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# Evaluation of the Technological Properties of the Al-Si Eutectic Alloy Based on Density Index Test

**M. Starczewski [a, b, *], A.J. Dolata [b], M. Dyzia [b]**
[a] ZŁOTECKI Sp. z o.o., Poland
[b] Silesian University of Technology, Poland
* Corresponding author. e-mail address: m.starczewski@zlotecki.pl

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## Abstract

Aluminium-silicon alloys are widely used in industrial practice due to their many advantages, including light weight and relatively high strength. The consumption of these light engineering materials is constantly increasing, especially in the automotive industry, due to new greenhouse gas (GHG) emission standards.
The sustainable development strategy in the foundry industry is related to reducing the amount of waste and pollution generated during the production process. In turn, reducing the number of production shortages and waste requires the production of good quality Al-Si castings, and thus the appropriate selection and monitoring of technological parameters affecting the quality of the liquid alloy, including the level of purity and the degree of its gasification.
The main objective of the research conducted to evaluate the technological properties of the AlSi12CuNiMg (AlSi12) alloy was to identify the causes of increased defect rates in piston castings during the production process at the Złotecki Sp. z o.o. The tests were carried out using two Al-Si alloys with silicon content close to eutectic (approx. 12%) used for piston castings, from two different suppliers.
Three measurement methods were used to evaluate the technological properties of the tested AlSi12 alloys: thermal analysis, fluidity test and density index for gasification measurement.
Based on the analysis of the results, it was concluded that an excessively low-density index level might be the cause of the increased casting defect rates observed in the production of pistons for internal combustion engines and compressors, particularly for castings with significant variations in wall thickness.

**Keywords:** Al-Si alloys, Piston, Solidification, Fluidity, Density index

## 1. Introduction

Aluminium-silicon alloys (Al-Si) are widely used in foundry practice due to their light weight, good strength-to-weight ratio, high corrosion resistance, good ductility and high electrical and thermal conductivity. Recyclability is one of the great features of Al-Si alloys, their products also are most often recycled [1,2]. Moreover, castings made of Al-Si alloys are characterized by ease of machining, which results in a relatively low cost of the finished parts. From this point of view, they find many different applications in the aerospace, defence, machinery and automotive industries [3,4].

Permanent mould castings made of Al-Si alloys are used to produce a wide range of products, including engine blocks, cylinder liners, camshafts, wheels, and different kind of pistons for air compressors and combustion engines [5,6]. Therefore, the foundry industry still plays an important role in the global economy, however it emits significant amounts of greenhouse gases. Thus, reducing $CO_2$ emissions is increasingly considered a key element of the strategy of both small and large foundries around the world, also in Poland [7].

The number of rejections (percentage of defective castings) and the product scrap are a common problem most foundries, especially those producing high-quality parts with complex shapes, such as Al-Si pistons. Therefore, the sustainable development policy of the foundry industry is closely related to reducing the amount of waste and pollution generated during the production process. In turn, limited the number of shortages and production waste requires the production of good quality Al-Si castings, and thus the appropriate selection and monitoring of technological parameters affecting the quality of the liquid alloy, including the level of purity and the degree of its gasification.

Casting defects are one of the main problems in the piston production process. They are one of the important factors influencing the quality of products and the number of rejects, and consequently the higher cost of all produced batch. Therefore, it is most important to identify the causes of their occurrence at each stage of process production [8].

The occurrence of casting defects is influenced by a variety of factors, including the design of the casting mould, the chemical composition and quality of the alloy, casting process parameters (such as molten metal temperature, solidification time, and refining parameters), cooling system parameters (such as mould temperature, cooling medium temperature, cooling activation time, cooling duration, and sectional division), environmental factors (such as ambient temperature and humidity), human factors, and many others.

As demonstrated by production practice, determining the quality of an alloy solely based on a comparison of the chemical composition given in the melt certificates with the requirements of the PN-EN 1676:2020-09 standard may be insufficient to predict the quality of a piston casting.

## 1.1. Casting defects in Al-Si pistons

The gravity casting method, also known as permanent mould casting (PMC), is widely used for manufacturing many automotive parts, such as combustion engine pistons (Fig 1). The typical pistons of automobiles are cast from near-eutectic aluminium alloys that contain about 11–13% silicon and various alloying components such as copper, nickel, and magnesium (Al–Si–Cu–Ni–Mg). Such Al-Si alloys exhibit a complex multi-phase microstructure providing good thermal, corrosion and mechanical properties [9].

The properties of finished piston products depend not only on the chemical composition of the alloy used and the proper execution of its modification and heat treatment processes but also on the elimination of the causes of casting defects, which are often revealed only after machining (Fig. 2). Poor metallurgical quality of the Al-Si alloy used (e.g., due to inadequate refining of the supplied alloy or secondary origin of the material) can result in a significant increase in gas porosity and oxide inclusions [10]. The identification of such defects (Fig. 3) requires detailed structural analysis.

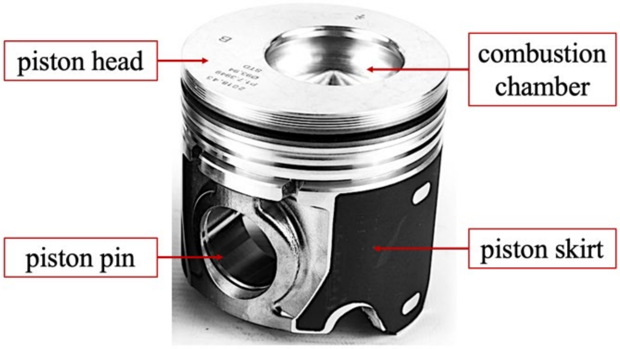
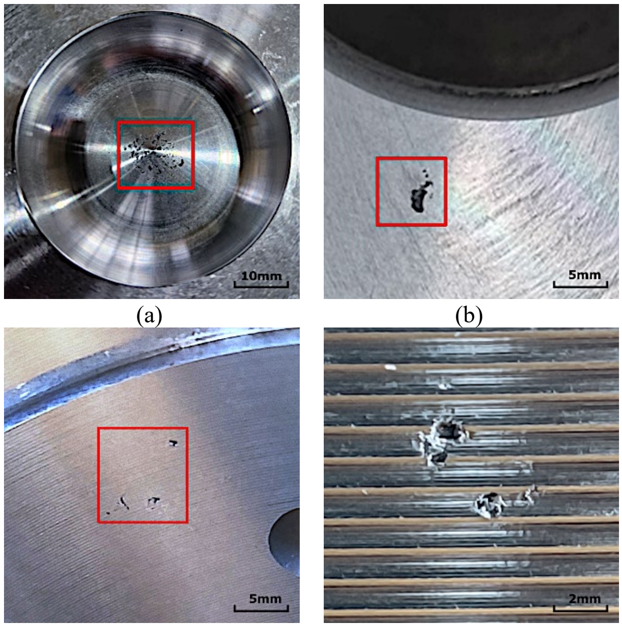


Fig. 1. View of the AlSi12CuNiMg combustion engine piston made by PMC

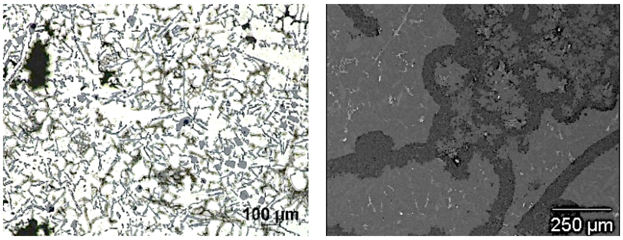


(a) (b) (c) (d)

Fig. 2. Casting defects revealed after machining in important piston parts: combustion chamber (a), piston head (b), piston pin hole (c), piston skirt (d) [unpublished own research]

Shrinkage porosity and gas-type porosity are one of the major defects occurring in piston castings made on Al-Si alloys [11]. Based on the literature review, it can be concluded that the final volume of macro- and microporosity in Al-Si castings depends mainly on the amount of hydrogen in the molten metal alloy [12], as well as on the chemical composition [13] and solidification conditions, such as cooling rate and mould material [14].

Dispinar et al. [1,15,16] presented an alternative approach to the problem of porosity in aluminium alloy castings, demonstrating a correlation between the occurrence of porosity and the presence of oxides in the alloy. The authors presented several studies confirming this relationship, most often analysing raw material that was not subjected to refining processes. In their studies, they used samples in the form of ingots supplied by alloy manufacturers and material from recycled aluminium scrap. They also drew attention to the process of oxide formation during the filling of the casting mould under turbulent flow conditions, according to one of Campbell's ten rules of casting quality [17].

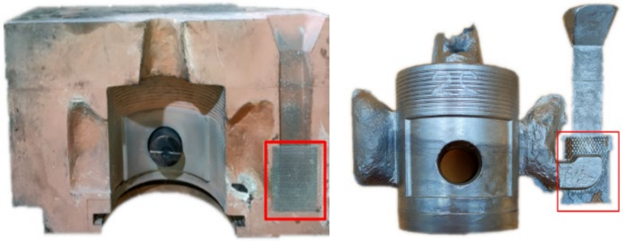



(a) (b)

Fig. 3. Microstructure of the representative AlSi12CuNiMg piston obtained by PMC: (a) the dendritic structure (light grey) and eutectic Si particles (dark grey) are shown along with identified porosities (black) and (b) magnesium (Mg) oxide inclusion cluster [unpublished own research]

The motivation to undertaking research on the technological properties of commercially available AlSi12CuNiMg (AlSi12) alloys, with a chemical composition according to the PN-EN 1676:2020-09, was the varying levels of defects observed in piston castings during serial production in an engine pistons factory (Złotecki Sp. z o.o. [18]).

Since all castings were produced using the same moulds equipped with an industrially proven pouring system with throttling and stabilization of the liquid flow (Fig. 4), it was assumed that the cause of the defects lies in the alloy preparation stage, particularly during melting and refining.



(a) (b)

Fig. 4. Filter mesh position: (a) casting mould, (b) casting

# 2. Materials and Methods

Two AlSi12CuNiMg alloys (accordance the PN - EN 1676:2020-09 standard) with near-eutectic silicon content (approx. 12%), obtained from two suppliers, were used in this work. The chemical composition of the tested alloys is given in Table 1.

Table 1.
Chemical composition of AlSi12CuNiMg alloy, wt. %

| AlSi12CuNiMg | Si | Cu | Mg | Ni | Fe | Mn | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| STANDARD PN-EN 1676:2020-09 | 10.5÷13.5 | 0.8÷1.5 | 0.8÷1.5 | 0.7÷1.3 | max 0.7 | max 0.35 | max 0.35 | max 0.250 | Bal. |
| Melt (I) | 12.44 | 1.03 | 1.20 | 0.92 | 0.45 | 0.18 | 0.15 | 0.020 | Bal. |
| Melt (II) | 12.05 | 0.97 | 1.14 | 0.9 | 0.43 | 0.15 | 0.07 | 0.030 | Bal. |

The materials for the study were prepared in two identical resistance melting furnaces, Nabertherm T 80/10 (Fig. 5), with each furnace processing a charge of 200 kg.


Fig. 5. Casting furnaces used in the study

The temperature of the molten material was continuously monitored and maintained at 730 ± 5 °C. The melts were designated as follows:

- Melt (I) – casting furnace PO-04 – material identified due to an increased rate of casting defects (defect rate of 30–40%).
- Melt (II) – casting furnace PO-03 – material used in ongoing production (defect rate of 5%).

During the remelting process, granulated Ecosal AL 113.M refining agent was introduced into the liquid alloy in the amount of 50 g per crucible. Then, gas refining was applied using the URO-200 XR device (IMN-OML Skawina) equipped with an XDR OX 140.70 rotor (Foseco) (Fig. 6). The barbotage process was carried out using argon 5.0 with a flow rate of 10 dm³/min. The rotation of the refining head at a speed of 350 rpm caused a vortex motion in the entire volume of the liquid metal, which ensured the active introduction of the refining agent under the alloy surface and its uniform mixing. The total refining time was 10 minutes. As a result of this process, the liquid metal was degassed, and the oxides were brought to the surface of the bath. The accumulated impurities were finally removed from the surface of the liquid alloy using a scraper.

(a) (b)

Fig. 6. Gas refining device (a) and gas flow rotor (b)

To determine the technological properties of the alloys, thermal analysis (TA), fluidity (FT) and density index (DI) tests were carried out.

Samples for the tests were collected at three-time intervals:

- the first series of samples were taken after the material was melted,
- the second series of samples was taken after the refining process,
- the third series of samples was taken approximately 1.5 hours after holding the molten charge in the crucible following the refining process, representing the maximum time allowed for material extraction during the standard piston casting process.

## 2.1. Thermal analysis (TA)

The thermal analysis of the alloys was performed using standard Quick Cup ceramic crucibles equipped with K-type thermocouples mounted on a dedicated base that allowed the connection of thermocouple contacts (Fig. 7).

The results were recorded at a frequency of 10 Hz using an HBM Octopus data logger and the dedicated Catman 3.0 software provided by HBM.


(a) (b)

Fig. 7. Stand used for ST (a) and quick cup after test (b).

The initial data processing was performed using the data logger software. Subsequently, the data collected were imported into an Excel spreadsheet for further processing and analysis. Solidification curves were plotted, and the start $t_{pk}$ and end $t_{kk}$ temperatures of solidification were determined.

## 2.2. Fluidity test (FT)

Fluidity is an important technological property of Al-Si casting alloys [19]. Testing the alloy's ability to fill the mould cavity is crucial for quality control and thus reducing the number of rejected castings. In this study, the fluidity of the tested alloys was assessed using the Metal Health® System stand (Fig 8).

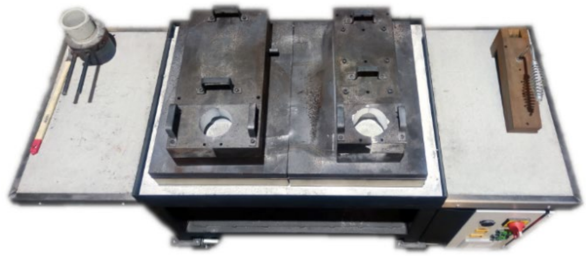
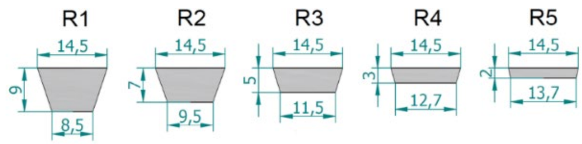


Fig. 8. Metal Health® System stand used for FT

The station controller ensures that the mould temperature is maintained at the set value of 300°C. The test casting was produced in the form of a five-arm structure with a constant rod length of 300 mm and varying cross-sections, as shown in Fig. 9.


(a)



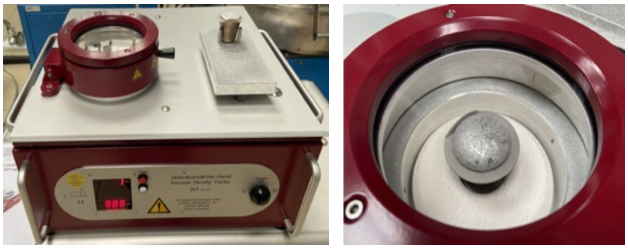

(b)

Fig. 9. Casting of a fluidity sample (a), drawing of the cross-section of the bars (b)

The total length of all cast rods was used as an indicator of the ability to fill the mould cavity (fluidity index). The length of each individual rod was adopted as the indicator of fluidity

## 2.3. Density index (DI)

The density index (DI) is usually measured to determine the melt quality of the Al-Si alloys and monitor its gasification level [20]. In the present study, a 3VT basic vacuum casting device manufactured by MK (Fig. 10) was used to determine the density index (DI).



(a) (b)

Fig. 10. Stand used for DI

The molten material was taken from the furnace and poured into two steel moulds: one solidified under reduced pressure (80 mbar) for 5 minutes, while the other solidified under ambient conditions (atmospheric pressure of 988 mbar).


Fig.11. Hydrostatic balance MK 300

The density index (DI) of the samples was determined using the MK 3000 balance (Fig. 11), manufactured by MK Industrievertretungen GmbH, in accordance with a programmed measurement procedure based on the formula (1):

$$DI = \frac{\rho A - \rho V}{\rho A} \cdot 100\% \quad (1)$$

where: ρA – density of the sample solidifying in the atmosphere,
ρV – density of the sample solidifying in the reduced pressure conditions.

# 3. Results and Discussion

## 3.1. Thermal analysis

Based on the results obtained from the thermal analysis (TA), solidification curves were developed. One of these curves, representing the state after the remelting of the alloys, is presented on Fig. 12.

The analysed materials exhibited differences in their solidification curves. Melt (I) was characterized by a longer solidification time.

After analysing the data, the start $t_{pk}$ and end $t_{kk}$ points of solidification were determined for each alloy at three-time intervals. The calculation results are presented in Table 2.

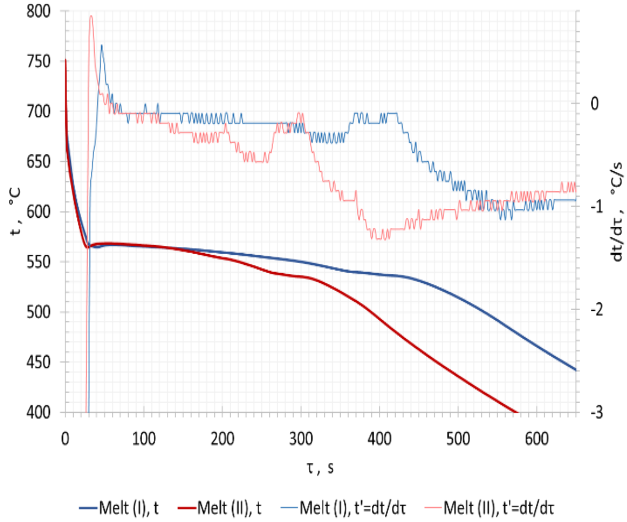



Fig. 12. Solidification: Melt (I) i Melt (II), after melting

Table 2.
Temperature of the beginning of solidification ($t_{pk}$) and the end of solidification ($t_{kk}$) of Melt (I) and Melt (II)

| Melt, $t_{pk}$, $t_{kk}$ | after melting, °C | after refining, °C | after holding, °C |
|---|---|---|---|
| Melt (I), $t_{pk}$ | 565 | 565 | 567 |
| Melt (I), $t_{kk}$ | 493 | 493 | 493 |
| Melt (II), $t_{pk}$ | 565 | 566 | 565 |
| Melt (II), $t_{kk}$ | 502 | 502 | 500 |

The results showed that the characteristic temperature points for each alloy remained constant throughout the test. For both alloys, the initial solidification temperature $t_{pk}$ was in the range of 566 ± 1 °C. The differences observed at the end of solidification temperatures $t_{kk}$. For Melt (I), the value was exactly 493 °C, while for Melt (II), it was 501 ± 1 °C. A slight difference in the content of silicon, copper and titanium in the tested alloys may affect their final solidification temperature, which was also confirmed in [21].

## 3.2. Fluidity

The fluidity test casting, consisting of five rods with decreasing cross-sections, demonstrates the filling of the mould cavity with aluminium alloy for different mould cross-sections (Figs. 9, 13).

In accordance with the stand instructions, the mould-filling capacity was determined using the total length of all cast rods as an indicator (Fig. 13). The fluidity characteristics were measured by plotting the length of each rod individually on a control chart (Fig. 14).

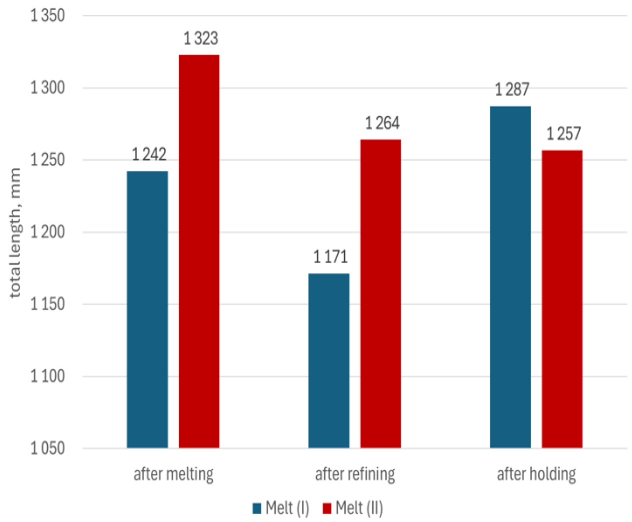



Fig. 13. Fluidity index

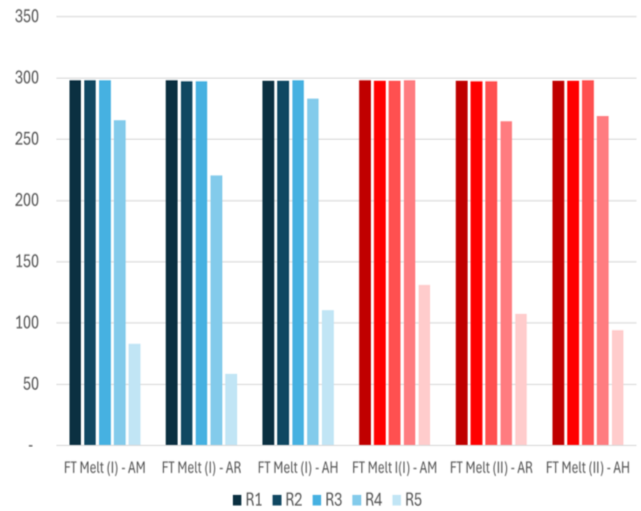



Fig. 14. Fluidity characteristic (AM – after melting, AR – after refining, AH – after holding)

## 3.3. Density index

The macrostructure of the cross-sections of the tested AlSi12 alloys made on the DI measurement stand and solidified under different conditions is shown in Figures 15-16.

The measured DI values at three-time intervals are presented in Fig. 17. The density index values for the alloys in the remelted state exhibited significant variation, with Melt (I) measuring 0.78% and Melt (II) 1.44%. After the refining process, similar density index values were obtained 0.40% for Melt (I) and 0.37% for Melt (II). However, after 1.5 hours of annealing, a notable difference was again observed: the density index of Melt (I) increased to 0.57%, while that of Melt (II) increase to 1.58%. These results suggest a tendency for Melt (II) to absorb hydrogen during holding [22].

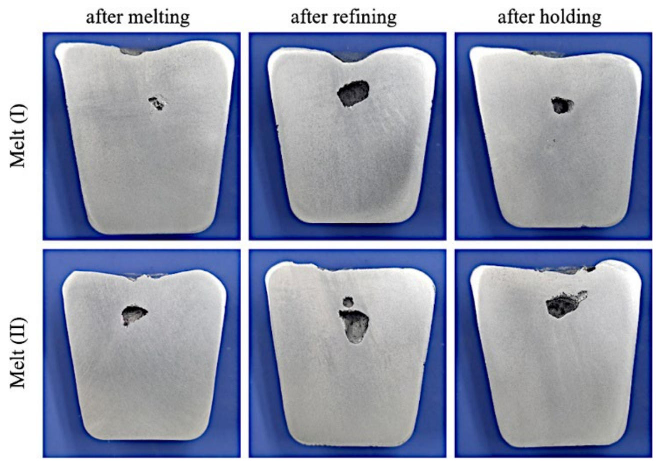



Fig. 15. Macrostructure of samples prepared in atmosphere

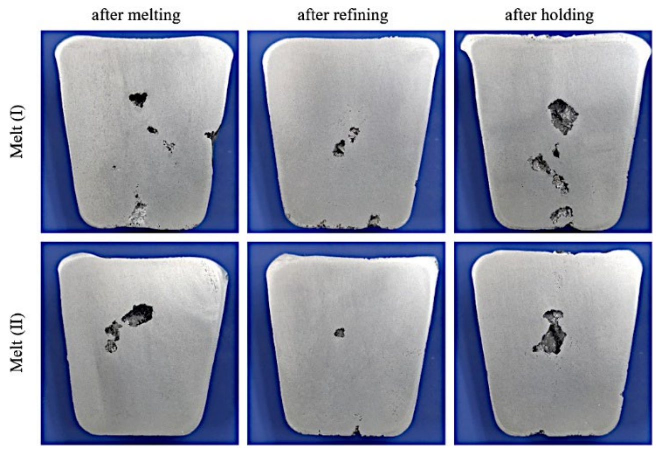



Fig. 16. Macrostructure of samples prepared in 80 mbar vacuum

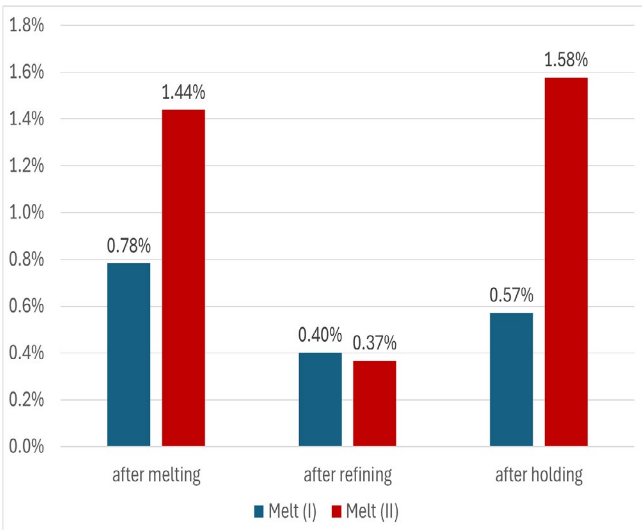



Fig. 17. Density index results

## 4. Summary

The obtained results indicate that even minor changes in the chemical composition of the alloy can influence its technological properties and the porosity of castings. The two tested alloys, whose compositions complied with the relevant standard the PN-EN 1676:2020-09, exhibited different properties both in their remelted state and after refining and holding for 1.5 hours at 730°C.

Observed differences in fluidity characteristic in cavity filling were in channels with wall thicknesses of 3 mm and 2 mm (Fig. 9b – R4 and R5), however it can be concluded that the defect observed in piston castings made from the Melt (I) alloy is not related to the fluidity of the alloy. In fact, in the produced pistons, the wall thickness of the casting exceeds 5 mm.

To assess the alloy's properties before the piston casting process, determining the density index (DI) is an appropriate method for evaluating the degree of outgassing, which affects the formation of gas porosity. The study demonstrates that, in the post-melting state, the tested alloys exhibited significant differences in their density index. After gas refining with argon, the density index of both alloys decreased to approximately 0.4%. However, after annealing for 1.5 hours, differences between the alloys reappeared. The density index of the Melt (I) alloy was 0.40% after refining and increased to 0.57% after annealing.

According to literature data [23, 24], at low $H_2$ concentrations and consequently low density indices voids associated with shrinkage porosity may form in areas adjacent to the mould wall during alloy solidification. Therefore, the relatively low density index of the Melt (I) alloy may have contributed to an increased number of defects in the casting series. These defects were associated with shrinkage porosity rather than gas porosity.

Further research will focus on determining the optimal density index (DI) level by developing a process for preparing the alloy with a stable and predefined value of this parameter. Achieving the appropriate density index value will most likely be carried out through secondary alloy gassing. In the first stage, hydrogen will be removed from the alloy through gas refining to obtain a low initial density index level. Subsequently, a mixture of argon and hydrogen at a low concentration will be introduced into the alloy using the same refining device. The gas mixture parameters and process conditions and the optimal value (DI) will be determined experimentally.

## Acknowledgements

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