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ANALYSIS OF THE MECHANICAL PROPERTIES OF THE TITANIUM LAYER OBTAINED BY THE MOLD CAVITY PREPARATION METHOD

The article presents the technology of layered casting with the use of 3D printing to make a frame insert. The insert was made of powdered titanium and then filled with liquid cast iron. The paper presents the results of research, including structure observation and hardness measurements, as well as abrasion resistance tests. The results indicate the possibility of creating a local reinforcement using a frame insert. The resulting casting is characterized by a local increase in hardness and, in addition, an increase in abrasion resistance of the entire surface layer. The quality of the obtained connection depends strongly on the casting parameters.

Keywords: Modular insert, Titanium layer, Cast iron, SLM

1. Introduction

In the last decades, there has been an intensive development of the science of the surface layer of metal alloys and technologies allowing to shape the microstructure and functional properties of this layer [1-3]. By using the surface layer modification techniques, the performance of construction materials can be significantly improved and their application possibilities extended [4,5]. There is a great variety of methods of obtaining the surface layer of metals [6,7].

In this paper, an attempt was made to enrich the known casting technology of surface layer production with a new technology of production of reinforcing inserts. The casting technology for the production of layers is gaining in importance, especially when the criterion of performance only concerns the working surface, while the rest of the casting is only the basic part, which is not exposed to direct influence of factors causing e.g. abrasion. This technology is the most economical way to enrich the surface of castings, as it allows for the production of layered elements directly in the casting process [8,9]. Therefore, this technology can be significantly competitive compared to commonly used technologies for improving the properties of external surfaces. This technology also does not create the possibility of developing cracks in the heat affected zone, which may arise from the layer being made by welding [10].

The method of casting production of surface layers on castings consists in preparing the mold by applying a layer to its appropriate cavity (wall) and then pouring liquid metal. This layer is formed by the interaction of liquid metal poured into the mold with the coating (monolithic, granular or frame insert), under thermo-physical conditions existing in the mold. The process of surface layer formation depends on many physical and chemical factors. The obtained properties depend mainly on the cooling conditions and on the reaction on the metal/insert surface, i.e. on the type of effect of the insert material on the casting's surface layer, in the conditions of pouring and cooling of the casting [8,10,11].

Within the scope of the research, an attempt was made to combine the traditional method of casting production (gravitational pouring of liquid metal into the mold) and quite innovative 3D printing method (to produce reinforcement) to produce material with increased local properties.

Fast prototyping, i.e. 3D printing, is a term that has been around for many years. It was used to describe a group of technologies that literally made prototypes, doing so in a fast and automated manner. Additive Manufacturing (AM) is the latest innovation in manufacturing technology [12]. Selective Laser Melting (SLM) is an additive manufacturing method that uses a laser in an inert atmosphere to selectively melt layers of loose metallic powder into a solid, building a piece layer by layer from

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bottom to top [14,15]. Selective laser and electron beam melting usually uses the entire melting mechanism, which completely dissolves all metal powder particles and generates a compact, stable solid [12]. This type of complete melting is very useful for the production of well-bonded structures of high density from technical metals [15]. Selective laser melting, as a process of production of layer additives, is used in various industrial sectors, such as automobile racing, automotive, aviation, space sciences, medical equipment etc. Titanium and its alloys are considered to be excellent implant materials, due to their associated biocompatibility and high strength-to-weight ratio [16,17]. 3D printing is not only the medical industry, but also the automotive and aviation industries.

In order to meet the demand of the industry and the availability of innovative methods of material production, an attempt was made to combine new and traditional methods of producing surface layers. The aim of the conducted research was to produce a cast iron casting with a titanium surface layer, formed as a result of contact of a liquid metal with a titanium frame insert printed using the SLM method. This paper attempts to describe selected properties (including hardness and abrasion resistance) of the titanium layer obtained by the casting method in a cast iron casting.

2. Materials and methods

The research included the production of layered castings consisting of two basic parts, i.e. the base part (casting) and the working part (layer). The basic (base) part of a layered casting is a typical casting metal (i.e. gray pearlitic cast iron with scale graphite – carbon content of approx. 3%), while the working part is a flooded frame reinforcement (insert) forming a titanium layer. The spatial insert was made using the 3D printing method in the Selective Laser Melting (SLM) process. The insert was printed from pure titanium powder with a granulation of up to 50 mm (regular spherical particles) in compliance. The shape of the inserts is a 50×15×15 mm cuboid. The insert is made of rods with a circular cross-section and a diameter of 1.5 mm. These rods are arranged vertically and horizontally and joined together at their intersection. Solid bars (Fig. 1b) and hollow bars with an internal diameter of 1 mm (Fig. 1a) were included in the tests.

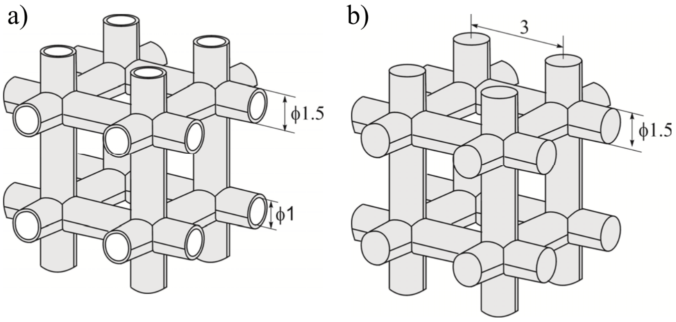

Fig. 1. View of the 3D printed spatial insert with dimensions

These inserts were placed in the mold cavity without preheating (as in Fig. 2). The form is made of a mixture of sand and bentonite. Then the mold with inserts was filled with pearlitic gray cast iron. The pouring temperature was 1400°C.

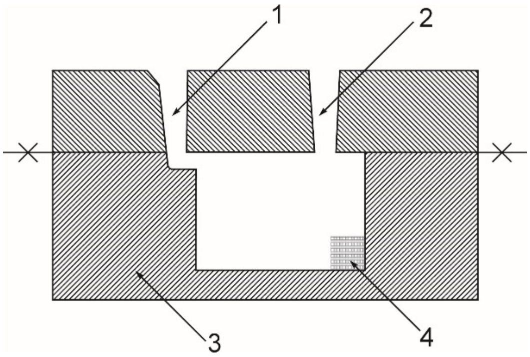

Fig. 2. Mold technology diagram for layered castings: 1 – gating system, 2 – overflow, 3 – molding sand, 4 – titanium insert

The chemical composition of the gray cast iron used was determined with the LECO GDS500A emission spectrometer and LECO CS-125 analyzer (Table 1).

TABLE 1

Chemical composition of the base of gray cast iron of the layered casting

C	Mn	Si	Cr	Ni	Cu	Ti	V	P	S	Fe
Elements content (wt%)										
3.20	0.60	2.10	0.25	0.05	0.20	0.01	0.01	0.11	0.08	Rest

Then, metallographic macro- and microscopic examinations were performed. NIKON light microscope (LOM) and Phenom ProX scanning electron microscope (SEM) with the chemical composition energy dispersive X-ray analysis (EDS) were used. Metallographic samples were etched in Mi1Fe reagent containing 3 cm^3 of nitric acid and 100 cm^3 of ethanol.

Microhardness measurements were taken with the FM 700 Future-Tech (HV0.01). In addition, abrasion resistance tests were carried out with the use of a device generating reciprocating movement of the sample on the surface of the counter-sample. In this method, after the initial placing of the samples, they were subjected to a cyclic test involving 2500 repetitions, which was about 500 m. The counter-sample was SiC (P50 grit abrasive paper) replaced by a new one every 500 repetitions. The results of abrasion wear resistance tests for layered castings were compared with the results obtained for other metal materials, i.e. gray pearlitic cast iron with scale graphite class EN-GJL-HB215, high chromium cast iron EN-GJN-HV600 (XCr18) [18] and high silicon cast iron ZlSi21 [19].

3. Research results and discussion

In the first stage of the study, it was found that the inserts were completely filled with liquid cast iron and there was a good bonding between the two parts of the layered casting for both types of inserts used. This is due to the fact, that the ratio between the base thickness of gray cast iron and the insert of Ti was 3:1, as stated in the literature [10], which allows to overcome the effect of insert cooling on liquid metal. In addition, as shown in Figure 3, the spatial frame insert material was partially dissolved in cast iron. Probably the dissolution of the insert depends on the parameters of the casting process, mainly on the pouring temperature of gray cast iron. Therefore, the thickness of the resulting layer reinforcement is irregular.

Fig. 3. Casting section with a titanium layer

Figures 4 and 5 show the microstructure of the casting reinforcement layer. As a result of the contact of the insert placed in the cavity of the sand mold with a liquid cast iron, the release of titanium carbides in the microstructure of the reinforcement can be observed (Fig. 3). As a result of high-temperature diffusion processes, carbon atoms are deposited on the octahedral gaps in the titanium atoms, forming carbide precipitates (similarly as [21-23]). The concentration of carbides decreases as the distance from the insert increases according to the literature [24]. In ad-

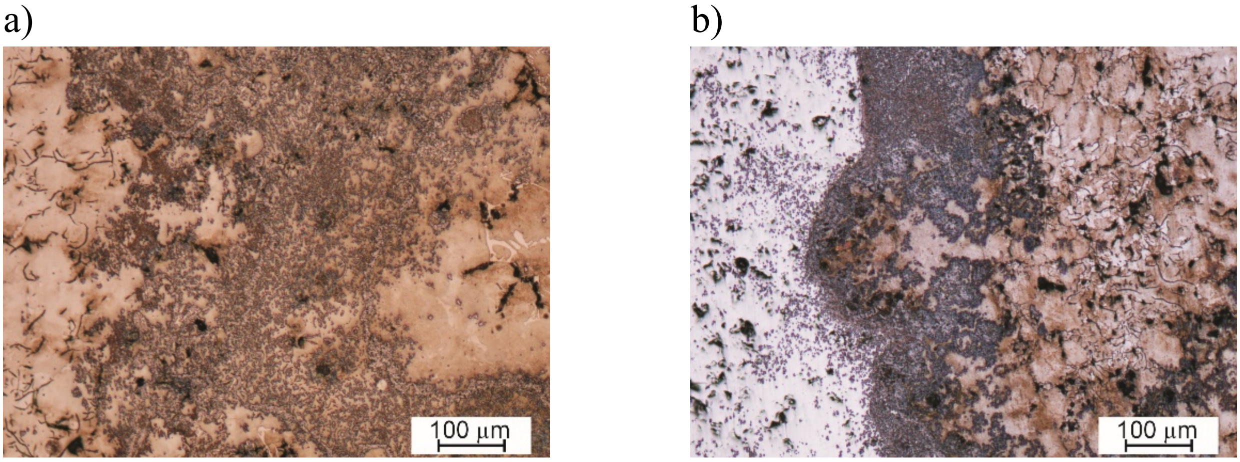

Fig. 4. Microstructure of the casting area reinforced with a spatial frame insert, zoom of 100×; a) hollow insert; b) full insert

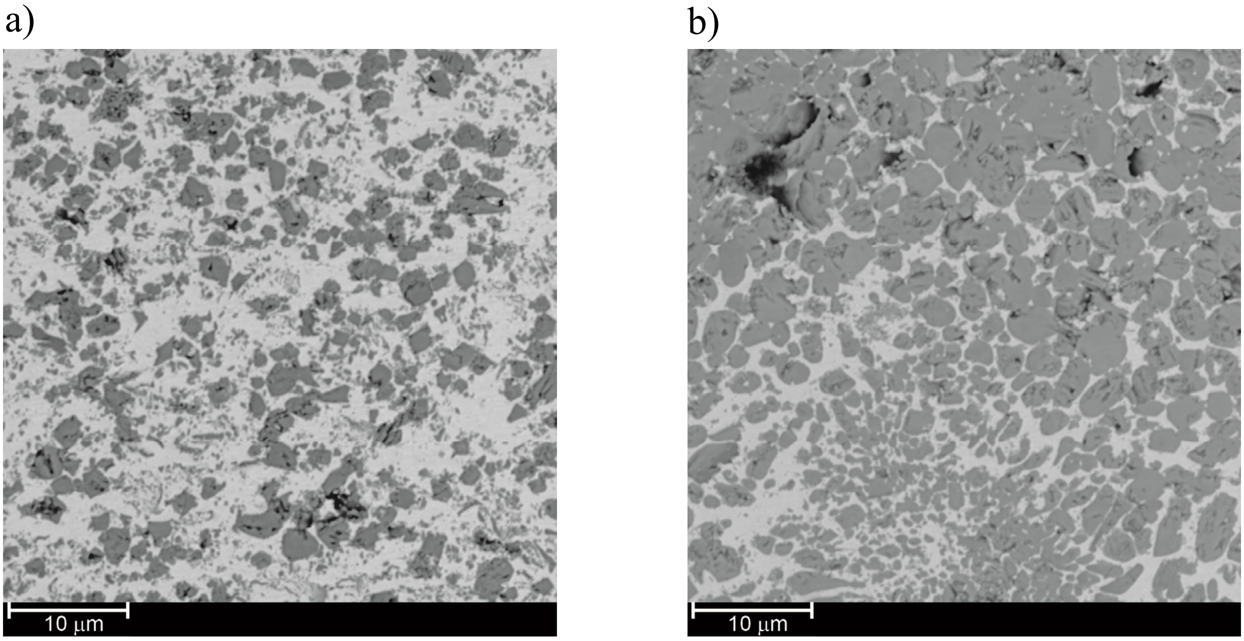

Fig. 5. View of titanium carbides in the formed microstructure of the working surface of a layered casting reinforced with a titanium frame insert, a) hollow insert, b) full insert

dition, the carbides show a variety of shapes and sizes (from 2 to 7 mm). The obtained carbides are very closely related to the gray cast iron matrix. Examples of titanium carbide placed in local casting reinforcement are shown in Figures 4 and 5.

Due to the limitations resulting from the EDS analysis [25], when determining in particular C, it is difficult to determine on the basis of the results obtained the type of carbides. However, based on the results of research by other authors [20,22] and based on the ratio of the content of individual elements obtained moreover, on the basis of EDS analysis (Table 2), carried out in selected points shown in Figure 6a, it can be concluded that non-stoichiometric TiCx carbides were formed in the microstructure of the reinforced surface layer. The resulting carbide-type release have the character of complex phases resulting from the distribution of elements, which is indicated by black areas in carbides (Fig. 6, 7).

The obtained metallographic test results also confirm that each reinforced layer is divided into two areas, i.e. the inner one with a small amount of titanium carbides and the outer one with a large amount of titanium carbides (Fig. 4, 5, 7). The inner area was created in the hollow space inside the rod (hollow insert), while the outer layer was created by the reaction between the liquid cast iron and the rod wall. Therefore, it can be considered that the reinforcing surface of the tested layer has the form of a composite in situ. On the other hand, in the

TABLE 2

Results of EDS analysis at measurement points in Figure 6a

No. of point	Element	at. %	at. % error	wt. %	wt. % error
1	C	55.1	± 0.6	23.4	± 0.2
	Ti	42.5	± 0.4	71.8	± 0.7
	Fe	2.4	± 0.2	4.8	± 0.5
2	C	39.9	± 0.8	13.4	± 0.3
	Ti	22.1	± 0.2	29.5	± 0.3
	Fe	35.5	± 0.7	55.1	± 1.1
	Si	2.5	± 0.1	2.0	± 0.1
3	C	15.5	± 0.9	3.9	± 0.2
	Fe	80.1	± 0.8	93.5	± 0.9
	Si	4.4	± 0.1	2.6	± 0.1

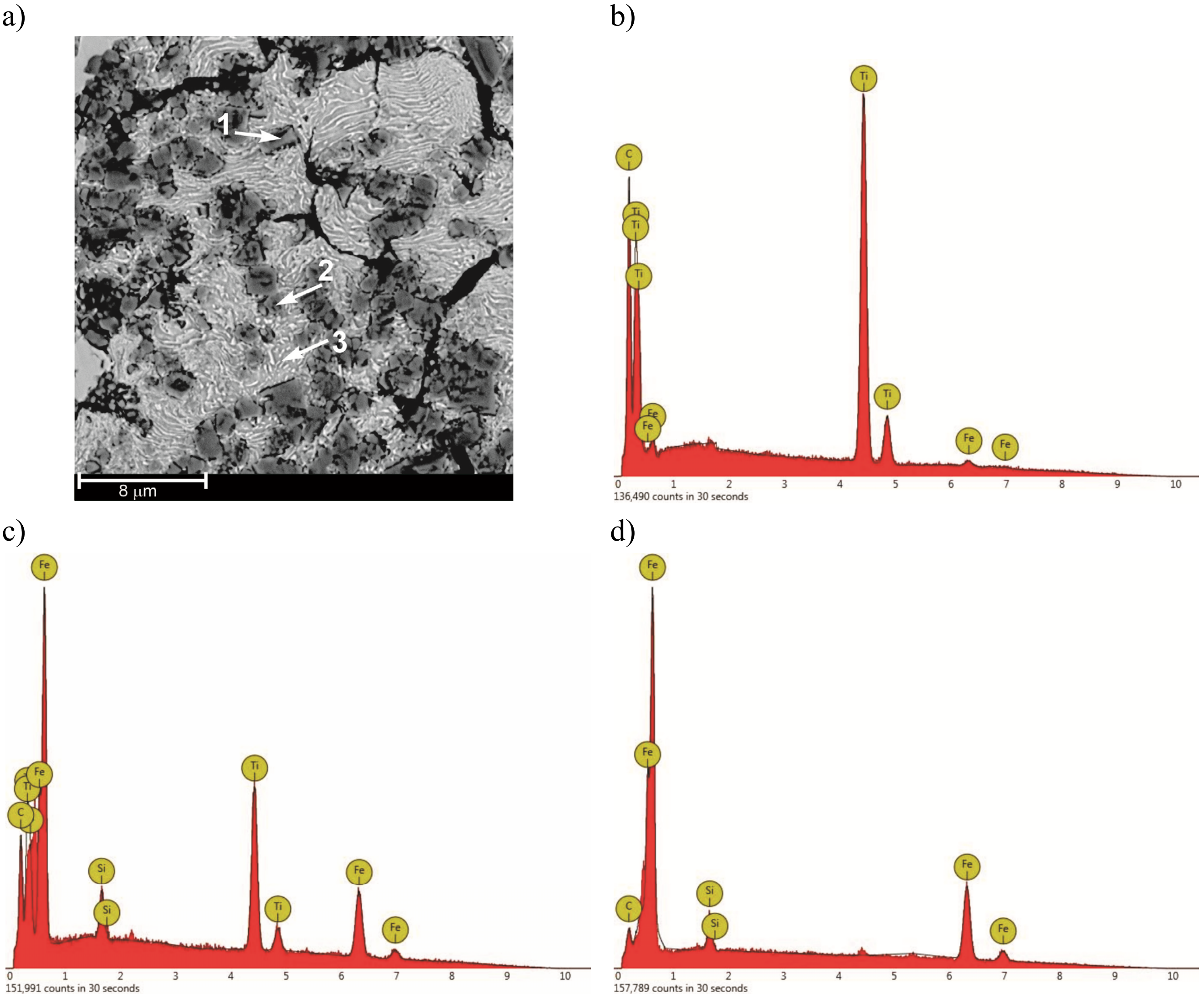

Fig. 6. Non-stoichiometric TiC carbides in the microstructure of a layered casting working surface: a) mag. ×9700, SEM b) EDS X-ray spectrum of point 1, c) EDS X-ray spectrum of point 2, d) EDS X-ray spectrum of point 3

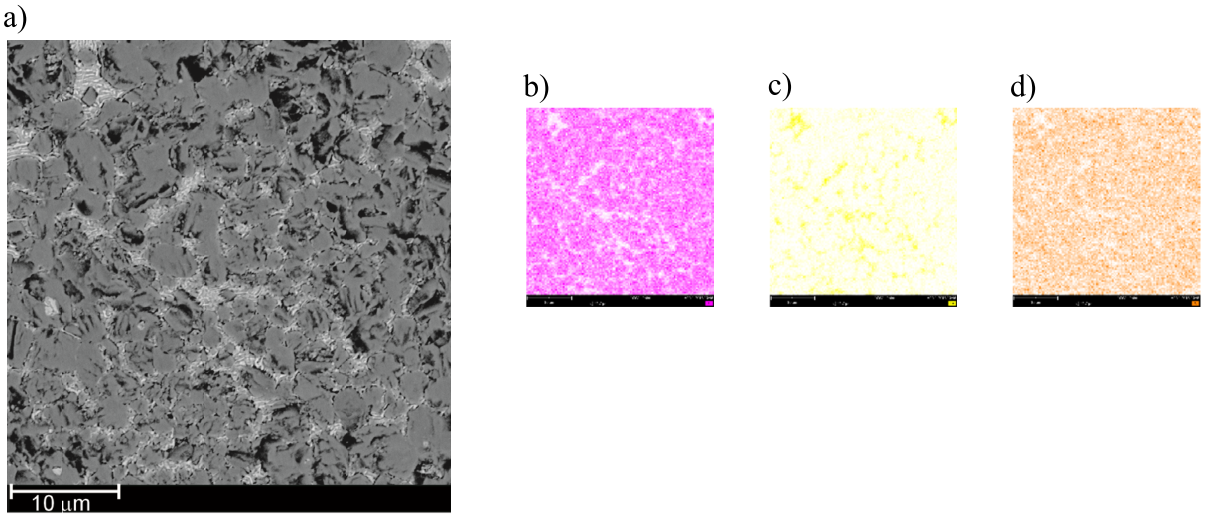

Fig. 7. Titanium layer microstructure (a) with EDS chemical analysis, maps for: b) Ti; c) Fe; d) C

case of a casting with an applied full insert, the internal area mostly consists of the original insert material (sintered titanium powder), together with a few primary titanium carbides. In both cases additionally observed of bonding zone according to the mechanism of heat and mass transport is described also in detail in paper [26].

The obtained results of the functional properties test show that the hardness of the reinforced casting layer varies and depends on the degree of density of titanium carbides similarly as literature indicates [8,24]. Therefore, the inner area with fewer carbides has a hardness of approx. 700 µHV, while the outer area with a high carbide content has a hardness of approx. 900 µHV. The local increase in hardness obtained increases the abrasion resistance of the entire surface layer of the casting (Table 3).

The wear resistance of the layered casting under test is higher than that of chromium cast iron [18] and comparable with silicon cast iron (ZlSi21) [19] – Fig. 8. However, a significant increase in abrasion resistance was observed in relation to the geometry of the applied titanium insert. The insert used, i.e. the “full” insert, characterizes the reinforced layer with higher resistance to abrasive wear.

TABLE 3

Losses of the materials under the load 10 kg/10 cm²

	Test number	Loss of mass, g
Hollow insert	1	0.128
	2	0.116
	3	0.108
	4	0.115
	5	0.118
	Average:	0.117
Full insert	1	0.125
	2	0.083
	3	0.083
	4	0.083
	5	0.095
	Average:	0.094

4. Conclusions

On the basis of the research, the following conclusions were drawn:

1. It is possible to reinforce the surface layer of a gray cast iron casting by means of a spatial Ti frame insert, obtained by

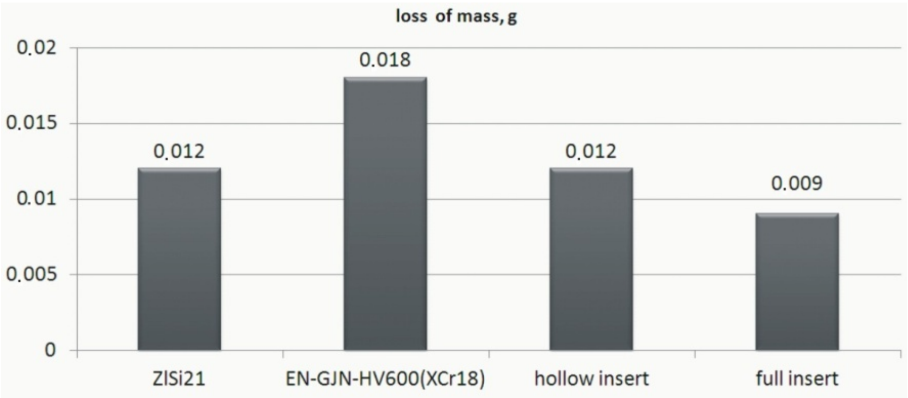

Fig. 8. Comparison of the average loss of mass in abrasion resistance tests using a device that generates reciprocal movement of the sample on the surface of the counter-sample (The results of the abrasion resistance test under the load 1 kg/1 cm²)

means of 3D printing, as part of the mold cavity preparation method; however, the quality of the obtained layer casting strongly depends on the casting parameters.

2. The working layer obtained by means of the tested technology does not guarantee equal section thickness and distribution of reinforcing titanium carbides on the casting surface.
3. The reaction between the Ti insert and liquid cast iron results in titanium carbides. Their presence in the microstructure of the working surface layer guarantees increased hardness and abrasion resistance of the casting.

REFERENCES

[1] Z. Górny, Solidification of Metals and Alloys **11**, 135-164 (1987).

[2] X. Zhi, Y. Han, J. Liu, M. Zhao, S. Ma, Int. J. Mater. Res. **105** (10), 953-960 (2014).

[3] M. Ingaldi, A. Czajkowska, 2nd International Conference on the Sustainable Energy and Environmental Development, IOP Conf. Series: Earth and Environmental Science **214**, 1-8 012003 (2019). DOI:10.1088/1755-1315/214/1/012003

[4] S. Žic, I. Džambas, M. Konić, Metalurgija **48** (1), 51-54 (2009).

[5] R. Zhou, Y. Jiang, D. Lu, Wear **255**, 134-138 (2003). DOI.org/10.1016/S0043-1648(03)00290-4.

[6] B.A. Moreira, R.O. Sousa, P. Lacerda, L.M.M. Ribeiro, A.M.P. Pinto, M.F. Vieira, Materials, **13**, 209, 1-14 (2020). DOI:10.3390/ma13010209.

[7] E. Olejnik, Ł. Szymański, P. Kurtyka, T. Tokarski, B. Grabowska, P. Czapla, Arch. Foundry Eng. **16** (2), 89-94 (2016). https://doi.org/10.1515/afe-2016-0032.

[8] A. Dulska, 12th International Conference Quality Production Improvement – QPI 2018, Zaborze near Myszków, Poland, June 18-20, 2018 . MATEC Web of Conferences. MATEC Web of Conferences **183**, 02005, 1-6 (2018). DOI: https://doi.org/10.1051/matecconf/201818302005 .

[9] N. Przyszlak, A. Dulska, T. Wróbel, J. Szajnar, Archives of Foundry Engineering **18** (1), 99-102 (2018). DOI: 10.24425/118819.

[10] T. Wróbel, J. Mater. Eng. Perform. **23** (5), 1711-1717 (2014). https://doi.org/10.1007/s11665-014-0953-4.

[11] R. Dojka, J. Jezierski, N.S. Tiedje, J. Mater. Eng. Perform. **28**, 7, 3922-3928 (2019). DOI 10.1007/s11665-019-03973-9.

[12] S. Negi, S. Dhiman, R.K. Sharma, Rapid Prototyping J. **20** (3), 256-267 (2014).

[13] P. Nuckowski, P. Snopiński, T. Wróbel, Materials **13**, 3, 576, 1-14 (2020). DOI:10.3390/ma13030576.

[14] A.B. Spierings, N. Herres, G. Levy, Rapid Prototyping J. **17** (3), 195-202 (2011).

[15] I. Cambell, D. Bourell, I. Gibson, Rapid Prototyping Journal **19**, 353-364 (2012).

[16] A. Szafrańska, A. Antolak-Dudka, P. Baranowski, P. Bogusz, D. Zasada, J. Małachowski, T. Czujko, Materials **12**, 886, 1-19 (2019). DOI:10.3390/ma12060886.

[17] J. Yu, M. Rombouts, G. Maes, F. Motmans. Physics Proc. **39**, 416-424 (2012).

[18] M. Dojka, R. Dojka, M. Stawarz, A. Studnicki, J. Mater. Eng. Perform. **28**, 7, 4002-4011

[19] M. Stawarz, M. Dojka, K. Janerka, 25th Anniversary International Conference on Metallurgy and Materials, Brno, Czech Republic, May 25th-27th, Conference Proceedings 229-233 (2016).

[20] S. Sobula, E. Olejnik, T. Tokarski, Arch. Foundry Eng. **17** (1), 143-146 (2017). DOI: 10.1515/afe-2017-0026.

[21] B.-X. Dong, F. Qiu, Q. Li, S.-L. Shu, H.-Y. Yang, Qi.-Ch. Jiang, Nanomaterials **9**, 1152, 1-40 (2019). DOI: 10.3390/nano9081152.

[22] W. Lengauer, Encyclopedia of Inorganic and Bioinorganic Chemistry, Chapter December 2012 (2012). DOI: 10.1002/9781119951438.eibc0032.pub2.

[23] Xiaowei Yin, I. Gotman, L. Klinger, E.Y. Gutmanas, Mater. Sci. Eng. A. **396**, 107-114 (2005). DOI:10.1016/j.msea.20085.01.011.

[24] A. Walasek, Designing of the structure and properties of the alloyed surface layer on the cast steel castings. Unpublished doctoral dissertation Silesian University of Technology, Poland (2012), in Polish.

[25] A. Wassilikowska, A. Czaplicka-Kotas, M. Zielina, A. Bielski, Technical Transactions Chemistry **18** (1), 133-148 (2014).

[26] T. Wróbel, Layered castings made by method of mould cavity preparation with monolithic insert, Archives of Foundry Engineering, Katowice – Gliwice (2016), in Polish.