BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 71(1), 2023, Article number: e144585
DOI: 10.24425/bpasts.2023.144585

MATERIAL SCIENCE AND NANOTECHNOLOGY

Assessment of surface waviness of casting patterns made using 3D printing technologies

Paweł ZMARZŁY*, Damian GOGOLEWSKI, and Tomasz KOZIOR

Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Poland

Abstract. The application of 3D printers significantly improves the process of producing foundry patterns in comparison to traditional methods of their production. It should be noted that the quality of the surface texture of the foundry pattern is crucial because it affects the quality of the casting mold and eventually the finished casting. In most studies, the surface texture is examined by analyzing the 2D or 3D roughness parameters. This is a certain limitation because, in the case of 3D printing, the influence of technological parameters is more visible for irregularities of a longer range, such as surface waviness. In the paper, the influence of the 3D printing layer thickness on the formation of waviness of the surface of casting patterns was analyzed. Three 3D printers, differing in terms of printing technology and printing material, were tested: PJM (PolyJet Matrix), FDM (fused deposition modeling) and SLS (selective laser sintering). In addition, the surface waviness of patterns manufactured with traditional methods was analyzed. Surface waviness has been measured using the Form Talysurf PGI 1200 measuring system. Preliminary results of the research showed that the layer thickness significantly influences the values of waviness parameters of the surface in the casting patterns made with FDM, PJM and SLS additive technologies. The research results indicated that the smallest surface waviness as defined by parameters Wa, Wq and Wt was obtained for patterns printed using the PJM technology, while the highest was noted when using the FDM technology.

Key words: 3D printing; foundry industry; casting pattern; surface waviness.

1. INTRODUCTION

The dynamic development of the foundry industry requires the implementation of modern manufacturing methods to produce casting patterns and casting molds. One of the main branches of the foundry industry is the production of casting patterns, which are then used to produce casting molds. [1]. Conventional casting patterns are made of wood or metal alloys by means of machining. The patterns can also be made of plastics [2]. However, all of the above-mentioned methods of producing casting patterns are time-consuming (manual machining of wooden patterns) and expensive (CNC machining of patterns). Moreover, the education of highly qualified pattern-makers is a very complex process. Currently, solutions allowing for fast production of test casting patterns and potential quick correction of their geometry are gaining popularity. This is especially important when creating test castings and prototypes. The solutions used include additive technologies also known as 3D printing [3].

Additive technologies are already commonly used in the foundry industry [4]. Mukhtarkhanov et al. [5] presented an overview of additive methods in the context of their application in investment casting. A similar overview of the applicability assessment of the fused deposition modelling technology for the production of casting patterns is presented in study [6]. In paper [7], comparative studies of three additive technologies, i.e. fused deposition modeling (FDM), stereolithography (SLA) and multi-jet fusion (MJF), are presented, which were used for the production of a master pattern for the vacuum casting process. The accuracy of the patterns produced and the Ra roughness parameter were assessed in this paper. Henderson et al. [8] conducted research aimed at assessing the possibility of using additive manufacturing technology (FDM) for the production of large-size casting patterns and molds. They compared the technology with conventional methods of making casting molds. They also proved that 3D printing can significantly reduce the cost of making casting molds. In studies [9, 10], the possibility of using the PolyJest Matrix technology to create patterns and casting molds was assessed. It was demonstrated that errors in the production of casting molds are transferred to the casting pattern. Moreover, it was observed that the printing direction is a key technological parameter that influences the dimensional and shape accuracy of the manufactured elements.

In the present paper, the assessment of using three different additive technologies for the production of casting patterns was analyzed, i.e. the PolyJet Matrix (PJM) technology, the fused deposition modeling (FDM) technology and the selective laser sintering (SLS) technology. The PolyJet Matrix technology is a liquid polymer resin photo curing technology. The technology is about spraying liquid resin through the dosing nozzle onto the working platform, and its subsequent hardening with UV irradiation. The FDM process is currently one of the most popular and cheapest methods of quick prototype making in the market [11,12]. It is about depositing molten plastic onto a platform, most often in the form of a line unwound from a spool and fed to printing heads. The heads heat the material above

---

*e-mail: pzmarzly@tu.kielce.pl

Manuscript submitted 2022-08-08, revised 2023-01-03, initially accepted for publication 2023-01-04, published in February 2023.

its melting point, to convert it into a semi-liquid form. As the head moves, the material is pressed through the head's nozzle and is deposited onto the platform as a thin thread. In the SLS technology, a very thin layer of powder is distributed on a moving platform that is later scanned with a CO_2 laser beam. As a result, the powder particles are sintered. Then, the platform is lowered by a given layer thickness and another layer of powder is spread, levelled and sintered. The process is repeated over and over until the pattern is built [13, 14].

Most of the research concerns the analysis of the influence of print direction on the dimensional and shape accuracy and the quality of the surface layer of the parts produced, taking into account only the change of print direction [15–17]. In most studies, the surface texture is examined by analyzing the 2D or 3D roughness parameters or by applying the multiscale method [18,19]. However, another critical parameter is the thickness of a single layer of the printing material. The thickness affects durability of the printed elements and the time of their printing, which is crucial in terms of the production of casting patterns. In addition, there is no research assessing the effect of the thickness of the material layer on the waviness of the printed surface. Therefore, the authors decided to perform such research and presented the results in the present paper.

2. MATERIALS AND METHOD

2.1. Research pattern

To assess the possibility of using additive technologies for the production of casting patterns, a special research pattern was designed. The shape of the pattern was designed taking into account the typical features of casting patterns such as appropriate draft, rounding radii, etc. Moreover, the pattern was designed to analyze surface topography in a non-invasive manner. The CAD model of the research pattern with the surface waviness measurement location is shown in Fig. 1.

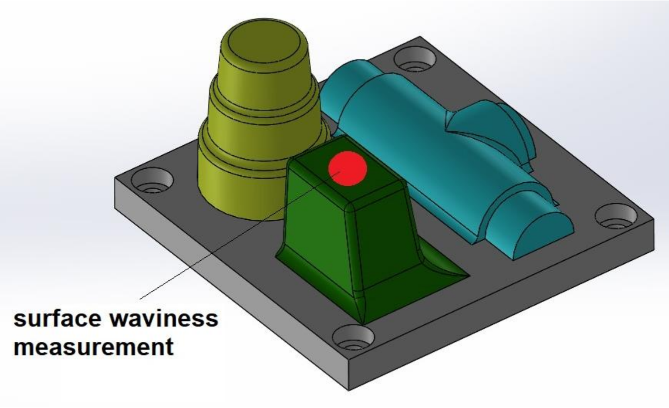

Fig. 1. Research model with the surface waviness measurement location

2.2. Additive technologies

The three most popular additive technologies were used to make the casting patterns, namely the PolyJet Matrix, fused deposition modeling and selective laser sintering. The patterns were printed taking into account the location on the working plate, i.e. the angle Pd = 0°. The variable parameter was the thickness of a single layer of the printing material, Lt. In order to carry out statistical tests, each variant of the casting pattern was produced in three pieces. The printers with the printed casting patterns are presented in Fig. 2.

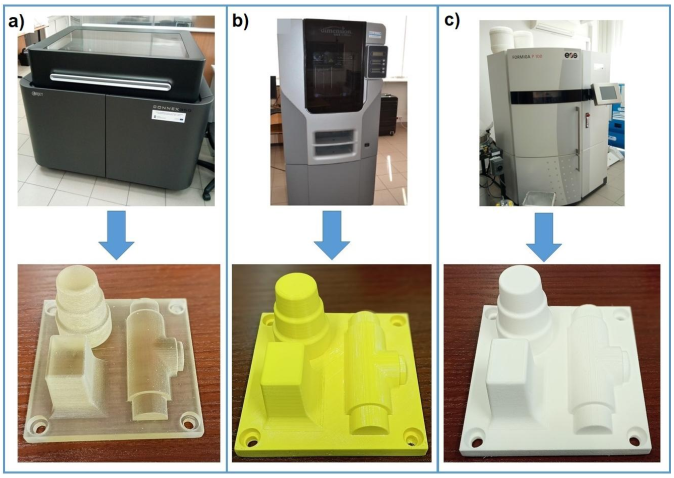

Fig. 2. 3D printers and printed patterns: a) PJM (Conex 350), b) FDM (Dimension 1200), c) SLS (Formiga P100)

In the PJM technology, the casting patterns were printed using a Connex 350 printer using the FullCure 720 printing material with the properties presented in Table 1. Support material is also used in this technology, which was removed when the printing was finished using a pressure washer. The analyzed variable parameter was the thickness of a single layer of the applied material, i.e. Lt = 0.016 mm and Lt = 0.032 mm. Fused deposition modeling was yet another additive technology used for the production of foundry patterns. A Dimension 1200 ES printer and ABS P430 material were used for printing (see: Table 1). The casting patterns were printed using a support material, which was then removed with alkaline cleaning agent. The change in the thickness of the material layer was analyzed, namely: Lt = 0.254 mm and Lt = 0.33 mm. The third 3D printing technology used in the research was the selective laser sintering technology. There was no need to use the sup-

Table 1
Selected mechanical properties of the materials used to make the casting patterns [20–22]

Type of additive technology	Material	Tensile strength, MPa	Young's modulus, MPa	Hardness
PJM	FullCure 720	60	2870	83 (Shore scale D)
FDM	ABS P430	37	2320	76 (Shore scale D)
SLS	PA2200	48	1700	75 (Shore scale D)

port material in this process. A Formiga P100 printer by EOS GmbH was used in the research. The patterns were made of PA2200 polyamide powder, the properties of which are given in Table 1. The following laser energy density was applied: ED = 0.056 J/mm^2. Two preset thicknesses of a single material layer were analyzed, i.e. Lt = 0.1 mm and Lt = 0.2 mm. In addition, for comparative purposes, casting patterns were made of wood and a PA6 aluminum alloy by milling on an AVIA VMC 800 vertical machining center.

2.3. Surface waviness measurements

Surface waviness of the casting patterns produced using the 3D printing technologies and conventional methods was measured using a Taylor Hobson Form Talysurf PGI 1200 measuring system. This instrument is equipped with a diamond blade with an angle of 90° and a rounding radius of 2 µm. The evaluation length for the individual samples was different depending on the irregularities and it was selected in accordance with the ISO standard. It was taking into account at least 5 sampling lengths for each evaluation length as well as the proper cut-off for individual samples depending on irregularities and aspects related to the filtering process and edge effect, which is also important during the analysis according to Gaussian filtration. In addition, it was set to a measurement speed of 0.5 mm/s, and a sampling density of $\Delta x = 1$ µm. Figure 3 shows an example of a casting pattern made of PA6 aluminum alloy.

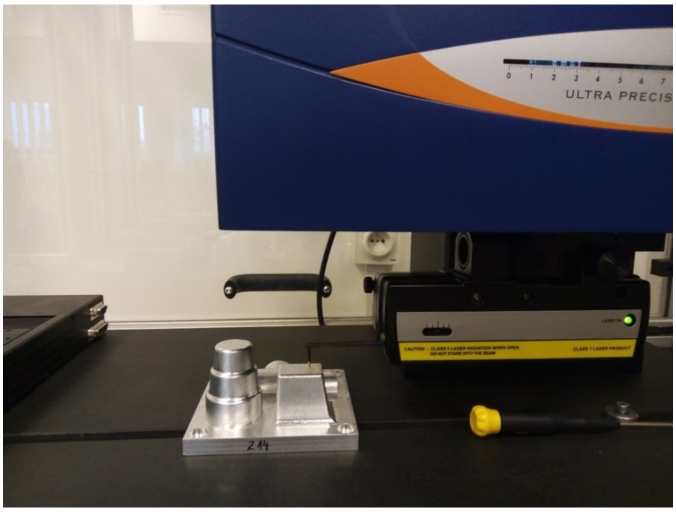

Fig. 3. Surface waviness measurement of a casting pattern made of PA6 aluminum alloy

3. RESULTS AND DISCUSSION

The casting patterns' surface waviness was assessed in two stages. The first stage consisted in assessing the values of the selected surface waviness parameters. In the second stage, the nature of the measured irregularities of the waviness profiles was assessed. Four parameters of surface waviness were used to assess waviness, i.e. Wa – arithmetic mean height waviness, which is the average of the absolute value along the sampling length; Wq – the root-mean-square height waviness deviation; Wt – the total height of the waviness profile along the vertical distance between the maximum profile peak height and the maximum profile valley depth along the evaluation length and Wsk (skewness) – cube of the root mean square deviation to display the dimensionless cube of the sampling length. Table 2 and Table 3 present the values of the surface waviness parameters for the tested samples.

Table 2

Measurement results of surface waviness of the casting patterns made with 3D printing

Technology name	FDM		PJM		SLS	
Material	ABS P430		FullCure 720		PA2200	
Single layer thickness (Lt), mm	0.254	0.33	0.016	0.032	0.1	0.2
Wa, µm	4.33	33.87	1.29	1.85	10.5	6.42
Wq, µm	4.99	38.6	1.42	2.08	12	7.44
Wt, µm	23.3	185.67	7.64	7.88	48.97	33.43
Wsk	0.17	–0.04	–0.18	–0.221	0.27	0.47

Table 3

Measurement results of surface waviness of the casting patterns made with milling technology

Technology name	Milling	
Material	Wood	Aluminum alloy PA6
Wa, µm	6.33	0.72
Wq, µm	7.46	0.76
Wt, µm	29.87	3.21
WSk	–0.08	0.07

By analyzing the test results presented in Table 2, it can be concluded that the type of additive technology used and the thickness of a single layer of the printing material affect the waviness values of the printed surfaces. When examining the most popular surface waviness parameter, namely the arithmetic mean height waviness (Wa), one can conclude that the best results were obtained for casting patterns printed in the PJM technology, taking into account a single layer of the printing material amounting to Lt = 0.016 mm. The highest values of the Wa parameter were obtained for the FDM technology at Lt = 0.3302 mm. Similar results were obtained for the amplitude and height parameters, i.e. Wq and Wt. When examining the influence of the layer thickness of the applied Lt material on the waviness of the printed surfaces, it can be stated that in the case of the fused deposition modeling and PolyJet Matrix technologies, the greater the value of thickness, the greater the waviness. The opposite relationship was noted for the selective laser sintering technology, where waviness was greater for the printed surface when a single layer of the printing material Lt = 0.1. By analyzing total height of the printed surface waviness profile, one can conclude that for all tested technologies Wt > 7 um. It should be added that with the increase of the Wt parameter, fatigue strength decreases, which is important for the lifespan of the casting patterns. Considering the Wsk parameter defining the skewness of the waviness profile, one can see that for the PJM technology, both for Lt = 0.016 mm and Lt = 0.032 mm, the Wsk parameter is < 0. This means that the material is concentrated closer to the peaks. On the other hand, in the case of the SLS technology, the Wsk parameter is > 0, which means that the material is concentrated closer to the valleys of the irregularities. For the FDM technology, for Lt = 0.17, Wsk > 0 was measured, while for Lt = 0.330 mm, the skewness is close to zero, which indicates the distribution of irregularities characterized by the Gaussian distribution.

Comparing the obtained results of surface waviness of the casting patterns to the patterns produced using conventional methods of wood and aluminum (see Table 3), it can be concluded that aluminum patterns were characterized by the lowest surface waviness among all the patterns tested. For aluminum samples, the values of Wa and Wq were more than forty times lower than for the patterns printed in the FDM technology, taking into account the parameters of Pd = 0° and Lt = 0.330 mm. However, it should be added that making aluminum patterns by means of milling on a CNC machining center is time-consuming and requires expensive tools and machinery. The wooden casting patterns' surface waviness was similar to the waviness of the printed patterns using the optimal thicknesses of a single material layer (see: parameters Wa and Wq in Table 2).

In order to assess the nature of surface waviness in detail, the waviness profiles of the selected casting patterns made with the use of 3D printing were presented in Fig. 4. Furthermore, Fig. 5 presents optical light microscopy images of analyzed surfaces. By analyzing the waviness profiles presented in Fig. 4 and optical light microscopy images presented in Fig. 5, one can see that, depending on the type of technology used, the irregularities are of a different nature. In the case of the FDM technology (Figs. 4a, 5a and Figs. 4b, 5b), distinct individual peaks are visible, which results directly from the method of joining individual layers of the material, where the printing head applies a single layer of melted material to the previously solidified layer. On the other hand, when considering the waviness profiles of samples made using the PolyJet Matrix technology (Figs. 4c and 4d), the presence of many peaks and valleys is clearly visible. It should be added that this technology produced the surfaces with the lowest waviness (Table 2). In addition, in the profile shown in Figure 4d, a greater distance between individual peaks is visible, which is the result of using a greater thickness of a single layer of the printing material. Whereas the profile measured for the casting patterns made with the SLS technology, taking into account the parameter Lt = 0.1 mm, is different from the other profiles. A single peak is visible here (Figure 4e). In this technology, the laser beam melts the previously applied layer of polyamide powder. It is possible that a local melting of the material and the formation of the so-called “flash” occurred on this surface, which resulted in such irregularity. When using a single layer of thickness Lt = 0.2 mm, a waviness profile with individual peaks similar to those occurring in the FDM technology was observed.

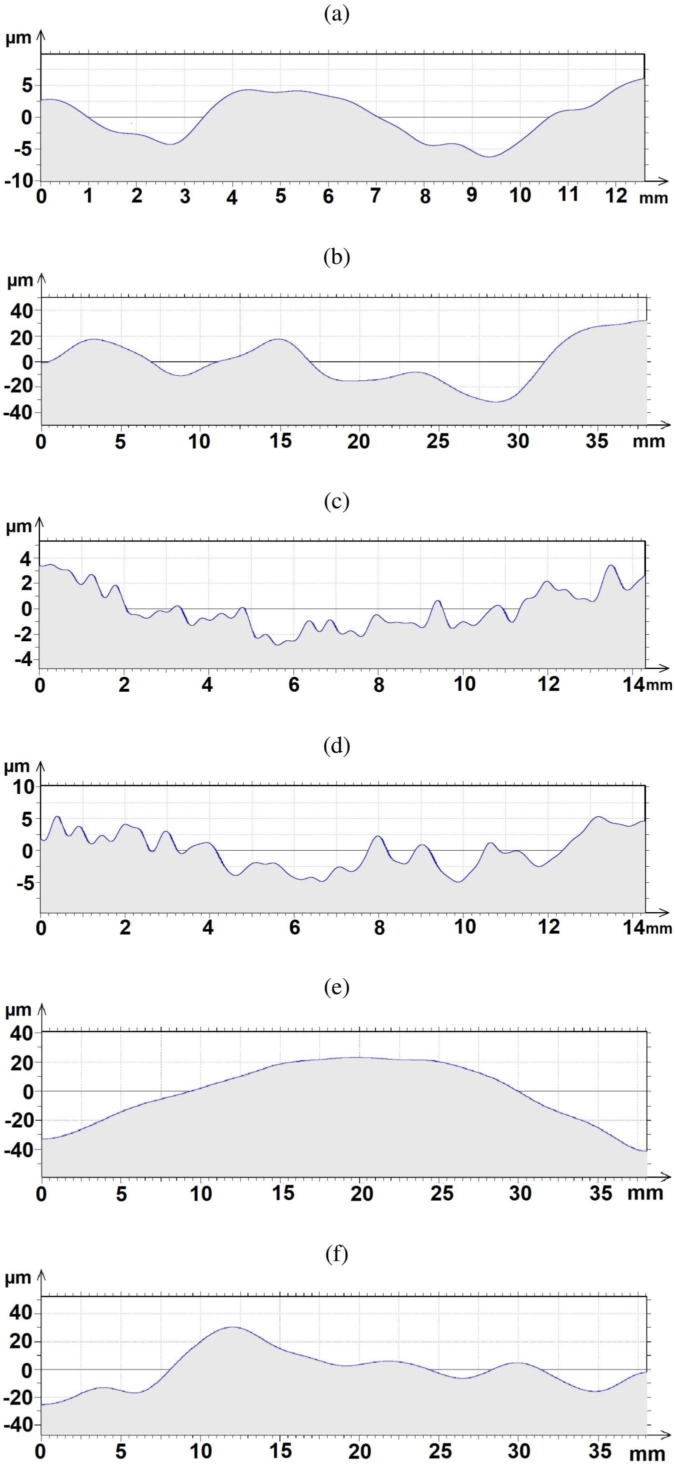

Fig. 4. Surface waviness profiles of casting patterns made with selected additive technologies, where: a) FDM technology (Pd = 0°, Lt = 0.254 mm), b) FDM technology (Pd = 0°, Lt = 0.330 mm), c) PJM technology (Pd = 0°, Lt = 0.016 mm), d) PJM technology (Pd = 0°, Lt = 0.033 mm), e) SLS technology (Pd = 0°, Lt = 0.1 mm), f) SLS technology (Pd = 0°, Lt = 0.2 mm)

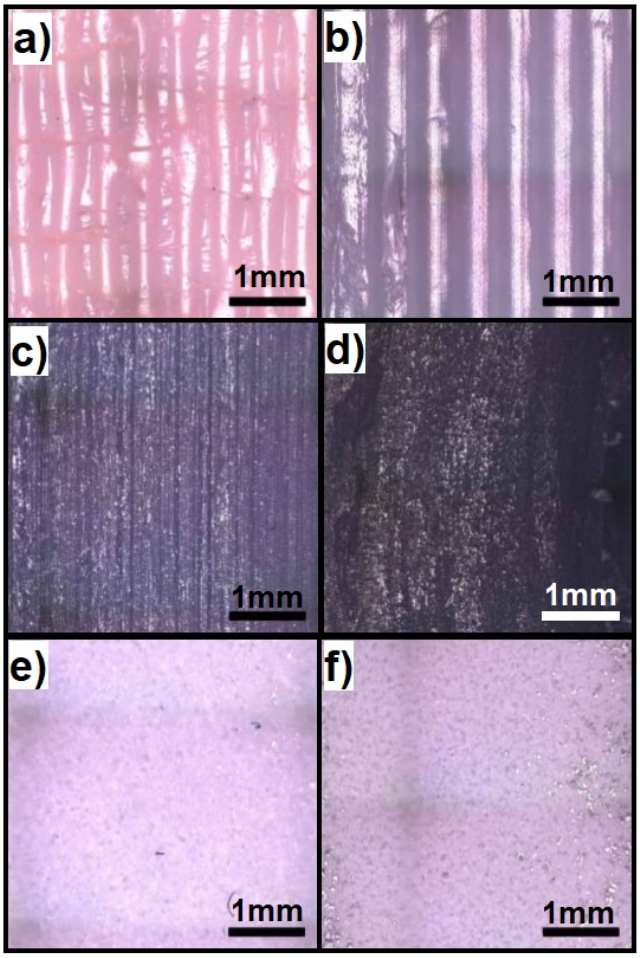

Fig. 5. Optical light microscopy images of analyzed surfaces of casting patterns made with selected additive technologies, where: a) FDM technology (Pd = 0°, Lt = 0.254 mm), b) FDM technology (Pd = 0°, Lt = 0.330 mm), c) PJM technology (Pd = 0°, Lt = 0.016 mm), d) PJM technology (Pd = 0°, Lt = 0.033 mm), e) SLS technology (Pd = 0°, Lt = 0.1 mm), f) SLS technology (Pd = 0°, Lt = 0.2 mm)

4. CONCLUSIONS

Initially, 3D printing was used for piece production of prototypes of low accuracy and durability. However, modern additive technologies are widely used in industrial and everyday applications. Due to the multitude of 3D printer types and printing materials, the selection of an appropriate printer for a specific range of applications may be difficult. In addition to selecting the appropriate additive technology, suitable technological parameters should be used so that the printed element has the requested characteristics. The main purpose of the research presented in the paper was to assess surface waviness of the casting patterns made with the use of three different additive technologies. In addition, it was assessed how the change in a single layer thickness of the printing material affects the shape of the printed patterns' surface waviness. The test results showed that:

- The smallest surface waviness defined by parameters Wa, Wq and Wt was obtained for patterns printed using the PJM technology, while the highest was noted when using the FDM technology.
- A single layer thickness increase when printing using FDM and PJM technologies resulted in the printed surface waviness increase. The opposite tendency was observed in the case of the SLS technology. This phenomenon may result from the method of sintering the layer of plastic powder by the CO_2 laser beam. When the layer of the printing material fed for sintering is too small, the concentration of energy in a given place may be too high, resulting in local penetrations, as seen in Figure 4d.
- When using the SLS technology, in addition to selecting the appropriate printing direction and the thickness of the powder layer being applied, the appropriate energy density generated by the laser should be controlled.
- By analyzing the waviness profiles of the surfaces made using additive processes, one can conclude that a lot of individual peaks and valleys were created on the samples made using the PJM technology. In the case of other technologies (FDM and SLS), only single peaks were observed on the profiles.
- The waviness of the surface of the casting patterns made with the FDM and SLS technologies was similar to that of the patterns made of wood using conventional techniques.
- For measuring surface waviness of the casting models made using additive technologies, it is recommended to use contact methods, because application of optical methods results in a large number of unmeasured points, which affects the accuracy of measurements.

As part of further research, the authors will investigate the influence of other technological parameters on the dimensional and shape accuracy and on the quality of the surface layer of the casting patterns. It is planned to carry out chemical treatment of the surface of the printed elements to improve quality of the surface layer. In addition, the printed patterns will be worn out in the process of making casting molds. Then, the degree of their wear caused by making molds will be assessed.

ACKNOWLEDGEMENTS

The research was financed by the National Centre for Research and Development as part of the Lider XI project, number LIDER/44/0146/L-11/19/NCBR/2020, under the following title: "An analysis of application possibilities of the additive technologies to rapid fabrication of casting patterns".

REFERENCES

[1] R. Anjul and S.K. Ganguly, "Artificial intelligence in metal castingindustries: A review," *Int. J. Adv. Manag. Technol. Eng. Sci.*, vol. 8, no. III, pp. 1416–1419, 2018.

[2] R.K. Tewo, H.L. Rutto, W. Focke, T. Seodigeng, and L.K. Koech, "Formulations, development and characterization techniques of investmentcasting patterns," *Rev. Chem. Eng.*, vol. 35, no. 3, pp. 335–349, 2019, doi: 10.1515/revce-2017-0068.

[3] H. Abdillah and U. Ulikaryani, "Hybrid manufacturing and rapidprototyping in metal casting industry: A review," in *Proc. of the 2nd International Conference of Science and Technology for the Internet of Things, ICSTI 2019*, Indonesia, 2021, doi: 10.4108/eai.20-9-2019.2290957.

[4] S. Yan Tang, L. Yang, Z. Tian Fan, W. Ming Jiang, and X. Wang Liu, "Areview of additive manufacturing technology and its application to foundryin China," *China Foundry*, vol. 18, no. 4, pp. 249–264, 2021, doi: 10.1007/s41230-021-1003-0.

[5] M. Mukhtarkhanov, A. Perveen, and D. Talamona, "Application of stereolithography based 3D printing technology in investment casting," *Micromachines*, vol. 11, no. 10, p. 946, 2020, doi: 10.3390/mi11100946.

[6] S. Singh and R. Singh, "Fused deposition modelling based rapid patterns for investment casting applications: A review," *Rapid Prototyping J.*, vol. 22, no. 1, pp. 123–143, 2016, doi: 10.1108/RPJ-02-2014-0017.

[7] N.N. Mohd Mustafa, A.Z. Abdul Kadir, N.H. Akhmal Ngadiman, A. Ma'aram, and K. Zakaria, "Comparison of different additive manufacturing patterns onthe performance of rapid vacuum casting for mating parts via the Taguchi method," *J. Mech. Eng. Sci.*, vol. 14, no. 1, pp. 6417–6429, 2020, doi: 10.15282/jmes.14.1.2020.17.0502.

[8] H.B. Henderson *et al.*, "Additively manufactured single-use molds and reusable patterns for large automotive and hydroelectric components," *Int. J. Met.*, vol. 14, no. 2, pp. 356–364, 2020, doi: 10.1007/s40962-019-00379-0.

[9] P. Zmarzły, D. Gogolewski, and T. Kozior, "Design guidelines for plastic casting using 3D printing," *J. Eng. Fiber. Fabr.*, vol. 15, pp. 1–10, 2020, doi: 10.1177/1558925020916037.

[10] P. Zmarzły, T. Kozior, and D. Gogolewski, "Dimensional and shape accuracy of foundry patterns fabricated through photocuring," *Teh. Vjesn.*, vol. 26, no. 6, pp. 1576–1584, 2019, doi: 10.17559/TV-20181109115954.

[11] R.B. Kristiawan, F. Imaduddin, D. Ariawan, Ubaidillah, and Z. Arifin, "A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters," *Open Eng.*, vol. 11, no. 1, pp. 639–649, 2021, doi: 10.1515/eng-2021-0063.

[12] A. Cano-Vicent *et al.*, "Fused deposition modelling: Current status, methodology, applications and future prospects," *Addit. Manuf.*, vol. 47, p. 102378, 2021, doi: 10.1016/j.addma.2021.102378.

[13] F. Lupone, E. Padovano, F. Casamento, and C. Badini, "Process phenomena and material properties in selective laser sintering of polymers: A review," *Materials*, vol. 15, no. 1, p. 183, 2022, doi: 10.3390/ma15010183.

[14] M.V. Kulkarni, "Selective laser sintering process – a review," *Int. J. Curr. Eng. Sci. Res.*, vol. 2, no. 10, pp. 91–100, 2015.

[15] J.S. Shim, J.E. Kim, S.H. Jeong, Y.J. Choi, and J.J. Ryu, "Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations," *J. Prosthet. Dent.*, vol. 124, no. 4, pp. 468–475, 2020, doi: 10.1016/j.prosdent.2019.05.034.

[16] D. Vysochinskiy, N. Akhtar, T. Nordmo, M.R. Strand, A. Vyssios, and M.K. Bak, "Experimental investigation of effect of printing direction and surface roughness on the mechanical properties of AlSi10Mg-alloy produced by selective laser melting," *24th International Conference on Material Forming ESAFORM 2021*, 2021, doi: 10.25518/esaform21.3627.

[17] A. Cazón, P. Morer, and L. Matey, "PolyJet technology for product prototyping: Tensile strength and surface roughness properties," in *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2014, vol. 228, no. 12, pp. 1664–1675, doi: 10.1177/0954405413518515.

[18] Z. Lei, W. Su, and Q. Hu, "Multimode decomposition and wavelet threshold denoising of mold level based on mutual information entropy," *Entropy*, vol. 21, no. 2, p. 202, 2019, doi: 10.3390/e21020202.

[19] D. Gogolewski, "Fractional spline wavelets within the surface texture analysis," *Measurement*, vol. 179, p. 109435, 2021, doi: 10.1016/j.measurement.2021.109435.

[20] S. Adamczak, P. Zmarzly, T. Kozior, and D. Gogolewski, "Assessment of roundness and waviness deviations of elements produced by Selective Laser Sintering Technology," in *23rd International Conference Engineering Mechanics 2017*, 2017, pp. 70–73.

[21] S. Adamczak, P. Zmarzly, T. Kozior, and D. Gogolewski, "Analysis of the dimensional accuracy of casting models manufactured by Fused deposition Modeling Technology," in *23rd International Conference Engineering Mechanics 2017*, 2017, pp. 66–69.

[22] J. Bochnia, "Evaluation of relaxation properties of digital materials obtained by means of PolyJet Matrix technology," *Bull. Pol. Acad. Sci. Tech. Sci.*, vol. 66, no. 6, pp. 891–897, 2018, doi: 10.24425/bpas.2018.125936.