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Research of Fluidity for new LPIC Technology

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Abstract

Today, the emphasis is on rapid development and research of new technologies in all technical fields. In most cases, research and development involves practical experiments, which can be very costly to carry out. Some experiments may not even work and can waste time and money, which are crucial for fast and high-quality research. In order to avoid these problems before conducting a practical experiment, we can use numerical simulation software, which is very reliable when the correct input parameters are given. Numerical simulation of the process can reveal how the practical experiment may turn out even before its implementation. The paper deals with the use of numerical simulations in investigating the problem of fluidity in a new low pressure investment casting (LPIC) technology, where the output is the agreement between the simulation and the practical experiment. The practical experiment consisted in the design of a fluidity test for stainless steels cast using the low pressure investment casting technology and the simulation carried out in simulation software. The new LPIC technology makes it possible to achieve a wall thickness of between 1 and 0.5 mm for steel castings, which significantly increases the potential of steel castings made by LPIC technology.

Keywords: Low-pressure investment casting (LPIC), Investment casting, Fluidity, Numerical simulation

1. Introduction

As the demands for shape complexity in castings and the casting of special materials continue to increase, it becomes essential to understand the foundry properties of alloys specific to each technology. The primary parameters of interest are heat removal from the melt and directional solidification. For complex shapes and thin-walled castings, the most critical factors are the fluidity of the alloy and the thermal conductivity of the mold material.

To address these challenges, we developed an experimental methodology, which is first validated using simulation software and then through practical experiments [1][2].

A significant issue arises when comparing different casting technologies that operate under varying process parameters (e.g., different mold materials), making direct comparisons difficult.

This challenge is even more pronounced with emerging technologies such as low-pressure investment casting (LPIC) [3].

Paper written by Shin et al. describes the study of fluidity for non-ferrous alloys and sand casting, using various methods to test the shapes, body, and channel cross-sections [3]. Additionally, it details the testing methodology for high-pressure die casting (HPDC) technology and its modification, squeeze casting [3]. The fluidity for steels and alloys with higher melting temperatures is also examined, with a focus on commonly used fluidity tests [3].

The fluidity of steels and alloys with higher melting temperatures is also examined, with a focus on commonly used fluidity tests [3]:

- Rod test (rods of different diameters - on a circular base around the casting stake or on a flat base - harp test [3],
- Spiral test [3],
- Staircase test



In low-pressure die casting technology, fluidity testing was addressed by conducting round bar tests in the horizontal parting plane, as described in paper written by Harding [4], focusing on Al alloys.

The team of authors developed a novel and unique LPIC technology, combining low-pressure die casting and investment casting for Fe-based, Ni-based, and Co-based alloys. No prior publications have addressed this topic, making this research unique and highly beneficial for enhancing the integrity of Fe, Ni, and Co alloy castings.

To expedite the testing process and avoid preparing multiple fluidity tests for different materials, a "test tree" was designed on which specimens were placed to determine the fluidity of individual materials at two different heights. This "tree" was used for both conventional gravity casting and the new LPIC technology [4].

Low-pressure investment casting was performed on an experimental low-pressure casting machine specifically designed for LPIC production.

As this machine is still experimental, features such as automation are not yet implemented but are planned for future practical experiments and simulations.

To reduce time-consuming experiments, foundry simulations were developed and compared with practical experiments of gravity and low-pressure investment casting. This comparison ensures the simulation is correctly set up and can be used to determine parameters for other materials present in the simulation software and commonly used in casting production [5].

The aim is to determine whether these simulations accurately reflect reality and can be applied to different materials without inaccuracies. This approach seeks to eliminate the time-consuming preparation of practical experiments that could impede the development of this new technology. Additionally, it aims to compare the aforementioned technologies in terms of qualitative properties to confirm or refute the assumed benefits of the new technology [5].

2. Methods of experiment

Compared to conventional investment casting or gravity casting, this technology should have the following characteristics:

- Increased surface quality of the casting
- Increased internal integrity of the material
- Possibility of casting more complex castings
- Process automation
- Stabilisation of the production process

To develop this technology, it is essential to understand the fluidity of each material under the conditions of LPIC technology. Test samples were designed based on prior research to assess whether shell filling would be influenced by pressure gradients as the cross-sectional area increased, resulting in a fan shape design (see Fig. 2).

The experiments were divided into two phases. The first phase focused on numerical simulations, including wax injection simulations to verify the manufacturability of wax models and simulations of the filling and solidification of the fluidity samples on the designed "tree" (see Fig. 1). The numbers in Fig. 1

correspond to the samples from the real experiment (see Fig. 11). Each tree included samples for tensile tests, flexural impact tests, and spectrometric analysis.

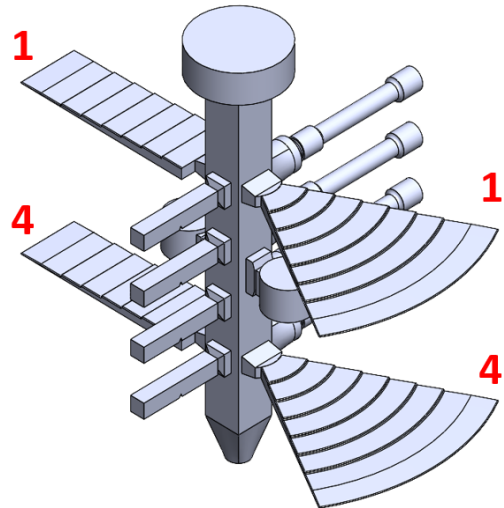


Fig. 1. Model of casted samples

2.1. Test samples for fluidity tests

The samples for fluidity tests were designed to give us as much information as possible for the material being tested.

There are two types of these tests on the tree. The first type consists of a fan-shaped configuration, comprising eight segments, each 15 mm long and graduated by 1 mm. The final segment is only 0.5 mm lower (see Fig. 3). The second type is staircase-shaped, also consisting of eight segments, each 15 mm long and graduated by 1 mm, with the final segment graduated by 0.5 mm (see Fig. 5).

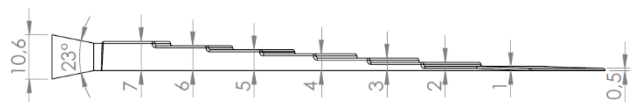
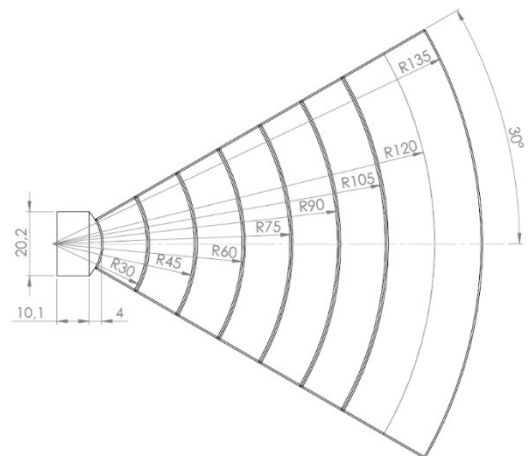


Fig. 2. Drawing of the fan sample

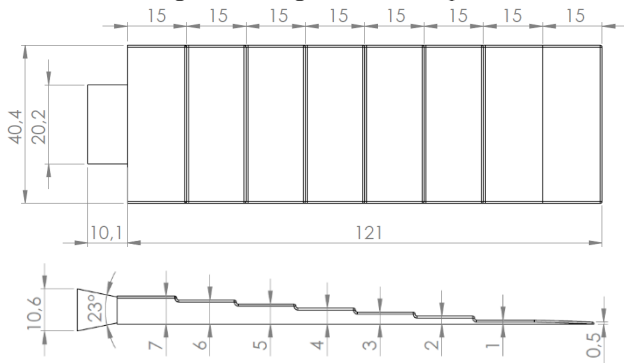


Fig. 3. Drawing of the staircase sample

2.2. Wax injection simulation

An analysis of wax injection into the molds was conducted to ensure the production feasibility of the test samples. Simulations were performed in CADmould for both samples using the following injection parameters:

- Injection time: 1.45 s
- Wax injection temperature: 68 °C
- Duralloy mold temperature: 35 °C

Experimental data [6] was utilized to determine the Not Flow Temperature (NFT), which was found to be 55 °C. Based on the NFT, the flow temperature of the samples was determined. Results indicate that the difference between the beginning and end of the flow temperature is less than 2 °C, suggesting no issues with the production of these samples.

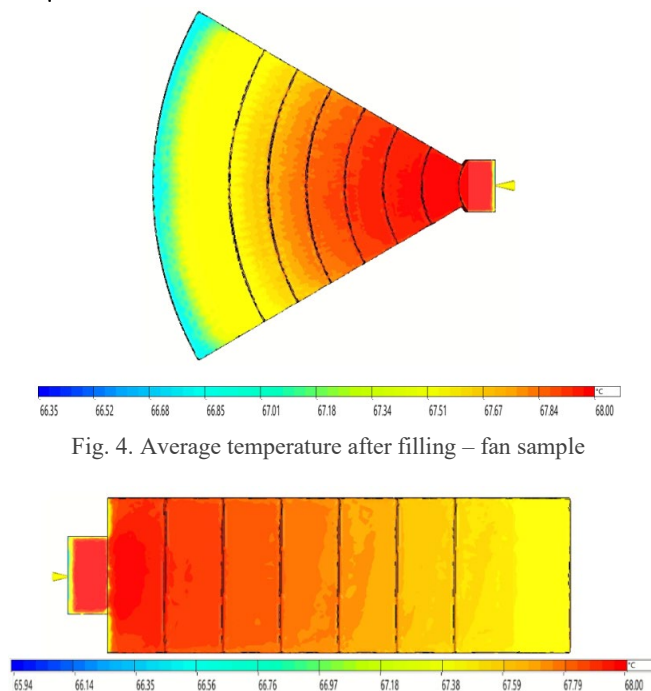


Fig. 4. Average temperature after filling – fan sample

Fig. 5. Average temperature after filling - staircase sample

The experiments were carried out on AISI 304L stainless steel (chemical composition See Table 1).

The shell was made from 6 layers of ethylsilicate and a quartz sand shell.

The technological parameters were chosen as follows:

- Casting temperature: 1580 °C
- Shell temperature: 900 °C
- Filling time: 2 s
- Filling pressure: 0,2 MPa

Table 1.

Chemical composition of AISI 304L

Element	C	Cr	Ni	Fe
Element content [%]	0,02	18,1	8,1	rest

To compare the results of low-pressure investment casting with gravity investment casting, the same trees were used and casted using the same material.

This comparison was carried out simultaneously in numerical simulation software with the same initial conditions as the casting technology.

2.3. Experimental LPIC casting machine

The research on LPIC technology was conducted using an experimental casting machine. The design is based on a conventional low-pressure casting machine, which was modified to allow the attachment of ceramic shells without difficulty. The ceramic shell comprises specialized layers designed to withstand the high pressure and temperature of molten alloys.

Fig. 6 presents the experimental LPIC machine with the top lid mounted and illustrates the method of attaching the ceramic shell to the casting machine.



Fig. 6. Experimental LPIC casting machine (left) and attachment of ceramic shell on casting machine (right)

3. Results

The results were cast and compared on three castings. The same was done for simulations using software Novaflow. Casting parameters were kept mostly identical for all castings. For instance, the shell was placed on the low-pressure machine with a variance of ± 5 seconds. Similar differences were also observed during gravity casting before the shell was removed from the furnace and casting started. [7] [8] [13]

Parameters for melting process:

- Furnace volume: 20 kg of Fe alloys
- Air melted (Can be protected by protection gas)
- Remelting ingots technology

Parameters have been set for the LPIC technology:

- Form filling time: 2 s
- Furnace melt pressure: 0.2 MPa

For gravity casting, a pan height above the sprue of 50 mm was chosen with a not completely filled casting stake:

- Filling time 2s
- Tree weight 3.2 kg
- Melt stream diameter 12 mm



Fig. 7. Casted trees (left: gravity casting, right: LPIC)

From the results, a significant difference was observed between the filling methods. In gravity casting, the material "flies" into the mold at a relatively high speed, reaching speeds of over 1.2 m/s, resulting in a large splash of metal. Consequently, significant reoxidation phenomena can occur, affecting the final mechanical properties of the castings. In LPIC casting the velocity was not above 0.5 m/s.

Fig. 8 depicts a simulation of mold filling by gravity casting, showing that the bottom floors of the shell and the impact test samples solidify as soon as the metal partially fills the cavity. A non-uniform temperature field (Fig. 8) is also evident, as the material is reheated due to the filling.

Due to the cooling of the metal in the upper floors of the shell, there is noticeable undercooling of the test bodies.

In LPIC technology (Fig. 9), mold filling is calm, with the level progressing slowly from the inlet upwards and spilling into the test samples. The entire mold of the test bodies is filled when the metal still contains approximately 65% of the liquid phase, minimizing

problems of non-pouring and non-swelling in the floor closer to the sprue. The shell floors on the far side from the sprue are already filled with cooler metal, so there are minimal issues with the straight filling tests. However, problems arise with the fan test as the filling area increases.

Regarding casting shrinkage, both casting variants utilize the casting stake as a riser during solidification. However, neither simulation variant predicted shrinkage, even at the largest thickness of 7 mm, and the actual castings exhibited no shrinkage (see Fig. 10).

Gravity casting was confirmed to achieve a thickness of 3-4 mm. These parameters are standard for investment casting technology, confirming that realistic wall thicknesses for small castings (up to 1 kg) can be in the units of millimeters (see Fig. 11).

According to the authors' assumptions, LPIC was able to fill almost the entire space in the staircase filling test, achieving a casting wall thickness of 0.5 mm even for an alloy with difficult fluidity. This was confirmed by simulation results (see Fig. 12 and Fig. 13). For the fan-shaped test, filling was less optimal, but thicknesses between 1-2 mm were still achieved.

The results on the three cast trees represent a deviation of $\pm 3.5\%$, with the sample closest to the mean values selected for comparison (see Fig. 12). Here it can be concluded that the real castings performed better than the numerical simulations. This deviation may be due to the limited definition of the initial conditions in the simulation software (it is possible to set the filling flow and counterpressure times), while we set the controlling filling pressure on the machine and the shell filling times are derived from the tree volume and the development of the low pressure machine). [17]

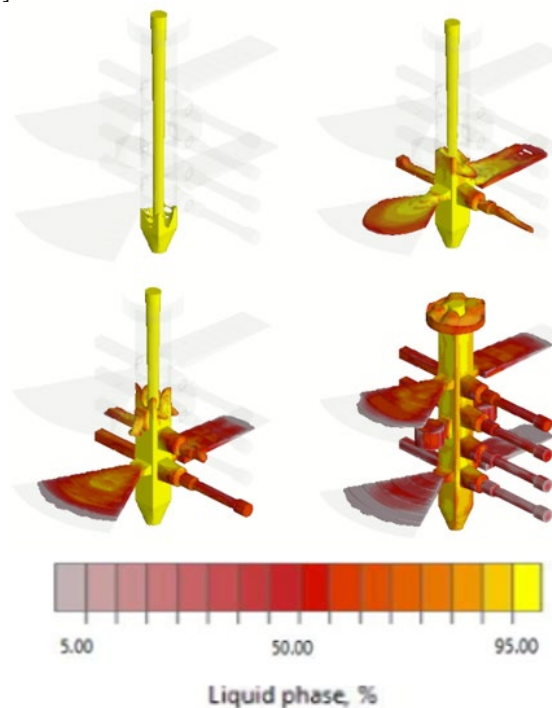


Fig. 8. Liquid Phase Percentage - Gravity Casting

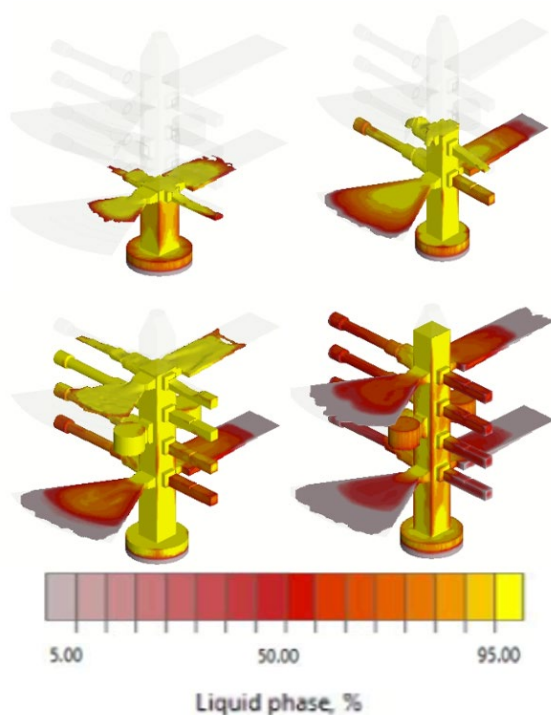


Fig. 9. Liquid Phase Percentage – LPIC

4. Discussion

Comparatively excellent results have been achieved by our team, notably including the development of a novel fluidity test (the stepped fan) [9]. While a similar stepped test for Fe alloys has been described elsewhere [9], it is designed for much larger castings, with wall thicknesses ranging from 20 to 80 mm. In contrast, our study focuses on smaller castings, typically weighing between 0.5 and 5 kg [15].

The fact is that the technology of investment casting is mainly used to cast castings from special alloys (based on Ni, Co) so the fluidity of Ni alloys was mentioned in paper written by Binczyk [18], where they tested fluidity on a spiral test cast into a standard bentonite mold (green sand mold), where the diameter of the spiral was 10 mm, which is again a significantly greater wall thickness than was dealt with in our paper.

As far as the research in the field of the fluidity of gravity investment casting technology is concerned, the only reference to fluidity research was found in paper written by Stręk [16], where the casting of aluminium foams (foam, sponge) into shell molds based on coated ethyl silicates (the same material as for shells in investment casting technology) was addressed. Here, the smallest thicknesses corresponded to a size of 1 to 2 mm, but this was a material with significantly better fluidity than steels.

No comparable publications have been found regarding low pressure die casting (LPDC) testing. It is generally reported that the runout of LPDC technology is very similar to gravity die casting technology [10], this is especially true for Al alloys. Mostly in die casting, HPDC technology [9] or modifications of HPDC

technology such as squeeze casting [12] and [14] have been addressed. All these papers dealt again with aluminium alloys.

In the foreign literature, we did not come across the finding that someone managed to achieve thicknesses below 1 mm.

In Figure 10, the LPIC technology shows small stagnations at the tip of the tree. This is due to the melt pressure. Whereas with GIC, standard gravity solidification occurs in air - so most of the stagnation occurs in the main casting sprue.

The distribution of shrinkages in the tip of the tree also corresponds to Fig. 7 - where the shape of the stagnation exactly matches the simulation. [11]

Similarly, when the casting stake was cut for the GIC technology, the defects were confirmed in the casting stake and again in position and size with a match of ca 95%. [11]

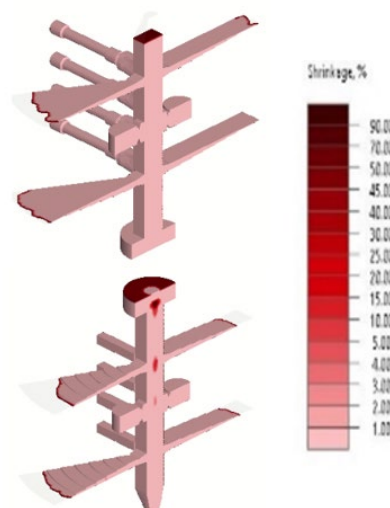


Fig. 10. Shrinkage – LPIC (Top) x Gravity casting (Bottom)

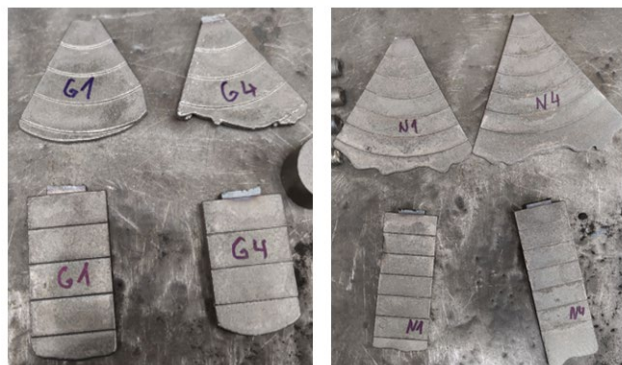


Fig. 11. Casted fluidity samples – Gravity casting (Left) x LPIC (right)

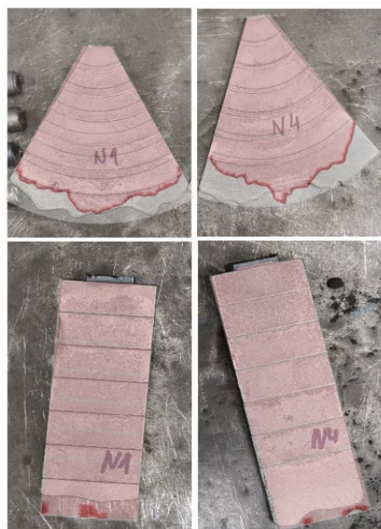


Fig. 12. Comparison of castings with simulation (LPIC)



Fig. 13. Comparison of castings with simulation (Gravity casting)

5. Conclusions

Our research demonstrates that the newly developed LPIC technology holds significant potential to revolutionize existing approaches in foundry engineering. Specifically, it challenges the notion that steel castings must have large wall thicknesses to ensure successful metal run-in and mold filling. This innovation may lead to an increase in the production of steel castings in industries such as automotive manufacturing, as the quiet filling process reduces defects commonly associated with conventional casting methods, minimizes reoxidation phenomena, and enhances the mechanical properties of the castings.

Our findings suggest that LPIC technology is capable of effectively filling castings with wall thicknesses as small as 1 mm, a significant advancement compared to gravity casting, where walls would need to be 3-4 times larger to achieve similar results. Despite the machinery and shell production requirements associated with LPIC technology, its potential to revitalize the declining production of steel castings is evident.

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References

- [1] Rahimian, M., Milenkovic, S., Maestro, L., De Azua, A.E.R. & Sabirov, I. (2015). Physical simulation of investment casting of complex shape parts. *Metallurgical and Materials Transactions A*. 46(5), 2227-2237. DOI: 10.1007/s11661-015-2815-6.
- [2] Bordas, S.P.A., Conley, J.G., Moran, B., Gray, J. & Nichols, E. (2006). A simulation-based design paradigm for complex cast components. *Engineering With Computers*. 23(1), 25-37. DOI: 10.1007/s00366-006-0030-1.
- [3] Shin, J., Kim, K., Ko, S., An, D. & Kim, M. (2013). Design and evaluation of aluminum casting alloys for thermal managing application. *Journal of Korea Foundry Society*. 33(1), 22-31. DOI: 10.7777/jkfs.2013.33.1.022.
- [4] Harding, R.A. (2006). Towards more reliable investment castings. *International Journal of Cast Metals Research*. 19(5), 289-301. DOI: 10.1179/136404606x153885.
- [5] Wang, T., Huang, J., Fu, H., Yu, K. & Yao, S. (2022). Influence of process parameters on filling and feeding capacity during high-pressure die-casting process. *Applied Sciences*. 12(9), 4757, 1-13. DOI: 10.3390/app12094757.
- [6] Kubelková, I. (2019). *Verification of injection simulation of wax moulding simulations*, Czech technical university in Prague, Prague, Czech Republic. (in Czech).
- [7] Dong, G., Li, S., Ma, S., Zhang, D., Bi, J., Wang, J., Starostenkov, M. D. & Xu, Z. (2023). Process optimization of A356 aluminum alloy wheel hub fabricated by low-pressure die casting with simulation and experimental coupling methods. *Journal of Materials Research and Technology*. 24, 3118-3132. DOI: 10.1016/j.jmrt.2023.03.214.
- [8] Kabnure, B.B., Shinde, V. D. & Patil, D.C. (2020). Quality and yield improvement of ductile iron casting by simulation technique. *Materials Today: Proceedings*. 27(1), 111-116. DOI: 10.1016/j.matpr.2019.09.022.
- [9] Saxena, S. & Sharma P. K.S. (2017). Casting Fluidity of Metals and Alloys. *International journal of innovative research in science, engineering and technology*. 6(2), 3018-3031. DOI: 10.15680/IJIRSET.2017.0602171.

- [10] Campbell, J. (1995). Review of fluidity concepts in casting. *Cast Metals*, 7(4), 227-237. DOI: 10.1080/09534962.1995.11819183.
- [11] Brůna, M., Galcik, M., Pastircak, R. & Kantorikova, E. (2024b). Effect of gating system design on the quality of aluminum alloy castings. *Metals*, 14(3), 312, 1-18. DOI: 10.3390/met14030312.
- [12] Martinec, D. & Pastirčák, R. (2023). Application of modular die for fluidity test and monitoring of the pressing force flow by semi-solid squeeze casting of ALSI7MG0.3. *Archives of Foundry Engineering*, 20(3), 69-73. DOI: 10.24425/afe.2020.133332.
- [13] Pastirčák, R., Ščury, J., Brůna, M. & Bolibruchová, D. (2017). Effect of technological parameters on the ALSI12 alloy microstructure during crystallization under pressure. *Archives of Foundry Engineering*, 17(2), 75-78. DOI: 10.1515/afe-2017-0054.
- [14] Pastirčák, R. & Martinec, D. (2020). Simulation fluidity test for semisolid squeeze casting. *MATEC Web of Conferences*, (vol. 328, p.02006). DOI: 10.1051/mateconf/202032802006.
- [15] Beeley, P.R., Smart, R.F. (1995). *Investment casting* (1st ed.). Cambridge: The University Press.
- [16] Stręć, A., Lipowska, B. & Wańczyk, K. (2023b). Selected aspects of manufacturing of aluminium sponge. *Archives of Metallurgy and Materials*, 64(3), 1145-1150. DOI: 10.24425/amm.2019.129507.
- [17] Santhi, S., Vadayar, S., & Srinivasan, S. (2023b). Estimation of mold filling ability and volume deficit characteristics of cast Al-Si alloys. *Archives of Foundry Engineering*, 19(3), 55-65. DOI: 10.24425/afe.2019.127140.
- [18] Binczyk, F., Cieśla, M., Gradoń, P., & Findziński, R. (2014). Evaluation of casting shrinkage and liquid metal fluidity of IN-713C alloy. *Archives of Foundry Engineering*, 14(1), 9-12. DOI: 10.2478/afe-2014-0002.