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Analysis of the Torsional Strength of Selected Photopolymers Additively Manufactured Using Polyjet Technology

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PolyJet technology, based on the printing and photopolymerization of model material, is currently, along with stereolithography or 3SP (Scan, Spin and Selectively Photocure), the most commonly used rapid prototyping method based on optically active resin. The article presents the results of torsional strength tests of samples made of optically active resins VeroDentPlus-MED690, VeroClear-RGD810, and Rigur-RGD450 by Stratasys in PolyJet technology. The samples were prepared in HQ (High Quality) mode with a layer height 0.016 [mm]. The tests included a static torsion test using a specialized research stand by the Department of Mechanical Engineering of the Rzeszów University of Technology. The scope of research significantly expanded the standard procedure, which complements the material data available with significant functional parameters due to the use of models. The results of the torsional strength analysis determined in the research process can be used to define the potential application area of the materials in question - optically active resins and their processing techniques for the production of parts subject to complex loads, i.e. machine shafts, clutches, and gear hubs.

Keywords: PolyJet Technology, Rapid Prototyping, Optically Active Resin, Strength Parameters, Torsional Strength

1 Introduction

Rapid prototyping techniques are widely used in many industries, including the aviation industry [1]-[5]. Due to the high accuracy of mapping the CAD (Computer Aided Design) model, additive techniques are used in the process of implementing new construction elements into the production [6]-[8]. The selection of the appropriate RP (Rapid Prototyping) technique depends on many factors [4], [9], such as prototype dimensions, surface quality, geometric accuracy, and the type of research on a test stand planned to be performed [8], [10]-[13]. The most frequently used are additive techniques whose model materials are optically active resins (photopolymers) [14]. These include stereolithography, PolyJet, 3SP [4], [10], [15].

To analyze the stress distribution using elasto-optics and the finite element method (FEM) [16]-[18], it is necessary to know the strength parameters of materials used in RP methods [4], [19], [20]. Numerical calculations of stress values are based on material data. The situation is similar in the case of the application of additively manufactured models in real systems - knowledge of the material properties is also necessary [17].

Taking into account the increase in the use of additive technologies for the production of functional products, there is a need to develop assumptions for the design methodology for the additive manufacturing of machine elements operating in various load ranges, especially torsional loads [21], [22]. Research work to date has mostly included the analysis of basic material and strength parameters in the area of used model materials based on normative samples. There is a small number of studies that would take into account the importance of torsional strength in the case of additively manufactured elements, especially additively processed composites. A clear percentage increase in the number of prototype parts manufactured in AM (Additive Manufacturing) processes used in industrial applications justifies the need to expand the spectrum of research to provide actual material properties under various load conditions.

The research included the creation of standard test models for static torsion testing and the analysis of torsional strength using a specialized test stand by the Department of Mechanical Engineering of the Rzeszów University of Technology. The models were made of optically active resins using the PolyJet technique using the StratasysObjet30 Prime apparatus.

2 Preparation of research models

Test samples were produced using PolyJet technology on an Objet 30 Prime device. The sample model was designed in the Inventor Professional environment and then saved in the .stl format (Standard Triangulation Language). The paths were generated using software dedicated to the printing device used. The dimensional and shape conditions of the samples used in the static torsion test are shown in Fig. 1.

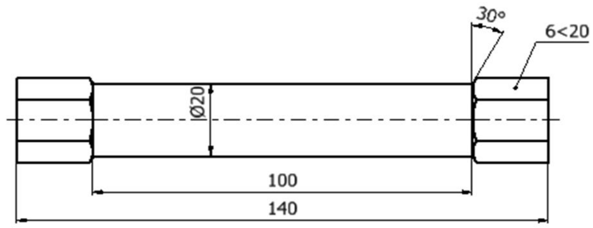

***Fig. 1** Dimensional and shape conditions of the sample for static torsional tests (dimensions are given in [mm])*

The optically active resin VeroDentPlus-MED690, VeroClear-RGD810, and Rigur-RGD450 from Stratasys were used for the tests. The samples were prepared in the HQ mode for a layer height 0.016 [mm]. The supports were generated appropriately to the selected version of the "gloss", in which the support material is only present where it is necessary, and the surfaces that are not in contact with the supports are shiny.

3 Carrying out tests of the functional characteristics of model materials

Torsional strength was determined based on an original test stand constructed for the purpose, equipped with an engine, gear, control system, torque and displacement sensor, test model assembly system, measurement system, and results recorder (Fig. 2).

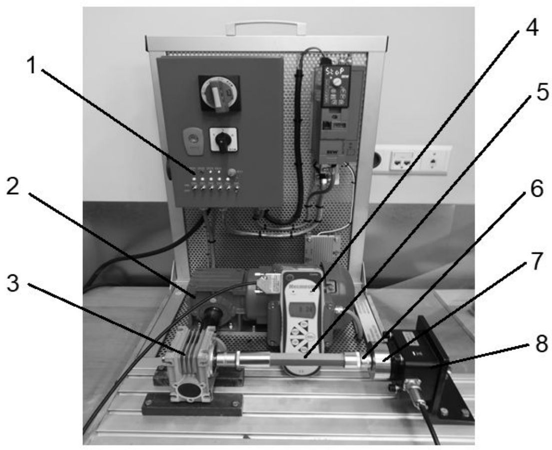

***Fig. 2** Torsion test stand*

Where:
1…Control panel,
2…Electric motor,
3…Gear train,
4…Torque recorder display,
5…Test sample,
6…Sample displacement sensor,
7…Torque sensor,
8…Measuring system.

4 Static torsion test

The test consisted of performing a static torsion test on circular samples. The torque input came from a three-phase motor controlled by an inverter. The torque was transmitted to the sample holder through two worm gears with a total ratio of 1:400. The test results were recorded using a static torque sensor connected to a Mecmesin recorder type AFTI 17-0135-1 equipped with a measurement path and software recording results in real-time. Program processing of the results made it possible to obtain graphs of torque as a function of angular displacement. The forcing was performed with an assumed rotational speed of 0.5 [rpm].

The results from the static torsion test are presented in Tab. 1. Based on the obtained results, average values, standard deviation, and coefficient of variation were calculated. The obtained test results are presented in Fig. 3÷5, which show the dependence of the torque on the torsion angle and a view of the samples after the test.

Based on the obtained test results, it was found that all samples fractured brittlely after the torsion test. However, based on the analysis of torsion curves for the VeroDentPlus-MED690 resin, a clear yield point was observed in the torsion angle range of 72.4 [°] of 82 [Nm]. It should be emphasized here that all determined values of the torque at the total torsion of the sample had much lower values than at the yield point and amounted to an average of 68 [Nm] at a total torsion angle of 207 [°].

Based on the results of torsion tests of samples made of VeroClear-RGD810 resin, the sample behaved like an elastic-brittle body. The samples after torsion tests had clear brittle fractures, which confirms the course of the torsion curve. The average torque value for these samples was approximately 67.7 [Nm] at a torsion angle of 37.3 [°].

In the last stage, torsion tests were performed on samples obtained from Rigur-RGD450 resin. Based on the course of the dependence of the torque on the torsion angle, it can be concluded that a clear yield point characteristic of elastic-plastic bodies was observed. A very high value of the total torsion angle of approximately 309 [°] indicates very good plastic properties of the material. The average torque value was 61.1 [Nm].

The tests carried out on samples made of photopolymers are characterized by repeatability. This confirms that the printing process for all samples was constant over time. Fig. 6 and 7 present the average values of the maximum torque and the torsion angle at fracture for the tested materials.

Tab. 1 *Summary of research results*

	Maximum torque [Nm]			Torsion angle at damage [°]		
	MED690	**RGD810**	**RGD450**	**MED690**	**RGD810**	**RGD450**
Sample 1	80.50	64.10	60.20	230.60	34.30	312.20
Sample 2	82.34	70.20	61.46	231.00	40.50	299.10
Sample 3	83.38	68.84	61.72	159.50	37.10	316.60
Average	82.07	67.71	61.13	207.03	37.30	309.30
Standard deviation	1.46	3.20	0.81	41.17	3.10	9.10
Coefficient of variation	1.78	4.73	1.33	19.88	8.32	2.94

a) b)

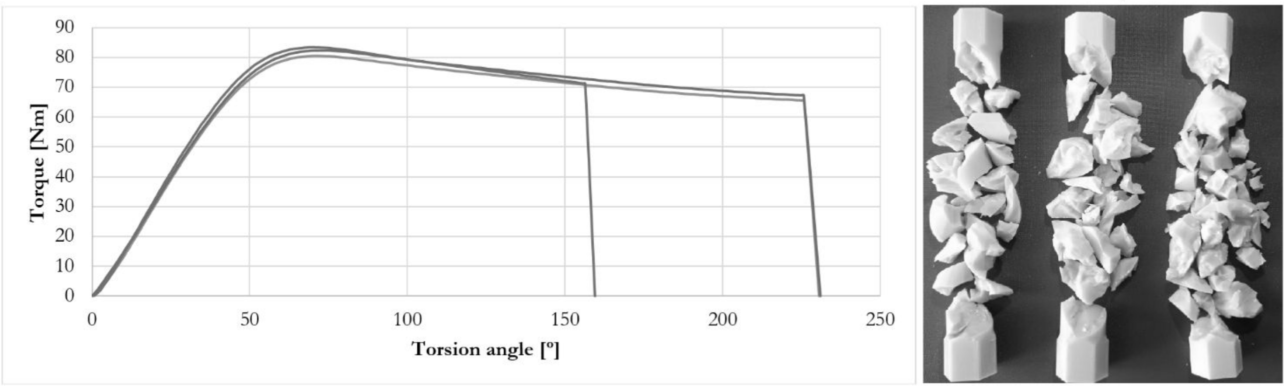

Fig. 3 *Dependence of the torque on the torsion angle for VeroDentPlus-MED690 resin (a) and view of samples after test (b)*

a) b)

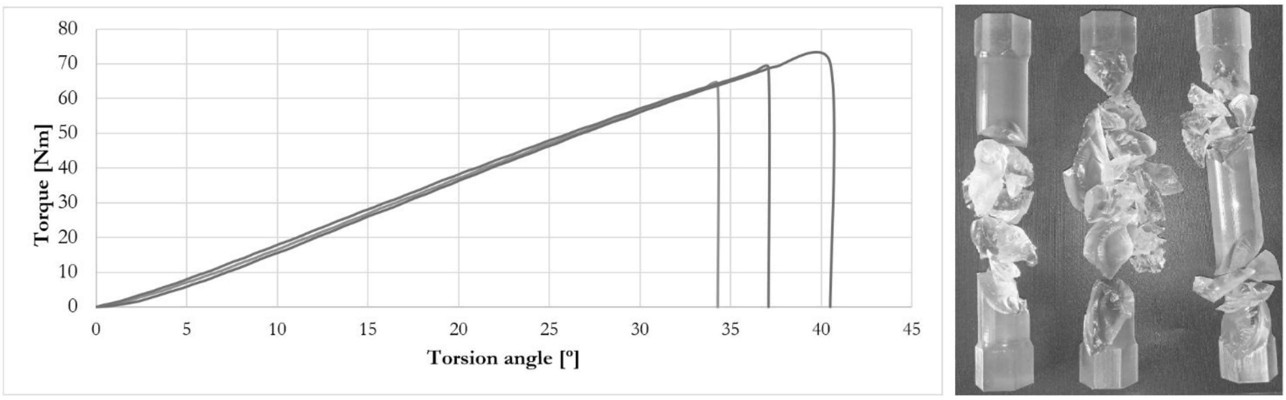

Fig. 4 *Dependence of the torque on the torsion angle for VeroClear-RGD810 resin (a) and view of samples after test (b)*

a) b)

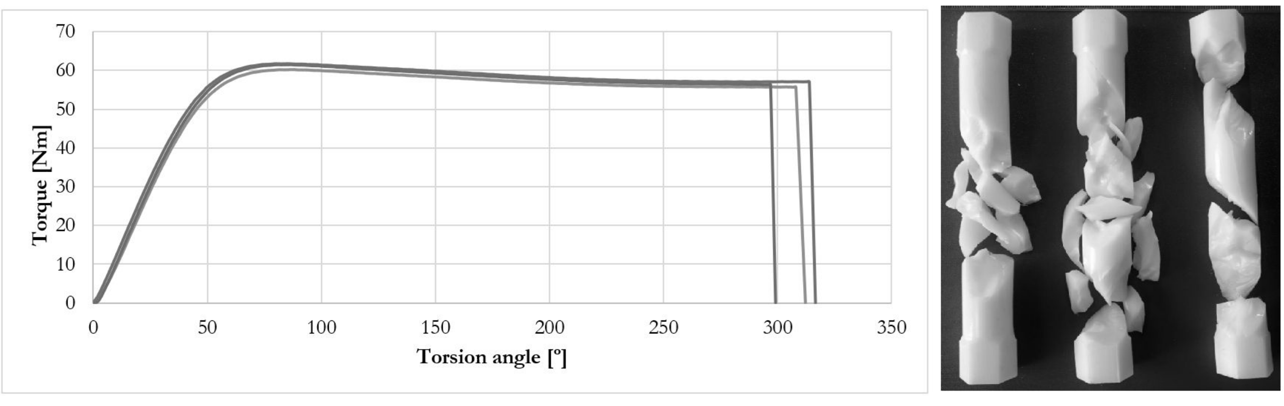

Fig. 5 *Dependence of the torque on the torsion angle for Rigur-RGD450 resin (a) and view of samples after test (b)*

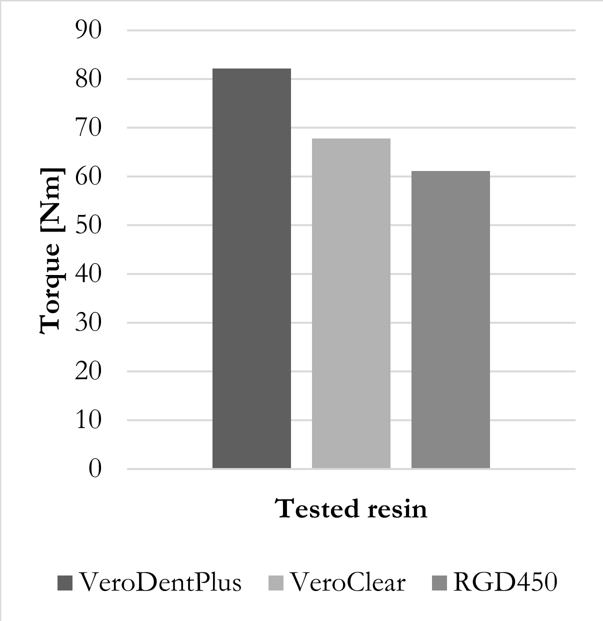

Fig. 6 *The influence of the type of material on the average values of the torque of elements manufactured using the PolyJet technique*

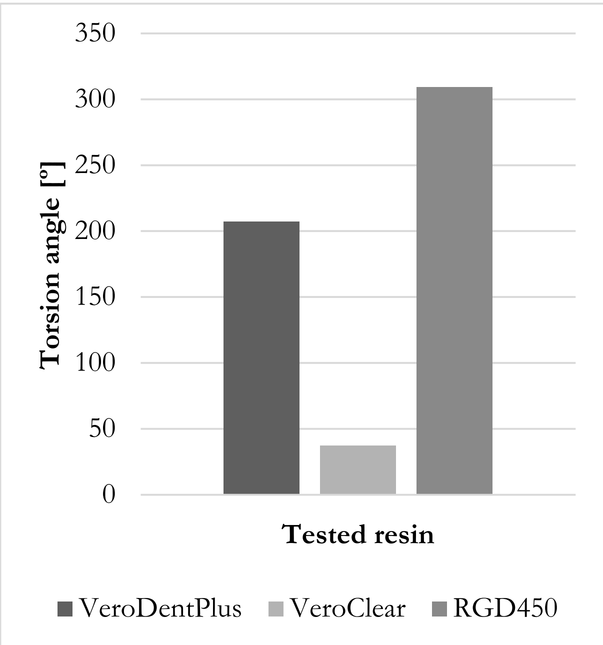

Fig. 7 *The influence of the type of material on the average value of the torsion angle of elements manufactured using the PolyJet technique*

To clearly illustrate the differences in question, a representative parameter for the torsion test was determined - the maximum average torsional stress ($\tau_{s\ max}$) (Tab. 2). Knowledge of the maximum torsional stresses, as well as other stress values determined in strength tests, will allow us to draw practical conclusions regarding the application possibilities of parts manufactured using the PolyJet optically active resin polymerization technique from a given model material.

Tab. 2 *Maximum average torsional stress of the tested materials*

Material	Maximum average torsional stress of tested materials ($\tau_{s\ max}$) [MPa]
MED690	52.27
RGD810	43.13
RGD450	38.94

The determined average value of the maximum torsional stress parameter representative for the question test indicates the best torsional strength of the MED690 material. The RGD 810 resin shows a reduction in strength by over 20 [%], while RGD450 by less than 30 [%].

5 Conclusion

Testing prototypes of machine parts using RP, FEM or elasto-optics requires knowledge of the actual characteristics of the material, including the strength parameters of the model materials. Determining the conditions and load amounts of prototypes on the experimental test stand and the actual (target) work system also requires knowledge of the basic data of material properties. It is worth emphasizing that the manufacturers of model materials (in the analyzed case of photocurable resins) provide only basic technical parameters, based on which it is not possible to carry out the full scope of tests of a given part strictly defined by the applicable testing standard. There are no published data on the torsional strength of the photopolymers in question. The conducted research provides several data regarding the properties of VeroDentPlus-MED690, VeroClear-RGD810, and Rigur-RGD450 resins. The results of strength tests of test models made of photocurable resins show reduced material properties compared to the data declared by the manufacturer (which was confirmed in the course of previously carried out research work).

In the scope of the research in question, it can be concluded that VeroDentPlus-MED690 and Rigur-RGD450 resins are characterized by high torsional strength with simultaneous high torsion angle values, which allows for expanding the area of their application for the production of elements such as shafts, clutches, gear hubs and other elements of drive systems, in which torque is transmitted, and which can increasingly be produced using additive technologies. VeroClear-RGD810 resin is characterized by lower torsional strength and a very small torsion angle (it has properties typical of brittle bodies).

References

[1] SENKERIK, V., BEDNARIK, M., JANOSTIK, V., KARHANKOVA, M., MIZERA, A. (2024). Analysis of Extrusion

Process Parameters in PLA Filament Production for FFF Technology. In: *Manufacturing Technology*, Vol. 24, No. 2, pp. 265–271. DOI: 10.21062/mft.2024.037

[2] BORETTI, A. (2024). A techno-economic perspective on 3D printing for aerospace propulsion. In: *Journal of Manufacturing Processes,* Vol. 109, pp. 607–617. https://doi.org/10.1016/j.jmapro.2023.12.044

[3] GISARIO, A., KAZARIAN, M., MARTINA, F., MEHRPOUYA, M. (2019). Metal additive manufacturing in the commercial aviation industry: A review. In: *Journal of Manufacturing Systems*, Vol. 53, pp. 124–129. https://doi.org/10.1016/j.jmsy.2019.08.005

[4] WOHLERS REPORT (2018). 3D Printing and Additive Manufacturing: State of the Industry. Annual Worldwide Progress Report

[5] BUDZIK, G., WOŹNIAK, J., PRZESZŁOWSKI, Ł. (2022). *Druk 3D jako element przemysłu przyszłości. Analiza rynku i tendencje rozwoju.* Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów, Poland.

[6] TULI, N. T., KHATUN, S., RASHID, A. B. (2024). Unlocking the future of precision manufacturing: A comprehensive exploration of 3D printing with fiber-reinforced composites in aerospace, automotive, medical, and consumer industries. In: *Heliyon*, Vol. 10, Issue 5. https://doi.org/10.1016/j.heliyon.2024.e27328

[7] ALI, M. H., ISSAYEV, G., SHEHAB, E., SARFRAZ, S. (2022). A critical review of 3D printing and digital manufacturing in construction engineering. In: *Rapid Prototyping Journal*, Vol. 28, No. 7, pp. 1312–1324. https://doi.org/10.1108/RPJ-07-2021-0160

[8] JANDYAL, A., CHATURVEDI, I., WAZIR, I., RAINA, A., HAQ, M. I. U. (2022). 3D printing - A review of processes, materials and applications in industry 4.0. In: *Sustainable Operations and Computers*, Vol. 3, pp. 33-42. https://doi.org/10.1016/j.susoc.2021.09.004

[9] ALEXOPOULOU, V. E., CHRISTODOULOU, I. T., MARKOPOULOS, A. P. (2024). Investigation of Printing Speed Impact on the Printing Accuracy of Fused Filament Fabrication (FFF) ABS Artefacts. In: *Manufacturing Technology*, Vol. 24, No. 3, pp. 333–337. DOI: 10.21062/mft.2024.042

[10] DEV, S., SRIVASTAVA, R. (2020). Experimental investigation and optimization of FDM process parameters for material and mechanical strength. In: *Materials Today: Proceeding*, Vol. 26, Part 2, pp. 1995-1999. https://doi.org/10.1016/j.matpr.2020.02.435

[11] PENG, F., VOGT, B. D., CAKMAK, M. (2018). Complex flow and temperature history during melt extrusion in material extrusion additive manufacturing. In: *Additive Manufacturing*, Vol. 22, pp. 197–206. https://doi.org/10.1016/j.addma.2018.05.015

[12] GE, Q., WANG, Y. (2024). Development and Simulation of a Hybrid Extrusion Mechanism for Enhanced Surface Quality and Precision in FDM Printing. In: *Manufacturing Technology*, Vol. 24, No. 3, pp. 338–343. DOI: 10.21062/mft.2024.045

[13] BECHNÝ, V., MATUŠ, M., JOCH, R., DRBÚL, M., CZÁN, A., ŠAJGALÍK, M., NOVÝ, F. (2024). Influence of the Orientation of Parts Produced by Additive Manufacturing on Mechanical Properties. In: *Manufacturing Technology,* Vol. 24, No. 1, pp. 2–8. DOI: 10.21062/mft.2024.021

[14] WEI, G., ZHU, J., YUAN, J., ZHOU, Y., MIAO, J.-T., YAN, J., LIU, R. (2024). Solvent-free high-performance photocurable 3D printing resin from a noncoplanar branched maleimide oligomer for high-resolution fabrication. In: *Additive Manufacturing*, Vol. 79. https://doi.org/10.1016/j.addma.2023.103924

[15] KOTROCZ, L., BAKONYI, P. (2023). Investigation the temperature-dependent surface mechanical properties of PolyJet printed samples by cyclic indentation testing in a DMA system. In: *Results in Materials*, Vol. 17. https://doi.org/10.1016/j.rinma.2022.100360

[16] STAMPONE, B, RAVELLI, M., GIORLEO, L., TROTTA, G. (2023). Thermal behaviour of resin inserts for micro injection moulding: a FEM analysis. In: *Procedia Computer Science*, Vol. 217, pp. 1360–1369. https://doi.org/10.1016/j.procs.2022.12.334

[17] BUDZIK, G., DZIUBEK, T., PRZESZŁOWSKI, Ł. P., SOBOLEWSKI, B., DĘBSKI, M., GONTARZ, M. E. (2023). Study of unidirectional torsion of samples with different internal structures manufactured in the MEX process. In: *Rapid Prototyping Journal*, Vol. 29, No. 8, pp. 1604-1619. https://doi.org/10.1108/RPJ-09-2022-0332

[18] KHOSRAVANI, M. R., SOLTANI, P., REINICKE, T. (2023). Failure and fracture in adhesively bonded 3D-printed joints: An

overview on the current trends. In: *Engineering Failure Analysis*, Vol. 153. https://doi.org/10.1016/j.engfailanal.2023.107574

[19] JIN, F., LU, W., AN, X., ZHU, H., WANG, J. (2024). Mechanical Properties and Compression Performance of 3D Printed HIPS Polymer Lattice Structure. In: *Manufacturing Technology,* Vol. 24, No. 3, pp. 378–392. DOI: 10.21062/mft.2024.054

[20] LEE, J., PARK, D., PARK, K., SONG, H., KIM, T.-S., RYU, S. (2024). Optimization of grid composite configuration to maximize toughness using integrated hierarchical deep neural network and genetic algorithm. In: *Materials & Design*, Vol. 238. https://doi.org/10.1016/j.matdes.2024.112700

[21] BALDERRAMA-ARMENDARIZ, C. O., MACDONALD, E., ESPALIN, D., CORTES-SAENZ, D., WICKER, R., MALDONADO-MACIAS, A. (2018). Torsion analysis of the anisotropic behavior of FDM technology. In: *The International Journal of Advanced Manufacturing Technology*, Vol. 96, pp. 307-317. https://doi.org/10.1007/s00170-018-1602-0

[22] DĘBSKI, M., MAGNISZEWSKI, M., BERNACZEK, J., PRZESZŁOWSKI, Ł., GONTARZ, M., KIEŁBICKI, M. (2021). Influence of torsion on the structure of machine elements made of polymeric materials by 3D printing. In: *Polimery*, Vol. 66, No. 5, pp. 298–303. dx.doi.org/10.14314/polimery.2021.5.3