency of intensification is significantly reduced.
The observed monotonic decrease in porosity with increasing intensification pressure is consistent with published results (Diler, 2021; Kaščák and others, 2021; Abdo and others, 2023), which show that pressure intensification increases material density through more effective compensation of volumetric changes during solidification.

Relationship Between Porosity and Permanent Deformation

The results clearly confirm a direct correlation between porosity and permanent deformation. Castings with higher porosity exhibit increased permanent deformation (Qi and others, 2020; Gaspar & Pasko, 2016), and this relationship is approximately linear within the investigated experimental range.

This behavior can be explained by the role of pores as local stress concentrators, which reduce the effective load-bearing cross-section of the material and promote plastic deformation at lower applied loads. In addition, porosity disrupts material continuity, reducing overall stiffness and stability of the mechanical response.

The results also indicate that permanent deformation can serve as a sensitive indicator of internal casting quality and may be used as an indirect measure of porosity formation in HPDC components.

Implications for Process Optimization

The obtained results demonstrate that optimal HPDC conditions are defined by a narrow plunger velocity interval combined with higher intensification pressure. Outside this interval, either insufficient cavity filling (low velocities) or increased defect formation due to turbulent flow (high velocities) occurs (Szymczak and others, 2020; Cai and others, 2021).

This implies that HPDC process optimization must be treated as a multivariable problem, where plunger velocity and intensification pressure cannot be evaluated independently but only as interdependent process variables.

The results provide practical guidance for parameter setting in industrial production of AlSi9Cu3 structural castings. The identified plunger velocity range of 2.6–3.0 $m \cdot s^{-1}$ combined with higher intensification pressure represents a suitable process window for minimizing porosity while maintaining favorable mechanical response. These findings may be directly applicable to process optimization in the automotive industry.

CONCLUSION

This study focused on the experimental assessment of the influence of selected HPDC process parameters, specifically plunger velocity and intensification pressure, on the quality of aluminium high-pressure die castings. Casting quality was evaluated in terms of permanent deformation and porosity in a critical region of the component.

The results confirmed that plunger velocity significantly influences mold filling behavior and consequently the formation of internal defects and mechanical response of the castings. The dependence of permanent deformation on plunger velocity is non-linear, and an optimal velocity interval can be identified in which both porosity and deformation are minimized. Outside this interval, casting quality deteriorates due to either insufficient mold filling or increased gas entrapment under turbulent flow conditions.

Intensification pressure proved to be a significant parameter affecting internal casting quality. Its increase led to a reduction in porosity and an improvement in deformation behavior, which is associated with more effective compensation of shrinkage during solidification. However, its effectiveness is limited by the maintenance of hydraulic connection between the cavity and the gating system.

The main conclusions can be summarized as follows:

- Plunger velocity has a non-linear effect on permanent deformation and porosity, with an optimal interval for minimizing both responses.
- Increasing intensification pressure reduces porosity and improves mechanical response, although its effectiveness is technologically limited.
- Porosity directly correlates with increased permanent deformation, confirming its detrimental effect on mechanical integrity of castings.

Despite being limited to a specific casting geometry and alloy system, the results provide a relevant basis for HPDC process optimization in industrial practice. Further research should include a broader range of process parameters, particularly thermal conditions, as well as numerical simulations of melt flow and validation on components with different geometries.

It should be emphasized that the presented findings are specific to the AlSi9Cu3 alloy, the investigated casting geometry, and the applied technological conditions. Transferability of the conclusions to other geometries or gating systems requires further experimental verification.

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