ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
UDC/UDK 620.191.083:621.941]:658.624

EXPERIMENTAL ANALYSIS OF SURFACE ROUGHNESS AND SURFACE TEXTURE OF MACHINED AND FUSED DEPOSITION MODELLED PARTS

Grzegorz Krolczyk, Pero Raos, Stanislaw Legutko

Subject review

The objective of the investigation was to identify surface integrity of machined parts by turning and by Fused Deposition Modelling (FDM) additive method produced ones. Surface analysis was made by using novel metrology methods: auto correlation and gradient distribution. An *Infinite Focus Measurement Machine (IFM)* was used for the surface texture analysis. The study was performed within a production facility during the prototyping process of new products.

Keywords: *Fused Deposition Modelling (FDM), rapid prototyping, roughness of surface, surface texture, turning*

Eksperimentalna analiza površinske hrapavosti i teksture tokarenih i taložno očvrsnutih proizvoda

Pregledni članak

Cilj istraživanja bio je utvrditi integritet površine dijelova proizvedenih klasičnim postupkom obrade odvajanjem čestica, tokarenjem i aditivnim postupkom taložnog očvršćivanja (tzv. FDM postupak). Pri analizi površine korištene su suvremene metrološke metode auto korelacije i gradijentne razdiobe. Površinska tekstura analizirana je pomoću *Infinite Focus Measurement Machine (IFM)* uređaja. Studija je provedena u stvarnom proizvodnom pogonu tijekom prototipne izrade novih proizvoda.

Ključne riječi: *brza izrada prototipova, površinska hrapavost, površinska tekstura, taložno očvršćivanje, tokarenje*

1 Introduction

Increased competitiveness in marketplace forced the production companies to a faster product development and reduction of new product implementation time to market. Among many manufacturing technologies there are rapid prototyping (RP) technologies which are able to perform the complete product directly from CAD (Computer Aided Design) model without any tooling. While with traditional methods the prototype needed to be constructed and finished manually, rapid prototyping attitude brings the possibility of changing the necessary properties usually responding with geometrical characteristics and of simply creating the new prototype on the basis of the file from the previous version [1]. Amongst many RP techniques, Fused Deposition Modelling (FDM) is considered as the most appropriate process for RP due to its ease of operation, inexpensive machinery and durability of built parts [2, 3]. Among the most important advantages of FDM are good mechanical properties [4]. In FDM, a nozzle extrudes the printing material. Similar to other RP methods, one layer at a time is printed but typically the material is directly deposited on a surface where it is desired. Extrusion through a nozzle results in a cylindrical coiled morphology of each layer [5]. Rapid Prototyping fabricates 3D physical models using a layered manufacturing (LM) process that stacks and bonds thin layers in one direction [6]. In comparison to the numerically controlled manufacturing technology, RP can rapidly fabricate difficult models without geometric restriction. A rapid prototyping system can be used for manufacturing complex shapes made of a porous material, and the pore distribution can be controlled as desired [7]. One of the most important disadvantages of FDM is high surface roughness, especially if compared to other processes. Surface properties of parts fabricating from polymers such as roughness, charge, modulus, and hydrophilicity react to a device [8]. A precise characterization of roughness and surface topography is of prime importance in many engineering industries [9]. Surface integrity describes the state and machined surface parameters and its relationship to functional performance and is important for the components adapting to mechanical loads during their application. Quality is defined as the scope of implementation of expected functions [10]. To ensure better surface integrity, particular attention must be given to the selection of the cutting parameters [11÷13] and tool coatings material and geometry [14]. Several of the researches related to the rapid prototyping topic were presented [15÷20], but most of them apply to technical and economic aspects optimizations of the process.

FDM technology is one of the established additive manufacturing methods [21÷23]. FDM builds concept models, functional prototypes and end-use parts in standard, engineering-grade and high-performance thermoplastics. 3D printers that run on FDM technology build parts layer-by-layer by heating thermoplastic material to a semi-liquid state and extruding it according to computer-controlled paths. FDM uses two materials to execute a print job: modelling material, which constitutes the finished piece, and support material, which acts as scaffolding. Material filaments are fed from the 3D printer's material bays to the print head, which moves in X and Y coordinates, depositing material to complete each layer before the base moves down the Z axis and the next layer begins. Once the 3D printer has done building, the user breaks the support material away or dissolves it in detergent and water, and the part is ready to use.

This paper focuses on research problems related to the geometrical parameters of surface integrity after FDM technology and turning by coated carbide tools. Surface and subsurface performed by these methods are easily damaged during the production process. The main purpose of this study was to determine using the novel method of analysis to the quality of surface integrity.

2 Experimental techniques
2.1 Workpiece

The machined material was PE1000 (Ultra High Molecular Weight Polyethylene PE-UHMW). The study of turning was conducted within a production facility during the production of prototypes of diaphragm pumps. The experiments performed with this material were comparative studies. FDM technology was the second method of workpiece obtaining.

All 3D samples used in our experiments have been printed by Stratysys Fortus 360mc 3D production system [24]. The material is production-grade ABS engineering thermoplastics (Acrylonitrile Butadiene Styrene ABS-M30) which exhibits great tensile, impact and flexural strength and environmental stability, furthermore ABS is characterized by versatility, low cost and wide use. ABS is an interesting material for engineering applications. The layer thickness was 0,127 mm in all test runs. The contact angle was recorded at least thrice for each sample and at least two samples for each experimental condition were prepared.

2.2 Surface integrity analysis

Surface integrity analysis is performed using Infinite Focus Measurement Machine IFM (Fig. 1). IFM is an optical 3D measurement device which allows the acquisition of datasets at a high depth of focus. The IFM is an optical 3D measurement device similar to the SEM. The IFM method allows for the capture of images with a lateral resolution down to 400 nm and a vertical resolution down to 20 nm [25]. The IFM 3.2 software version was used for the measurements.

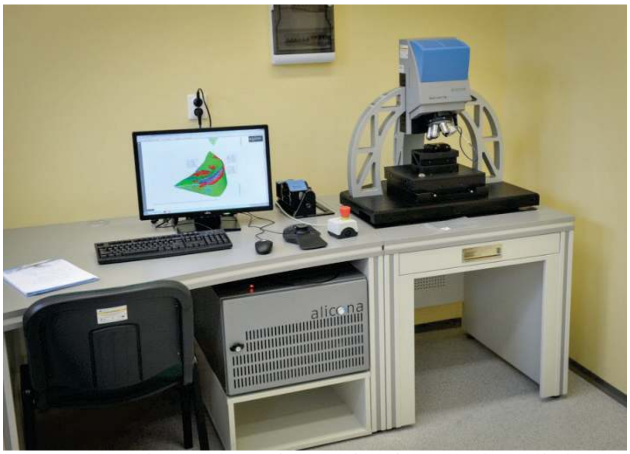

Figure 1 The experimental setup of Surface Integrity analysis

3 Results and discussion
3.1 Surface roughness

Analysing the machined surface (Fig. 2), one can state that it has an anisotropic and periodical structure. A structure of this type occurs on contactless surfaces, mostly unloaded ones and co-acting with various kinds of wave interaction. On loaded faces, this surface is often found in immobile contacts of undeformable bodies with deformable ones. After 3D printing (Fig. 3) the surface has undirected structure.

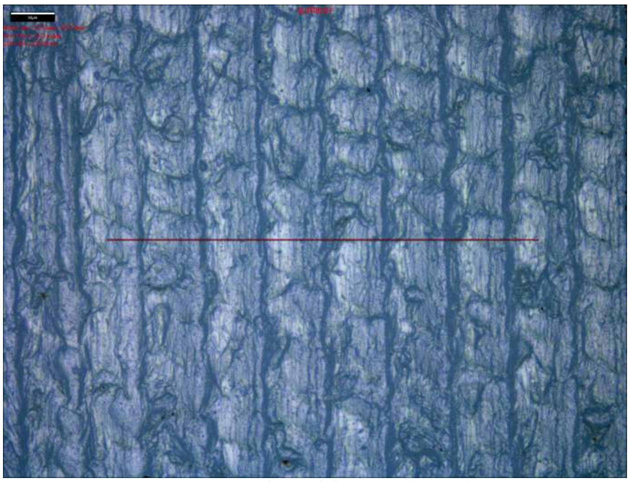

Figure 2 Surface of the turned sample

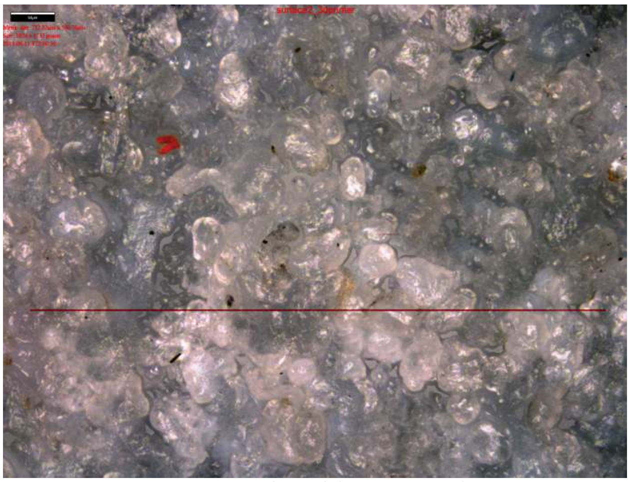

Figure 3 Surface of the FDM sample

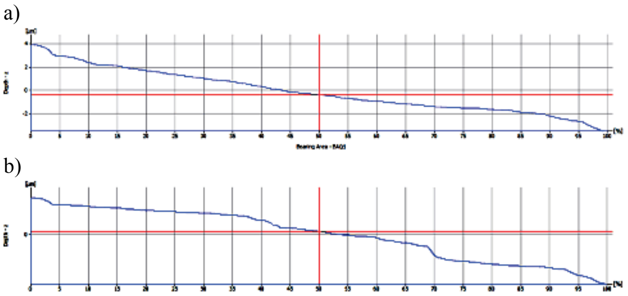

Figure 4 Load capacity curves a) after turning b) after FDM technology

A comparison of the load capacity curves depending on the cutting speed can be seen in Fig. 4. The shape of the load capacity curve (Abbott – Firestone Curve) mainly depends on the shape of irregularities in the direction perpendicular to the reference surface. The bearing area curve tells us how much of the surface is above a certain height. Bigger bearing area sample after FDM technology is equivalent to most of the surface being close to the peak of the surface. Honed surface, for example, has a large bearing area (surface is close to peak). Nielsen [26] found that the honing process can be controlled by R_k parameters. According to Sedlacek et al. [27], the R_{vk} and R_{pk} parameters can have an influence on friction. The representative measured values of roughness parameters and material ratio parameters (R_k parameters group) are listed in Tabs. 1 and 2. Large R_k parameter in FDM surface value implies a surface composed of high peaks providing small initial contact area and thus high areas of contact stress when the surface is contacted.

Fig. 5 shows the differences in roughness profiles of both analysed samples. Higher roughness parameters in FDM sample lead to a decrease of friction providing a small initial contact area.

Figs. 6 and 7 show histograms of the distribution of vertices and upgrades located on the surface samples. It can be seen that the distribution of printed sample is characterized by a large fluctuation of changes in the value of R group parameters and a larger changes range values of these parameters. This proves that the surface of the printed sample has undirected structure.

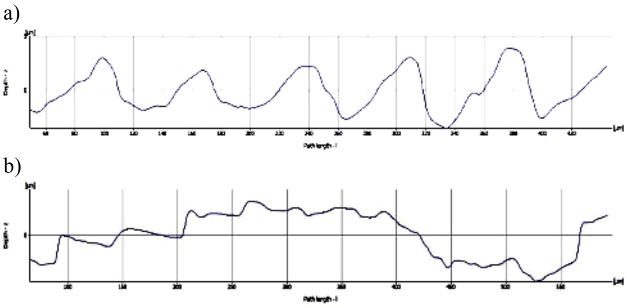

Figure 5 Surface roughness profiles a) after turning and b) after FDM technology

Table 1 Roughness parameters in µm

Production method	*Ra*	*Rq*	*Rt*	*Rz*	R_{max}	*Rp*	*Rv*	*Rc*
Turning	1,5427	1,7972	7,4269	5,3318	6,5333	3,9212	3,5057	5,2774
FDM technology	19,716	22,578	79,103	41,121	65,067	33,906	45,197	79,103

Table 2 Material ratio parameters

Production method	R_k / µm	R_{pk} / µm	R_{vk} / µm	R_{mr1} / %	R_{mr2} / %
Turning	4,18	1,76	0,93	19,63	92,31
FDM technology	52,15	6,50	15,27	3,35	72,01

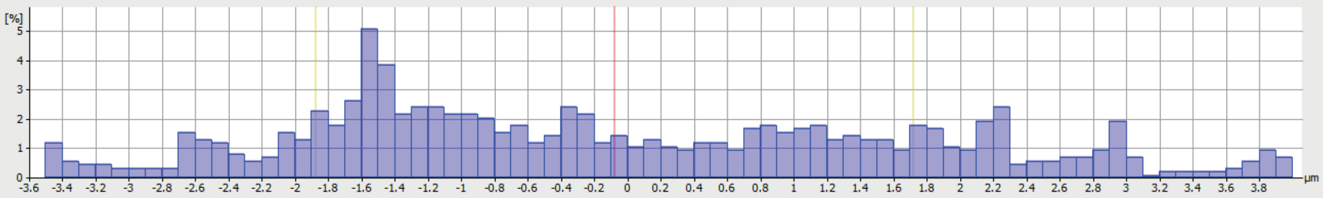

Figure 6 Parameters histogram of roughness profile of the turned sample

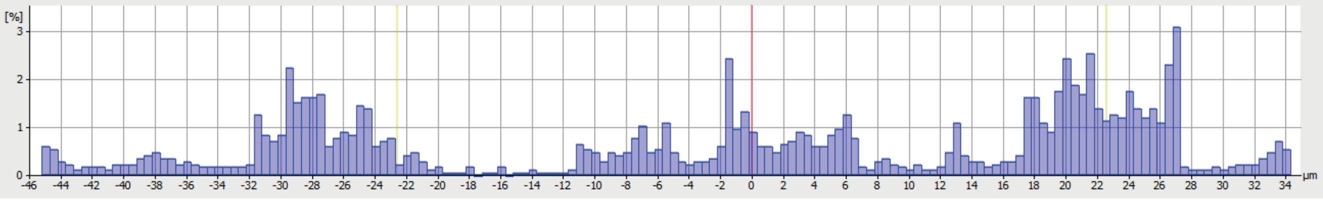

Figure 7 Parameters histogram of roughness profile of the FDM sample

3.2 Surface texture

The surface texture analysis has been performed by means of an Infinite Focus Measurement Machine. The aim of the characterisation of surface topography is to represent the surface topography with parameters to control the manufacturing process and the functional performance of surfaces. The geometrical structures of the surface shown below have been observed after longitude turning and after 3D printing. Fig. 8 shows the preferential direction of a periodically iterated surface structure. The autocorrelation can be used to detect non-randomness in data and to identify an appropriate time series. The autocorrelation function (ACF) describes the general dependence of the values of the data at one position on the values at another position. ACF is used for surface topographic assessment, it is a good method to indicate randomness and directionality of surface features [28]. S_{al}, S_{tr} and S_{tdi} parameters have a higher value. Tab. 3 presents calculated parameters for auto correlations. Dominated high frequencies and weak dominant structures of texture aspect ratio surface are after FDM technology.

Table 3 Calculated parameters for auto correlations

Production method	S_{al} / µm	S_{tr} / –	S_{td} / °	S_{tdi} / –
Turning	17,32	0,30398	0	0,37928
FDM technology	53,55	0,48236	−90	0,66169

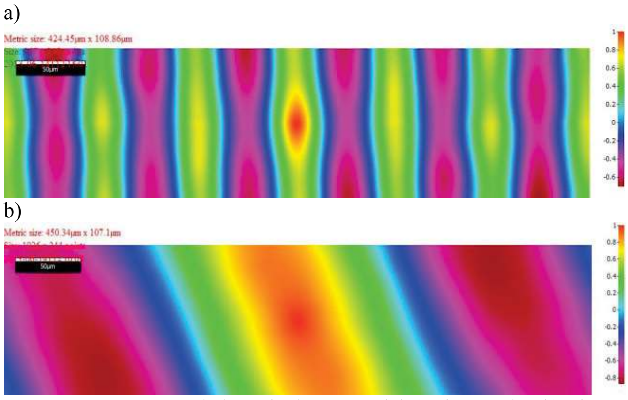

Figure 8 Auto correlation of primary model a) after turning b) after FDM technology

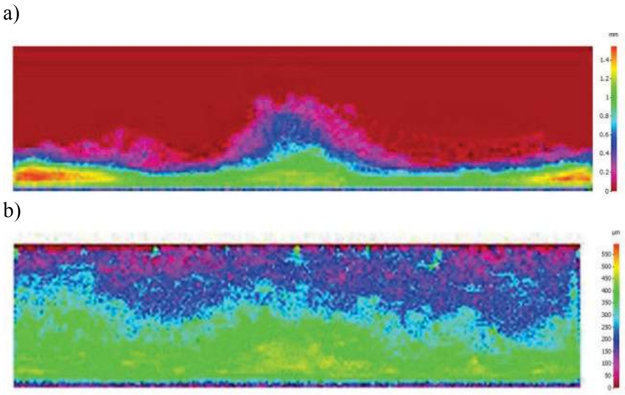

Figure 9 Gradient distributions of primary model a) after turning b) after FDM technology

Fig. 9 shows the gradients of the surface of the whole models of ISO Gradient Distribution. In the figure it can be observed the surface after turning with smooth gradients of primary model and the FDM surface characterized by steep gradients.

Figs. 10 and 11 show two views of spectral distributions (Surface Texture Spectrum) of the selected region. Selected parameters were S_a parameter (average height of selected area). Spectrum of the analysed samples confirms earlier observations that the surface manufactured by Fused Deposition Modelling has steeper slopes than the surface after turning.

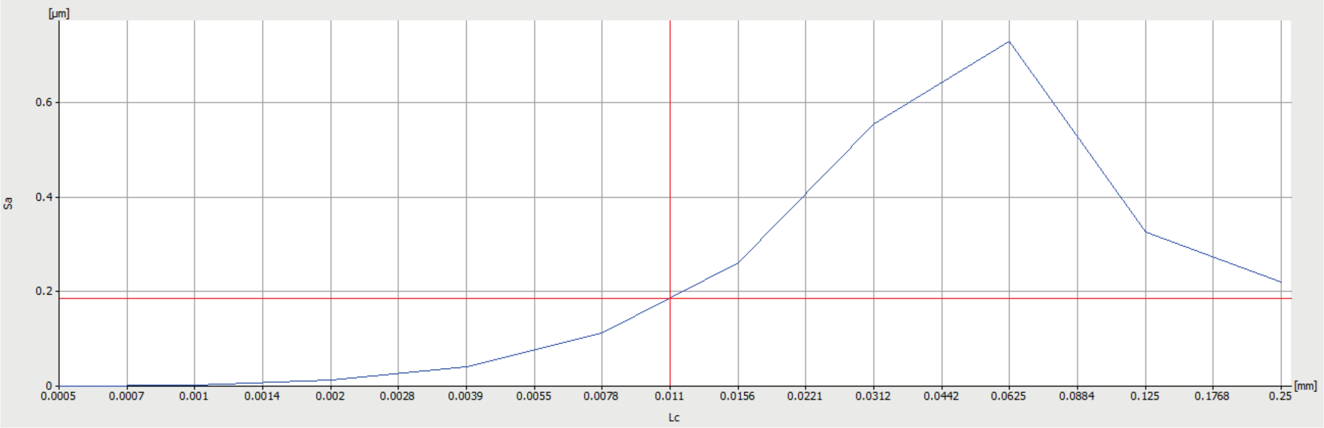

Figure 10 Spectrum of sample after turning of primary model

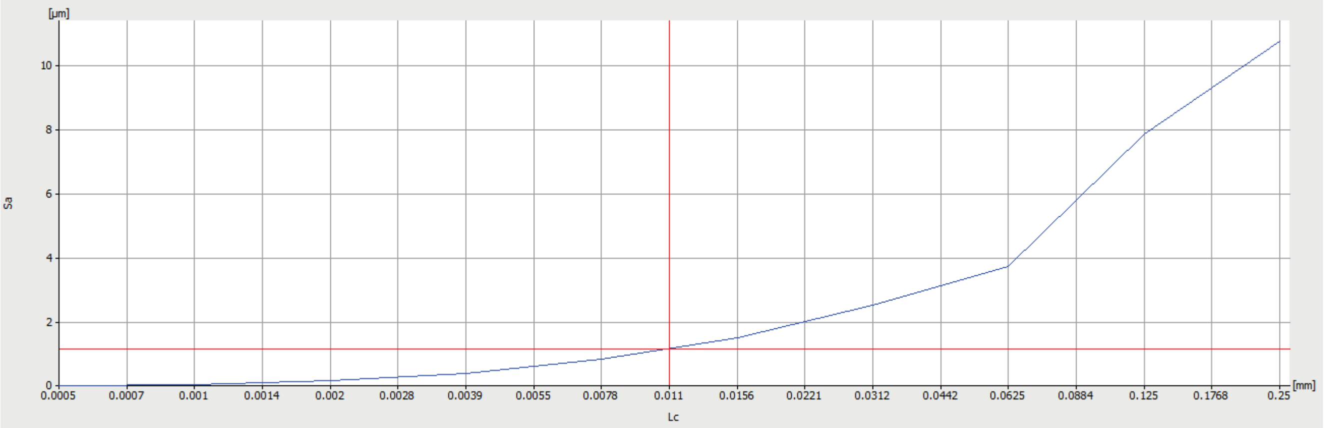

Figure 11 Spectrum of sample after FDM technology of primary model

4 Conclusions

1) Surface obtained by turning is intended to the surface of mostly unloaded ones and co-acting with various kinds of wave interaction.
2) Surface obtained by FDM technology is the surface composed of high peaks providing a small initial contact area and thus high areas of contact stress when the surface is contacted.
3) Gradient distributions of printed sample are characterized by large fluctuation changes in the value of R group parameters and a larger changes range values of these parameters.
4) High frequencies and weak dominant structures of texture aspect ratio dominate on the surface after FDM technology.
5) Smooth gradients are observed on the surface after turning while FDM surface is characterized by steep gradients.

5 References

[1] Novak-Marcincin, J.; Novakova-Marcincinova, L.; Barna, J.; Janak, M. Application of FDM rapid prototyping technology in experimental gearbox development process. // Tehnički vjesnik-Technical Gazette. 19, 3(2012), pp. 689-694.

[2] Levy, G. N.; Schindel, R.; Kruth, J. P.; Leuven, K. U. Rapid manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies – State of the Art and Future Perspectives. // CIRP Annals Manufacturing Technology. 52/2, (2003), pp. 589-609.

[3] Rosochowski, A.; Matuszak, A. Rapid Tooling – The State of Art. // Journal of Materials Processing Technology, 106, (2000), pp.191-198.

[4] Percoco, G.; Lavecchia, F.; Galantucci, L. M. Compressive Properties of FDM Rapid Prototypes Treated with a Low Cost Chemical Finishing. // Research Journal of Applied Sciences, Engineering and Technology, 4, 19, (2012), pp. 3838-3842.

[5] McCullough, E. J.; Yadavalli, V. K. Surface modification of fused deposition modeling ABS to enable rapid prototyping of biomedical microdevices. // Journal of Materials Processing Technology, 213, 6, (2013), pp. 947-954.

[6] Ahn, D.; Kweon, J. H.; Kwon, S.; Song, J.; Lee, S. Representation of surface roughness in fused deposition modeling. // Journal of Materials Processing Technology, 209, (2009), pp. 5593-5600.

[7] Sakata, S.; Ashida, F.; Ohsumimoto, K. Stochastic homogenization analysis of a porous material with the perturbation method considering a microscopic geometrical random variation. // International Journal of Mechanical Sciences, 77, (2013), pp. 145-154.

[8] Gray, J. J. The interaction of proteins with solid surfaces. // Current Opinion in Structural Biology, 14 (2004), pp. 110-115.

[9] Mahovic Poljacek, S.; Risovic, D.; Furic, K.; Gojo, M. Comparison of fractal and profilometric methods for surface topography characterization. // Applied Surface Science, 254, (2008), pp. 3449-3458.

[10] Królczyk, J.; Tukiendorf, M. Research on the impact mass fractions of Multi-element granular structure on the mixing process. // International Agrophysics, 22, (2008), pp. 45-52.

[11] Krolczyk, G.; Gajek, M.; Legutko, S. Predicting the tool life in the dry machining of duplex stainless steel. // Eksploatacja i Niezawodnosc – Maintenance and Reliability. 15, 1(2013), pp. 62-65.

[12] Krolczyk, G.; Legutko, S.; Raos, P. Cutting wedge wear examination during turning of duplex stainless steel. // Tehnički Vjesnik-Technical Gazette. 20, 3(2013), pp. 413-418.

[13] Krolczyk, G.; Legutko, S.; Gajek, M. Predicting the surface roughness in the dry machining of duplex stainless steel. // Metalurgija, 52, 2 (2013), pp. 259-262.

[14] Krolczyk, G.; Legutko, S.; Gajek, M. Effect of the cutting parameters impact onto tool life in duplex stainless steel turning process. // Tehnički Vjesnik-Technical Gazette, 20, 4(2013), pp. 587-592.

[15] Gajdoš, I.; Slota, J. Influence of printing conditions on structure in FDM prototypes. // Tehnički vjesnik-Technical Gazette 20, 2(2013), pp. 231-236.

[16] Novak-Marcincin, J.; Barna, J.; Novakova-Marcincinova, L.; Fecova, V. Analyses and solutions on technical and economic aspects of rapid prototyping technology. // Tehnički vjesnik-Technical Gazette 18, 4(2011), pp. 657-661.

[17] Paul, B. K.; Voorakarnam, V. Effect of layer thickness and orientation angle on surface roughness in laminated object manufacturing. // Journal of Manufacturing Processes, 3, 2(2001), pp. 94-101.

[18] Luis Pérez, C. J.; Calvet, J. V.; Sebastián Pérez, M.A. Geometric roughness analysis in solid free-form manufacturing process. // Journal of Materials Processing Technology, 119, (2001), pp. 52-57.

[19] Pandey, P.M.; Reddy, N.V.; Dhande, S.G. Improvement of surface finish by staircase machining in fused deposition modeling. // Journal of Materials Processing Technology, 132, (2003), pp. 323-331.

[20] Li, Y.; Zhang, J. Multi-criteria GA-based Pareto optimization of building direction for rapid prototyping. // International Journal of Advanced Manufacturing Technology, 69, 5-8 (2013), pp. 1819-1831.

[21] Pilipović, A.; Raos, P.; Šercer, M. Experimental analysis of properties of materials for rapid prototyping. // International Journal of Advanced Manufacturing Technology, 40, 1-2(2009), pp. 105-115.

[22] Pilipović, A.; Raos, P.; Šercer, M. An Experimental Testing of Quality of Polymer Parts Produced By Laminated Object Manufacturing – LOM. // Tehnički vjesnik-Technical Gazette, 18, 2, (2011), pp. 253-260.

[23] Galeta, T.; Raos, P.; Somolanji, M. Impact of structure and building orientation on strentgh of 3D printed models. // Kautschuk und Gummi Kunststoffe, 65, 10(2012), pp. 36-42.

[24] N. N. Fortus 360mc. Stratysys Corp. 2013. URL: http://www.stratasys.com/3d-printers/production-series/fortus-360mc. (27.06.2013).

[25] Schroettner, H.; Schmied, M.; Scherer, S. Comparison of 3D Surface Reconstruction Data from Certified Depth Standards Obtained by SEM and an Infinite Focus Measurement Machine (IFM). // Microchimica Acta, 155, (2006), pp. 279-284.

[26] Nielsen, H.S. New approaches to surface roughness evaluation of special surfaces. // Precision Engineering, 10, 4, (1988), pp. 209-213.

[27] Sedlacek, M.; Podgornik, B.; Vizintin, J. Influence of surface preparation on roughness parameters, friction and wear. // Wear, 266, (2009), pp. 482-487.

[28] Stout, K. J.; Sullivan, P. J.; Dong, W. P.; Mainsah, E.; Luo, N.; Mathia, T.; Zahouani, H. The development of methods for the characterisation of roughness in three dimensions. Printing Section, University of Birmingham Edgbaston, Birmingham 1993.

Authors' addresses

Grzegorz Krolczyk PhD
Faculty of Production Engineering and Logistics
Opole University of Technology
76 Prószkowska Street, 45-758 Opole, Poland
E-mails: g.krolczyk@po.opole.pl

Pero Raos, Prof. dr. sc.
J. J. Strossmayer University of Osijek
Mechanical Engineering Faculty in Slavonski Brod
Trg Ivane Brlić-Mažuranić 2
35000 Slavonski Brod, Croatia
E-mail: praos@sfsb.hr

Stanislaw Legutko Prof. DSc. PhD. Eng., Prof. h. c.
Faculty of Mechanical Engineering and Management
Poznan University of Technology
3 Piotrowo Street, 60-965 Poznan, Poland
E-mail: stanislaw.legutko@put.poznan.pl