Arch. Metall. Mater. **68** (2023), 2, 757-763

DOI: https://doi.org/10.24425/amm.2023.142458

I. KROUPOVÁ[1*], M. BAŠISTOVÁ[1], P. LICHÝ[1], V. MERTA[1],
F. RADKOVSKÝ[1], J. JEZIERSKI[2]

TECHNOLOGY OF PRODUCTION OF MOLD FILLING MATERIAL FOR SPECIFIC PURPOSES IN THE FIELD OF METALLIC FOAM CASTING

This paper describes the technology for the production of precursors (space holder material) used to form the complex internal structure of cast metal foam. The precursor material must exhibit sufficient refractoriness, resist contact with liquid metal and at the same time should exhibit good collapsibility after casting. With regard to the greening of foundry production, the focus of this paper was on materials that could exhibit the above properties and at the same time do not have a negative impact on the environment. In this paper, the technology for the production of spherical precursors from a self-hardening mixture with a geopolymer-based binder system is described and verified. The motivation for the choice of material and all the sub-steps of the process – molding into the core box, tumbling, including the necessary accompanying tests of the mechanical properties of the core mixture being verified – are described.

Keywords: molding mixture; metallic foams; precursor; abrasion loss; 3-point bending strength

1. Introduction

The trend in the development of modern structural materials is to find a suitable combination of low specific weight and sufficient strength. These properties are achieved by a number of materials, including some foundry alloys (such as aluminum [1,2] and magnesium alloys [3]). However, in order to achieve thin-walled components that also meet the low weight requirement, the limiting factor in the foundry industry is the use of existing technological processes. Another possible way to reduce the weight of manufactured components without negatively impacting their mechanical properties is to use metallic materials with artificially created pores in the structure – metallic foams.

Nowadays, there are a number of scientific articles and literature devoted to the issue of metallic foams-from the oldest sources describing the basic procedures of their production and evaluation of their properties [4-6] to the current knowledge describing specific applications of this material [7-10]. The specific application then depends on the structure of the metal foam itself. Metallic materials with open pores are permeable and can thus be used for flow applications [11]. The mechanical properties of metal foams with open and closed cells are significantly different. The linear elastic reactions in open cell foams are due to the flexing of the cell walls. In closed-cell foams, the cell walls stretch as air or other enclosed gas is compressed within them due to pressure [12,13]. Metallic foams with open pores have excellent thermal conductivity and resistance to high temperatures. They are therefore mainly used as heat exchangers [14], non-combustible heat shields [15], high temperature filters [16], etc. Other applications are also possible in the chemical, aerospace, marine and automotive industries [17].

Metallic foams are one of the materials that have received tremendous attention in recent decades. In view of the complexity involved in the current processes (e.g. additive manufacturing, powder sintering, etc. [18,19]) for the production of the material under study, the attention of experts has been directed in recent years towards finding other, less complicated processes.

Foundry technology appears to be an ideal solution in this respect – foundry technology represents a fast and efficient transition from raw material (metal material) to product (casting). In addition, foundry technologies could be used to produce shaped cast porous parts without the need for further processing.

The production of castings in the Czech Republic is at a high level, there are traditional manufacturers and companies using

[1] VŠB-TECHNICAL UNIVERSITY OF OSTRAVA, FACULTY OF MATERIALS SCIENCE AND TECHNOLOGY, DEPARTMENT OF METALLURGICAL TECHNOLOGIES, 17. LISTOPADU 2172/15, OSTRAVA-PORUBA, CZECH REPUBLIC
[2] SILESIAN UNIVERSITY OF TECHNOLOGY, FACULTY OF MECHANICAL ENGINEERING, DEPARTMENT OF FOUNDRY ENGINEERING, 2 TOWAROWA STR., 744-100 GLIWICE, POLAND
* Corresponding author: ivana.kroupova@vsb.cz

special technologies for the production of castings from advanced materials. At the same time, however, there is no company or institution dedicated to the production of metallic foams. These facts were the main motivation for the work, the basis of which is the design of a suitable foundry process for the production of metallic foams, which could be implemented in conventional foundries. The introduction of a completely new type of material into the production portfolio of Czech companies could lead to an increase in their competitiveness not only on the domestic market.

1.1. Molding mixtures in current foundry production

Foundry methods for the production of porous metals depend on the use of so-called molding mixtures, i.e. materials from which foundry molds (or cores) are formed. These materials are absolutely crucial for foundry practice. Despite the fact that nowadays we are witnessing the development of modern and special casting production processes (in most cases involving the use of permanent metal molds), the technology of casting into disposable molds from molding compounds is still the most widely used, both in the conditions of domestic foundries and on a global scale. The use of standard materials in the production of metal foam castings is an essential step for the possibility of implementing the proposed procedures in foundry practice.

The current trend towards greening production is looking for a suitable alternative in 'green' inorganic binders. Although for many decades standard inorganic binders could not be compared with organic resins in terms of technological properties, new inorganic binder systems are currently being developed that can largely eliminate disadvantages, which include, in particular, significantly lower collapsibility and reclaimability, and lower mechanical strength values [20].

2. Experiment

The experiment described in this article is devoted to the field of production of cast metallic foams. Although the authors are primarily concerned with the development of a low-cost process for the production of this material, the issue is very complex and involves many technological steps. Therefore, the focus of the experiment is mainly on the evaluation of core mixtures with respect to their possible use for the production of precursors (space holder material). In view of the above-mentioned trends in the field of molding (or core) mixtures, a mixture based on the inorganic binder system Geopol was chosen as the precursor material. This is a system using so-called modified sodium silicate with improved properties, particularly in the area of residual strengths.

2.1. Composition and preparation of the mixture for the production of cores and precursors

Precursors and cores (test beams) were made from a Geopol core mix. The individual materials and quantities selected are shown in TABLE 1.

TABLE 1

Composition of core mixture based on Geopol binder

	Basic sand	Binder	Catalyst
	Foundry silica sand	**Based on Geopolymer**	—
Name	BG 27 (Biala Góra)	GEOPOL 618	SA 73
Supplier	Sand Team	Sand Team	Sand Team
Dosage [wt. %]	100	1.8	18 (to the binder content)
Dosage [g]	4000	50	12.96

TABLE 2

Summary of the number of samples for each test

Sample type	Total pieces	Test	Time	Pieces per test
Beams	25	3-point bending strength test + abrasion loss	After 1 h	5
			After 24 h	5
			After 240 h	5
			After 480 h	5
		Determination of collapsibility of cores after casting	After 24 h	5 (resp. 10×1/2)
Precursors	1200	Abrasion loss	For 0 s	100
			For 20 s	100
			For 40 s	100
			For 60 s	100
			For 80 s	200
			For 100 s	200
			For 120 s	200
			For 140 s	200
		Casting of metallic foam	0-140 s	approx. 100 pcs/casting

The mixture of basic sand and catalyst was mixed on a laboratory paddle mixer (Kenwood KM 636 Major Classic, Great Britain) for 1 minute for better homogenization. After this time, binder was added to the mixture and the mixtures were again mixed for 1 minute.

TABLE 2 is attached to give a better idea of the experimental procedure in the evaluation of the molding mixture on different types of samples.

2.2. Test samples

The mixture was immediately used for the production of cores (test beams) and precursors. The mixture has gained sufficient manipulation strength to remove the cores (beams and precursors) after 20 minutes from molding.

The production of specific samples proceeded as follows:

– Beams – Standardized test specimens (beams) with dimensions 22.5×22.5×170 mm (Fig. 1) were made by compacting the mixture into the core box.
– Precursors – For the fabrication of the precursors, 2 special 100-cell (10×10) core box were designed, and 3D printed (Fig. 3) to produce 100 cube-shaped precursors of 10×10×10 mm (Fig. 2).

A total of 25 beams and 1200 precursors were produced by these processes.

Fig. 1. Test beams

Fig. 2. Precursors

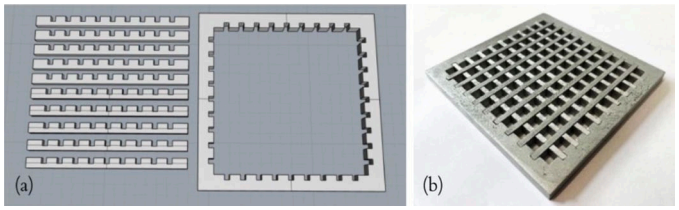

Fig. 3. Core box for precursor production – 3D design (a), 3D printed core box (b)

The samples were left in a laboratory environment at a constant temperature of 23°C and humidity of 20%. Subsequently, selected tests were performed on these samples – 3-point bending strength test, abrasion loss test and determination of collapsibility of cores after casting.

2.3. 3-point bending strength (beams)

To evaluate the properties of the core mixture (Geopol), 20 test beams were taken. These 20 samples were divided into 4 groups of 5 each. Each group was then tested under specific conditions – at given times from the curing of the mixture (1 h, 24 h, 240 h, 480 h). The possible change in strength properties after longer storage of the cores gives us an indication of the suitability of the core production technology for storage or direct consumption. The mechanical strength of cores is characterized by a measurement known as the 3-point bending strength. This measurement was carried out on a molding mixture strength measuring device (LRu-2e, Multiserw-Morek, Poland) under normal laboratory conditions. Measurements of the specimens were carried out using a load of 0.1 MPa.s^{-1}. The size of the samples 22.5×22.5×170 mm is given by the measurement method. A schematic of the measurements and the sample is shown in Fig. 4.

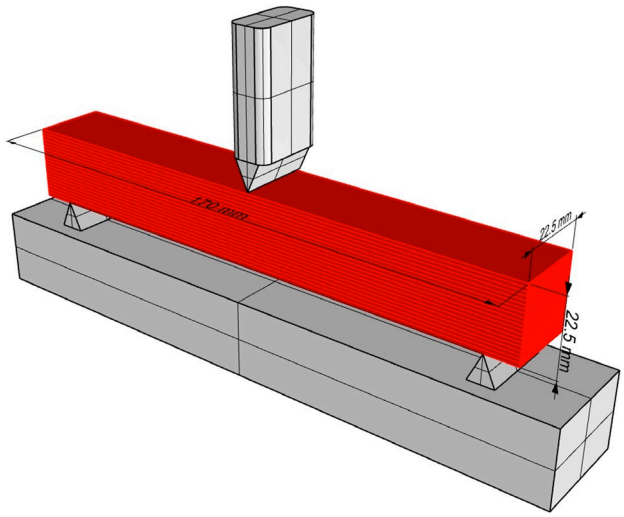

Fig. 4. 3-point bending strength test scheme

2.4. Abrasion loss (beams)

The purpose of this test was to determine the effect of the storage time of the beam (1 h, 24 h, 240 h, 480 h) on the abrasion resistance. This parameter is important with respect to the manufacture of precursors by rubbing.

The evaluation of abrasion loss was performed on the specimens after bending strength testing (i.e., the test specimens were the halves of the broken beam) using a laboratory apparatus with a perforated rotating sieve (Fig. 5). The specimens were weighed, then placed in the 180 mm diameter perforated sieve and then rubbed for 60 s at 57 rpm. After rubbing, the samples

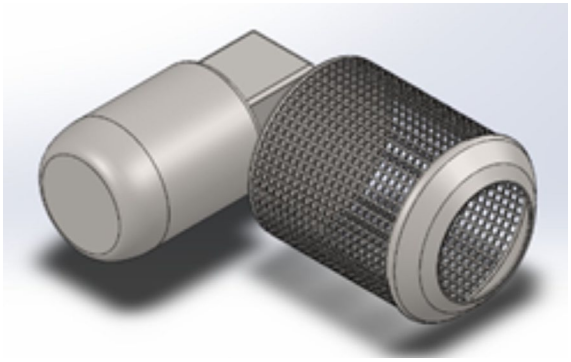

Fig. 5. Schematic of the abrasion loss test apparatus (diameter of rotary sieve –180 mm)

were weighed again. The resulting decrease in weight compared to the original weight of the measured samples gives the percentage abrasion loss values.

2.5. Abrasion loss (precursors)

In the case of precursors, these are not standardized samples. The abrasion loss test is carried out on these samples to determine the possibility of changing the shape of the precursor from an initial cube with a 10 mm edge to a shape close to the ideal spherical shape.

The 1200 precursors produced were divided into several test batches of 100 pcs per batch. These batches were weighed and sequentially placed in a laboratory apparatus with a rotary sieve designed for determination of abrasion loss. One batch was left completely without abrasion in its original state in the shape of a 10×10×10 mm cube. Each batch of precursors (100 pcs) was then rubbed in the device for a predefined period (20-140 s). The batch was then weighed again to determine the abrasion value. Rubbing the precursors for different times for each batch was designed to obtain precursors of different shapes, approximating the ideal spherical shape. Because of the assumption of decreasing precursor size, two batches (i.e., a total of 2×100 precursors) were always chosen for longer rubbing times (from 80 s).

In the literature we can encounter various precursor materials (space holder material). However, the most common are water-soluble materials [21-23] (for easy removal of the metal foam from the final casting). The experiment presented here is unique not only in the precursor production process itself, but also in the material used – a conventional core mixture.

2.6. Collapsibility of cores after casting (beams)

The determination of the collapsibility of the mixture (or of the cores) after casting is a very important indicator. If the core mixture is to be used for the production of precursors, one of the most important parameters that it should meet is good collapsibility after casting, or the possibility of their easy removal from the complex internal structure of the metallic foam.

Test castings were designed to determine this property – their design can be seen in Fig. 6. In each casting, 2 beams were established to serve as cores. After casting, these cores were removed with a special knocking-out mandrel. This was attached to a standard sand ramming machine for making standard rollers from molding compounds (see Fig. 7).

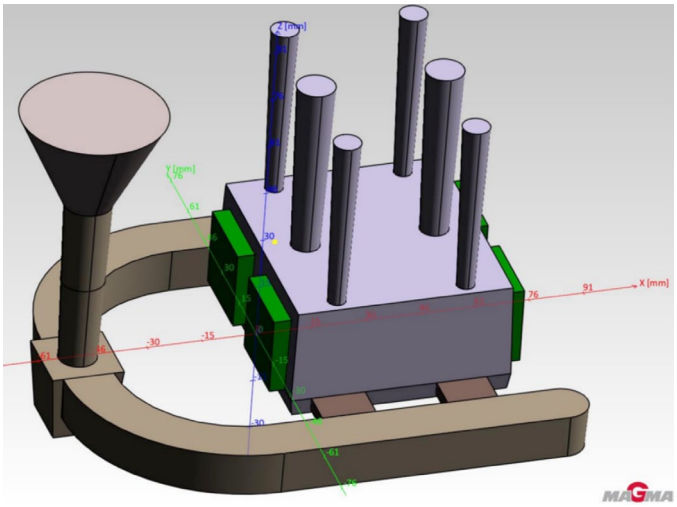

Fig. 6. 3D design of the test casting [13]

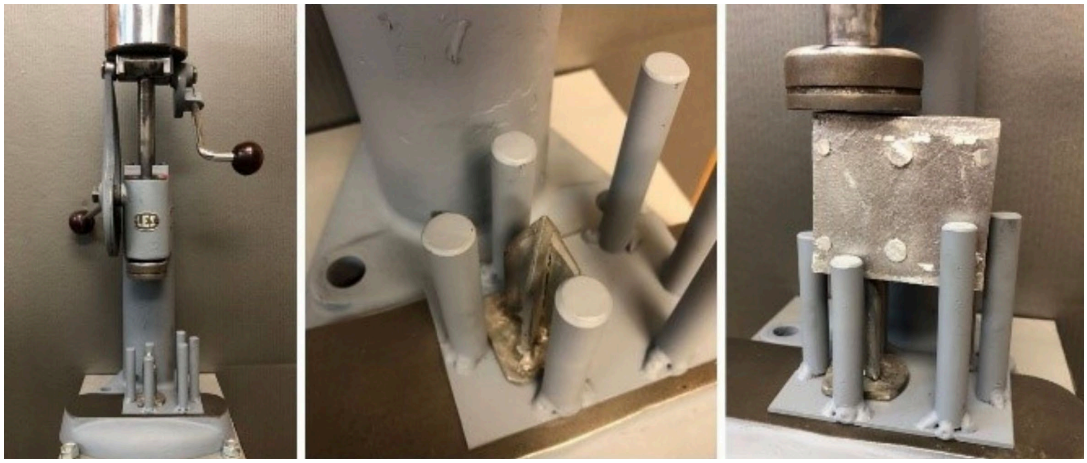

Fig. 7. Special equipment for removing the cores from the casting – determination of the collapsibility of the cores after casting

The composition of the molding mixture for the production of molds for making test castings can be seen in TABLE 1. The composition and preparation of the mixture was the same as for the precursors. After molding, the mixture was allowed to cure for 20 min at normal laboratory temperature and humidity and after this time, i.e., after gaining handling strength, the mold was disassembled, and the individual parts of the pattern were removed. The disassembled mold was cured in free air for 2 h before casting. After that time, the cores (beams) were placed in the molds.

Prefabricated test beams (2 hours after curing, same as mold) were used as cores and were shortened to a length of 70 mm for this purpose. Thus 2 cores were made from each test beam for casting.

A total of 5 molds with established beams (cores) were cast to evaluate the collapsibility of cores after casting. The aluminum alloy AlSi7Mg0.3 according to EN 1706:2020 was chosen for casting. The material was supplied in the form of pre-alloy clusters with guaranteed chemical composition by the supplier according to the standard. The used alloy was not alloyed, modified, or refined in any way. The melting of the AlSi7Mg0.3 alloy was carried out in an electric resistance furnace in a 2 l SiC crucible. The melt preheating temperature for casting was set at 740°C to ensure sufficient melt run-in and was controlled using a digital thermometer. The casting time was 4 s. The molds were disassembled, and the castings removed and prepared for further measurements 24 hours after casting.

3. Results

After performing all the above tests, the properties of the Geopol core mixture and the test samples (beams, precursors) were evaluated.

3.1. 3-point bending strength (beams)

The fabricated test cores (beams) were subjected to mechanical properties tests. Each measurement was carried out on 5 samples. The shelf life of the cores was monitored for a period of up to 480 hours after manufacture, while the beams were left in a normal laboratory environment of constant temperature of 23°C and humidity of 20%. The suitability of the cores for storage was evaluated as the change in 3-point bending strength as a function of storage time and external conditions.

A graphical representation of the evolution of beam strength as a function of storage time can be seen in Fig. 8.

The measured results show a significant increase in bending strength of 87.9% within the first 24 hours. Between 24 and 240 hours, the strength increases only gradually, i.e. by 10,1%, and then decreases gradually, by a total of 1,1%, with further storage time up to 480 hours.

The increase in bending strength during the first 24 hours after curing was consistent with the results of other authors evaluating this mixture [24-26].

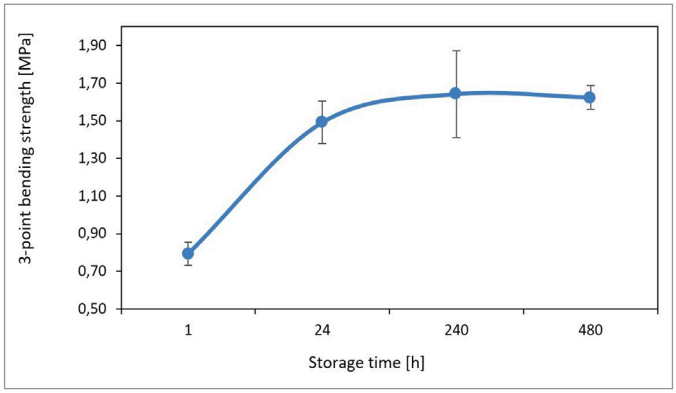

Fig. 8. The evolution of beam strength as a function of storage time

3.2. Abrasion loss (beams)

The abrasion loss increases significantly with increasing storage time, by 24,4% in the first 24 hours, and then by only 1,9% over 240 hours. Thereafter, there is a significant decrease in abrasion of 17,4%. Average abrasion as a function of storage time can be seen in Fig. 9.

In general, mixtures with Geopol, and in general mixtures bonded with alkaline silicates, can be considered unsuitable for storage due to their embrittlement in contact with air humidity and the surrounding atmosphere. They are mainly recommended for immediate use, i.e. for casting within a few hours after molding. This can also be confirmed by measuring the abrasion loss, which shows an increase in abrasion with increasing storage time. This is due to the embrittlement of the bonding bridges, especially on the surface of the test bodies, which is most in contact with the surrounding environment.

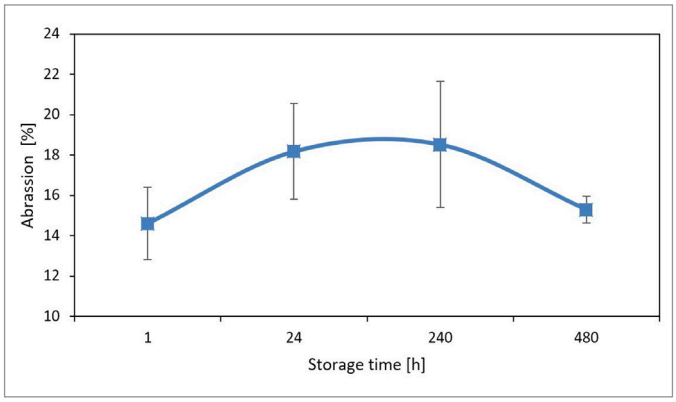

Fig. 9. Average abrasion as a function of storage time – beams

3.3. Abrasion loss (precursors)

Individual sets of precursors, 100 each, were wiped in a specialized apparatus for a predefined period. For the average measured values, it can be observed how much material is removed from the precursors as the abrasion time increases. In the case of an abrasion time of 140 s, this is more than half

of the precursor mass, as shown in Fig. 10. The standard deviation for the abrassive test did not exceed 5% for any of the samples.

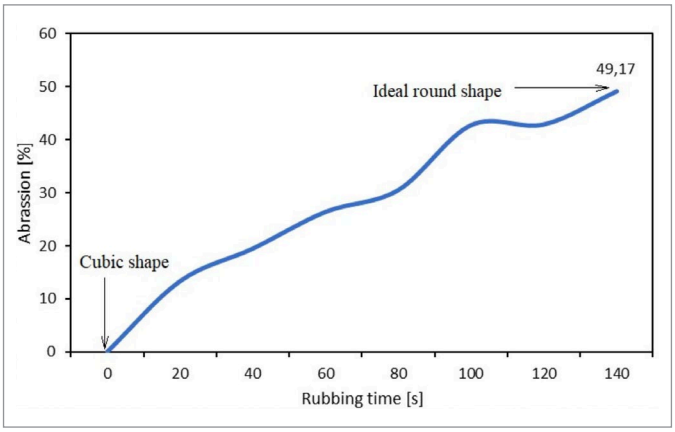

Fig. 10. Increase in abrasion loss with increasing rubbing time – precursors

The shape of the precursor changed in parallel with increasing abrasion time. However, there was no loss of material in the entire volume at the same time, i.e. all surfaces were abraded, but only a gradual rounding of the edges and corners of the precursor and thus a gradual change from a cubic to a spherical shape. The gradual evolution of the change in shape from the original cubic shape can be seen in Fig. 11. The precursor after 140 s of abrasion is already close to a nearly perfect spherical shape, which is the most favorable for us in terms of the resulting porous structure of the cast metallic foam.

3.4. Collapsibility of cores after casting (beams)

The collapsibility of the mixture (or of the beams) was evaluated 24 hours after casting. For the actual discharge of the cores by means of a special jig, the so-called knocking-out mandrel, placed in the laboratory sand ramming machine, it was necessary to apply 19-20 knocks of the rammer, i.e., to exert a knock-out work of 62,7-66 J. Thus, the deteriorated collapsibility of the mixture after thermal exposure was observed, which is typical for mixtures based on alkaline silicates. During the discharge process, the nuclei were not completely removed, residues still remained, especially in inaccessible corners (see Fig. 12).

4. Conclusion

In the present experiment, it has been demonstrated that the proposed precursor fabrication procedure can provide precursors close to the ideal spherical shape. By molding a self-hardening mixture with a geopolymer-based binder system, it is possible to use it for the production of precursors. The strength of the mixture increases slightly with increasing storage time, but the loss by abrasion tends to increase, suggesting a priori assumptions about the unsuitability of the storage of this mixture. In general, mixtures with Geopol, and alkaline silicate-bound mixtures, can be considered unsuitable for storage because of their embrittlement on contact with air moisture and the surrounding atmosphere. They are mainly recommended for immediate use, i.e. for casting within a few hours after molding. This can also be confirmed by measuring the abrasion loss, which shows an

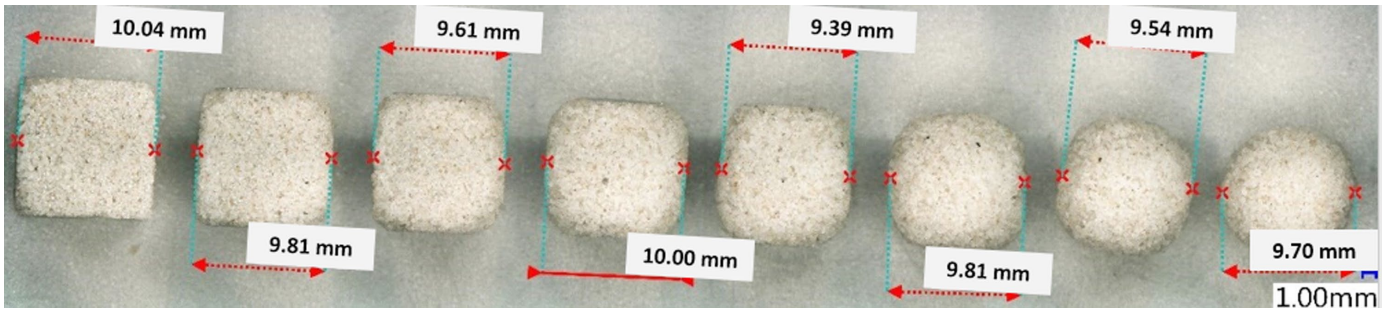

Fig. 11. Development of precursor shape change with increasing abrasion time, from the left: 0 s, 20 s, 40 s, 60 s, 80 s, 100 s, 120 s, 140 s

Fig. 12. Test casting after core discharge

increase in abrasion with increasing storage time. This is due to the embrittlement of the bonding bridges, especially on the surface of the test samples which is most in contact with the surrounding environment. In contrast, storage does not have such a significant effect on the flexural strength of the Geopol mixture. After an initial curing period of 24 hours, there is no further significant increase in strength.

A certain problem was noted only in the evaluation of the collapsibility of the mixture after casting. The collapsibility of this material is poor and thus poses the risk of not being able to completely remove the precursors from the complex internal structure of the metallic foam.

For this reason, further experiments will focus on the possibility of increasing the collapsibility of the cores after casting, e.g. by further modification of the mixture composition.

Acknowledgement

This research was funded by the project No. CZ.02.1.01/0.0/0.0/17_049/0008399 (Development of intersector cooperation of RMSTC with the application sphere in the field of advanced research and innovations of classical metal materials and technologies using modelling methods). The contribution was worked out with the support of the Technology Agency of the Czech Republic – TH02020668. Work was carried out in the support of projects of "Student Grant Competition" numbers SP2022/15, SP2022/68 and SP2022/83.

REFERENCES

[1] B. Stojanovic, M. Bukvic, I. Epler. Application of aluminum and aluminum alloys in engineering, Applied Engineering Letters **3**, 52-62 (2018). DOI: https://doi.org/0.18485/aeletters.2018.3.2.2

[2] M. Brůna, A. Remišová, A. Sládek, Effect of filter thickness on reoxidation and mechanical properties of aluminium alloy AlSi7Mg0.3, Arch. Metall. Mater. **64** (3), 1100-1106 (2019). DOI: https://doi.org/10.24425/amm.2019.129500

[3] J.P. Weiler. A review of magnesium die-castings for closure applications, J. Magnes. Alloy. **7**, 297-304 (2019). DOI: https://doi.org/10.1016/j.jma.2019.02.005

[4] J. Banhart, Light-Metal Foams—History of Innovation and Technological Challenges, Adv. Eng. Mater. **15**, 82-111 (2013). DODOI: https://doi.org/10.1002/adem.201200217

[5] L.J. Gibson, M.F. Ashb, Cellular Solids – Structures and Properties, Cambridge University Press, Cambridge, United Kingdom (1997).

[6] J. Banhart, Manufacturing Routes for Metallic Foams, JOM. **52** (12), 22-27 (2000).

[7] M. Salehi, S.M.H. Mirbagheri, A. Jafari Ramiani, Efficient energy absorption of functionally-graded metallic foam-filled tubes under impact loading, Trans. Nonferrous Met. Soc. China, 31, 92-110 (2021). DOI: https://doi.org/10.1016/S1003-6326(20)65480-2

[8] J. García-Peláez, J.M. Rego-Junco, L. Sánchez-Ricart, Reduction of Underwater Noise Radiated by Ships: Design of Metallic Foams for Diesel Tanks, IEEE J. Ocean. Eng. **43**, 444-456 (2017). DOI: https://doi.org/10.1109/JOE.2017.2700085

[9] S.S. Sharma, S. Yadav, A. Joshi, R. Khatri, Application of metallic foam in vehicle structure: A review, Materials Today: Proceedings **60** (7) (2022). DOI: https://doi.org/10.1016/j.matpr.2022.03.201

[10] H. Zhang, Z. Zou, L. Qi, H. Liu, Investigation of metallic foam in the application of turbine cooling, Procedia Engineering **27**, 752-761 (2012). DOI: https://doi.org/10.1016/j.proeng.2011.12.516

[11] L.P. Lefebvre, J. Banhart, D. Dunand, Porous Metals and Metallic Foams: Current Status and Recent Developments, Adv. Eng. Mater. **10** (9), 775-787 (2008).

[12] S. Amjad, PhD thesis, Thermal Conductivity and Noise Attenuation in Aluminium Foams. University of Cambridge Cambridge, England (2001).

[13] D.M. Elzey, H.N.G. Wadley, The limits of solid state foaming, Acta Mater. **46**, 849-859 (2001).

[14] P.T. Sardari, D. Giddings, D. Grant, D. Gillot, G.S. Walker, Discharge of a composite metal foam/phase change material to air heat exchanger for domestic thermal storage unit, Renew. Energy **148**, 987-1001 (2020). DOI: https://doi.org/10.1016/j.renene.2019.10.084

[15] C. Körner, F. Singer, Processing of Metal Foams – Challenges and Opportunities, Adv. Eng. Mater. **2**, 159-165 (2000). DOI: https://doi.org/10.1002/(SICI)1527-2648(200004)2

[16] S. Baek, J. Cho, K. Kim, S. Ahn, Ch.-L. Myung, S. Park, Effect of the Metal-Foam Gasoline Particulate Filter (GPF) on the Vehicle Performance in a Turbocharged Gasoline Direct Injection Vehicle over FTP-75, Int. J. Automot. Technol. **21**, 1139-1147 (2020). DOI: https://doi.org/10.1007/s12239-020-0108-6

[17] M.G. Pinca, Ch. Ayapana, J. Tan, Metallic foams [online]. URL: http://www.scribd.com/doc/79425905/metal-foam, accessed: 20.05.2022.

[18] S.-O. Agbedor, D. Yang, J. Chen, L. Wang, H. Wu, Low-Temperature Reactive Sintered Porous Mg-Al-Zn Alloy Foams, Metals **12** (4), 692 (2022). DOI: https://doi.org/10.3390/met12040692

[19] A. Cañadilla, A. Romero, G.P. Rodríguez, Sustainable Production of Powder Metallurgy Aluminum Foams Sintered by Concentrated Solar Energy, Metals **11** (10), 1544 (2021). DOI: https://doi.org/10.3390/met11101544

[20] V. Merta, J. Beňo, T. Obzina, F. Radkovský, I. Kroupová, P. Lichý, M. Folta, K. Janovská, I. Nguyenová, M. Dostál. Innovative Inorganic Binder Systems for the Production of Cores for Non-Ferrous Metal Alloys Reflecting the Product Quality Requirements, Metals **11** (5), 733 (2021). DOI: https://doi.org/10.3390/met11050733

[21] L. Dahil, A. Karabulut, S. Baspinar, Damping properties of open pore aluminum foams produced by vacuum casting and NaCl dissolution process, Metalurgija **52**, 489-492 (2013).

[22] Y. Hangai, K. Zushida, H. Fujii, R. Ueji, O. Kuwaruzu, N. Yoshikawa, Friction powder compaction process for fabricating open-celled Cu foam by sintering-dissolution process route using NaCl space holder, Mater. Sci. Eng. A-Struct. Mater. Prop. Microstruct. Process. **585**, 468-474 (2013). DOI: https://doi.org/10.1016/j.msea.2013.08.004

[23] N. Jha, D.P. Mondal, J.D. Majumdar, A. Badkul, A.K. Jha, A.K. Khare, Highly porous open cell Ti-foam using NaCl as temporary space holder through powder metallurgy route, Mater. Des. **47**, 810-819 (2013). DOI: https://doi.org/10.1016/j.matdes.2013.01.005

[24] M. Vykoukal, A. Burian, M. Přerovská, GEOPOL®. The Innovated Environment Friendly Inorganic Binder System, Arch. Foundry Eng. **19** (1), 109-116 (2019). DOI: https://doi.org/10.24425/afe.2019.127103

[25] M. Holtzer, D. Drożyński, A. Bobrowski, W. Plaza, Influence of Binding Rates on Strength Properties of Moulding Sands with the GEOPOL Binder, Arch. Foundry Eng. **14** (1), 37-40 (2014). DOI: https://doi.org/0.2478/afe-2014-0009

[26] D. Drożyński, A. Bobrowski, M. Holtzer, Influence of the Reclaim Addition on Properties of Moulding Sands with the Geopol Binder, Arch. Foundry Eng. **15** (1), 138-142 (2015).