



Evaluation of Various AM Technologies Focused on their Accuracy and Strength

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Abstract. The paper deals with an evaluation of the manufacturing accuracy of various Additive Manufacturing technologies. Firstly, a special test artifact was designed for accuracy assessment and investigated not only with respect to the dimension tolerances but also regarding the possibility to assemble/disassemble specific protrusions and holes. Similarly, appropriate criteria were proposed and used to compare test artifacts made by various machines. The second main part of the paper focuses on the mechanical investigation of a selection of tested materials/technologies. To verify their tensile and compressive tests under high temperature conditions were performed. In conclusion, study tables, including accuracy and strength parameters, are presented.

Keywords: Additive Manufacturing, 3D scanning, geometrical tolerances, tensile/compressive test.

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Nomenclature

ABS	Acrylonitrile Butadiene Styrene = amorphous thermoplastic
AM	Additive Manufacturing
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
HDT	Heat Deflection Temperature
PC-ABS	Polycarbonate-ABS
PLA	Polylactic Acid = biodegradable thermoplastic
SLS	Selective Laser Sintering
ULTEM	Advanced polyetherimide
Alumide	Composite material consisting of nylon filled with aluminum particles

1 INTRODUCTION

In view of the wide range of Additive Manufacturing (AM) technologies available, it has become essential to distinguish suitable machines and materials for specific intentions. Architecture focuses on building thin walls and huge models, medicine focuses on biologically friendly materials and mechanical properties, while artistic design focuses on various colors and visual properties of the end product. In case of mechanical engineering, if it is taken generally, tolerances fulfillment and strength of material are important in AM technologies applied in the industry.

Even though AM has strong potential, even big companies are very careful with procurement of state-of-the-art technology. They have several reasons, such as machine training and service costs, incertitude of investment return, preparation of designers, lack of possible effective applications replacing traditional technologies, etc. This paper describes the initial phase of AM implementation into traditional heavy industry. ZF is a global leader in the field of powertrain and technologies of chassis as well as active and passive safety technology, and it is one of three biggest suppliers for the automotive industry worldwide. Portfolio of ZF Slovakia involves chassis components, suspension modules, transmission modules, complete clutches and torque converters. The team which elaborated this study is focused on research of a dual-mass flywheel with the objective to improve its quality and to minimize its assembling and weight. Fabrication using AM technology may bring expected improvement of the end product. Nevertheless, only advanced plastics and durable composites were chosen for further tensile/compressive tests since those are the best candidates for expected applications.

2 TEST ARTIFACT SELECTION

There have been several research projects dealing with AM technologies in terms of their accuracy [1–8]. Authors have usually described general comparisons of devices and selected geometrical tolerances. Some authors have divided several technologies into IT grades [8] and some have even investigated the surface texture characterization [10]. The collaborative project in the framework of which the presented study has been performed investigates the artifact from the design point of view and looks into another important aspect of 3D printed components – their assembling.

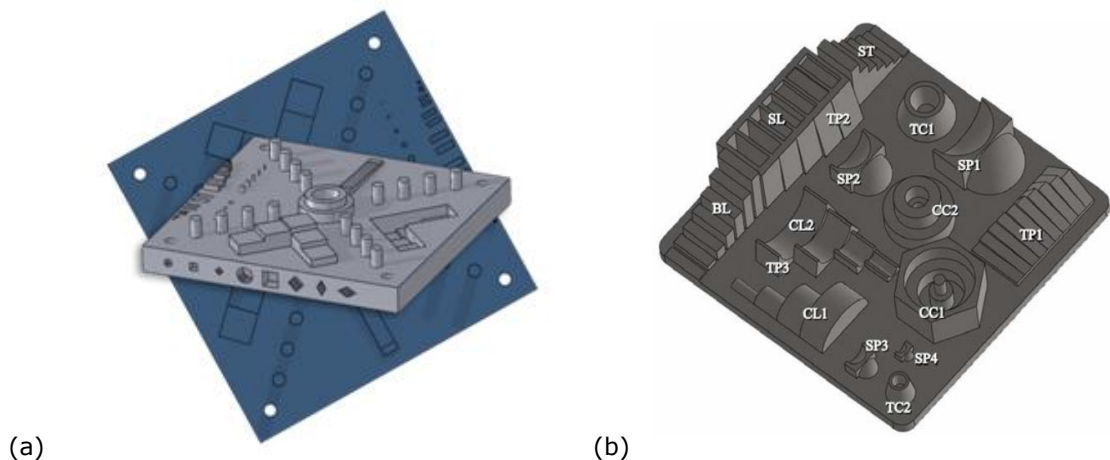


Figure 1: (a) Moylan test artifact for AM machines and processes from NIST [9], (b) a benchmarking model for enhancing the dimensional accuracy of a low-cost 3D printer [11].

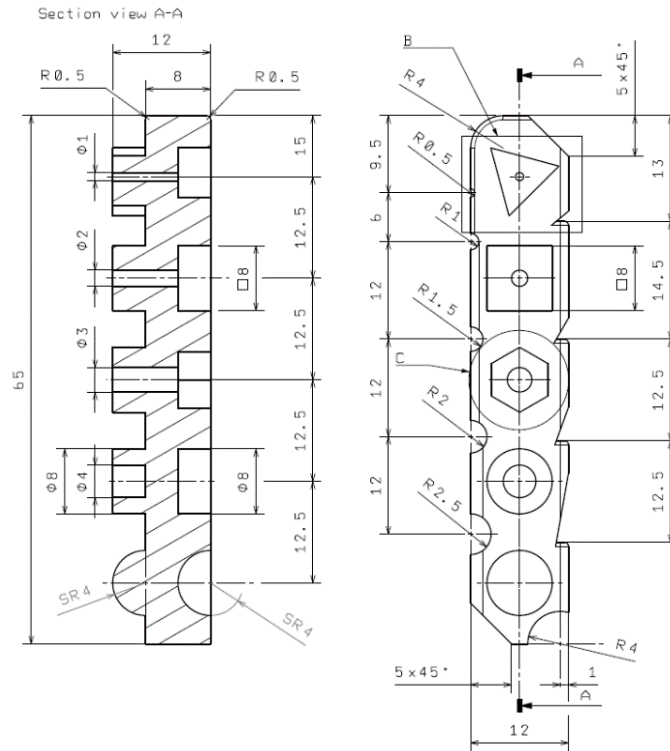


Figure 2: Dimensions [mm] of a test artifact designed specifically for this study.

Previous works were focused on the evaluation of dimensional accuracy using similar artifacts to verify it. Figure 1 shows artifacts from some previously published studies [9,11]. The main goal there was to compare features of various dimensions with the virtual model. Various protrusions or holes with dimensions from only several tenths of a millimeter up to several dozen millimeters were built. Selection of the size of the artifact and its details are based on commonly fabricated components using devices of build volume noted in Table 1.

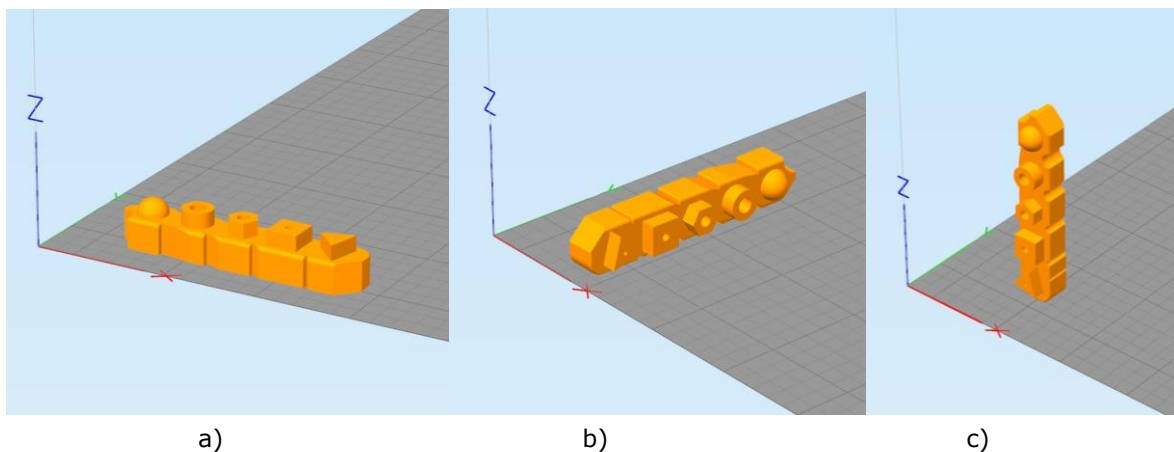


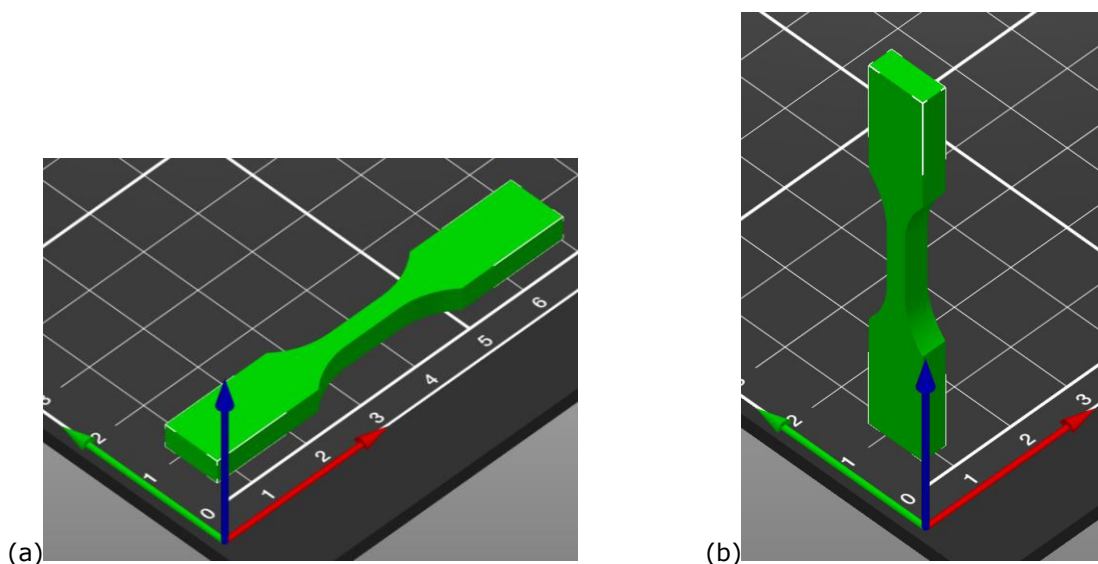
Figure 3: Three different orientations of the test artifact labeled as: a) XY, b) YZ, c) ZX.

The main advantage of using consolidated design of a test artifact is to compare results with other workplaces using the same base, such as Moylan artifact shown in Figure 1a. However, for this project it was necessary to design an artifact of a relatively small volume having fewer protrusions and holes in order to minimize the evaluation time. Accuracy evaluation was prepared in form of a template and any new artifact was automatically verified after 3D scanning. Dimensions of the proposed artifact is shown in Figure 2. Finally, the reason for designing our own model was to enable assembly testing. It means the study involves the fastening of protrusions into holes to compare specific assembly possibilities. Important requirement here is to simply verify fitting spherical, cylindrical or planar features into designated holes. Result of such study is in a form of 0% or 100% for fitting of each to each artifact in one set. Every set consists of three identical artifacts printed from the same material using the same printer having the same orientation. Three proposed orientations are shown in Figure 3. It was expected and later confirmed that the orientation ZX has a too small surface of contact with the printer base, therefore SLA technology and hobby printers were unable to build it [5].

3 MATERIALS AND TECHNOLOGIES SELECTION

At the time this study was launched, tough materials became popular for printing technology development and advanced materials are now more common and may be chosen from wider range than before this study. The selection of evaluated technologies was influenced by the choice of suppliers in the region, therefore any future supplying would be efficient. Materials selected for further tensile and compressive testing have all heat deflection temperature HDT over 100°C and ultimate tensile strength over 45 MPa except for PC-ABS. PC-ABS was chosen as a tough replacement of a common ABS. An accuracy comparative study helped to omit Digital ABS from mechanical testing, while specimens made of it are difficult to be assembled.

Table 1 shows a list of hobby and professional machines used to print the test artifact. Comparatively common size of the base is about 200x200mm, while professional devices have at least one dimension bigger, such as Fortus 250mc, Objet Eden 260, Fortus 400mc and EOS P380. Resolution of any AM machinery is limited by the minimum thickness of the layers. Hence SLA technology declare lower deviation from theoretical dimensions.



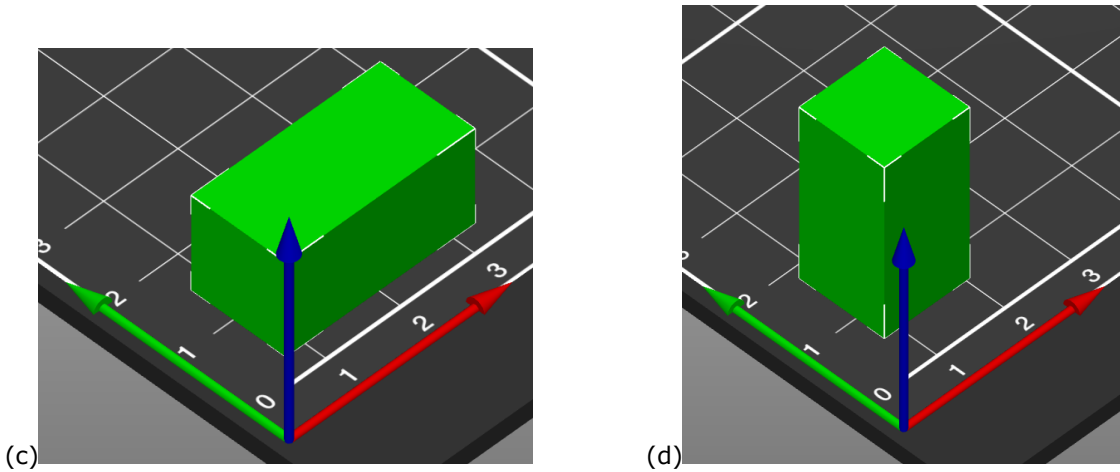


Figure 4: Orientation setup of printing for tensile and compression sample: (a) tensile sample orientation XY, (b) tensile sample orientation ZX, (c) compressive sample orientation XY, (d) compressive sample orientation ZX.

Accuracy of the technology is a crucial limit which disqualifies most of the AM devices from implementation to industrial applications. On the other hand, the accuracy is quite predictable and future designing process might be adjusted to this fact. Comparatively important here are mechanical properties of future products. Datasheets of plastic and composite materials normally involves Young modulus, tensile/compressive strength, density, hardness, elongation at break, impact strength and limiting temperatures. For the investigation of tensile/compressive strength, three materials were chosen from the selection in Table 2 – ULTEM, PC-ABS, Alumide. These were predicted to be used for fabrication of tooling, fixtures and advanced prototypes.

	Type of AM technology	Materials selection for the study	Build volume [mm]	Layer thickness [μm]	Accuracy declared [μm]
LeapFrog Creatr HS	FDM	PLA, ABS	240x280x180	200	± 200
Prusa i3 MK2	FDM	PLA	250x210x200	50	-
Fortus 250mc	FDM	ABS	254x254x305	178	± 241
Fortus 400mc	FDM	ULTEM, PC-ABS	406x355x406	127	± 127
Objet Eden 260	SLA	VeroWhite, Rubber-like, Digital ABS	255x252x200	16	$\pm 20 \div 85$
Makerbot	FDM	PLA	285x153x155	100	-
EOS P380	SLS	Alumide	350x350x627	150	± 150

Table 1: Basic parameters of machinery used for fabrication of artifacts.

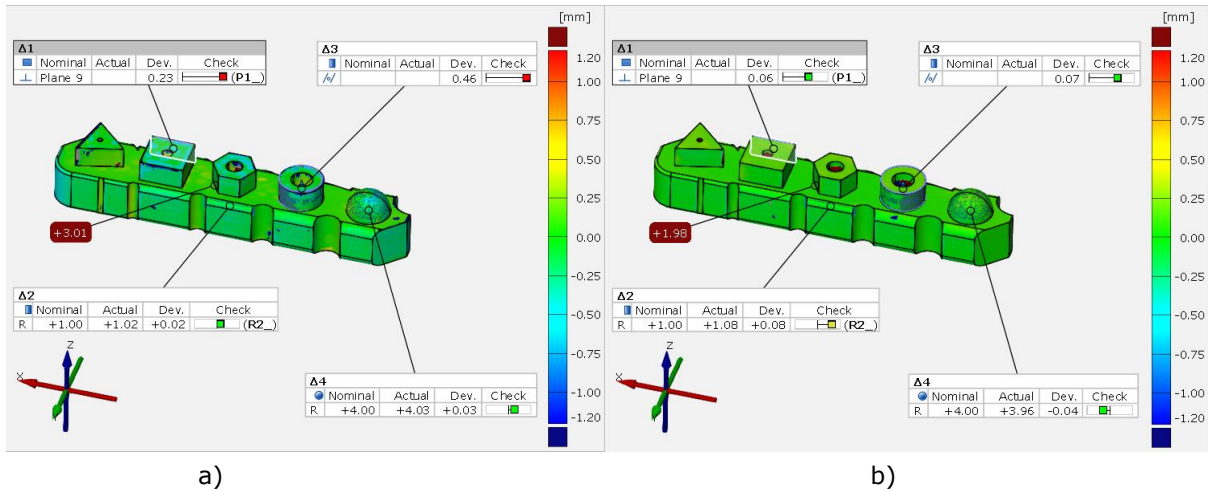


Figure 5: Overall deviation map with labels of specific tolerances: a) More accurate artifact, b) Less accurate artifact.

4 A COMPARATIVE STUDY

The dimensional accuracy assessment of the artifacts' geometry was performed using an ATOS Compact scan 2M optical 3D scanning device, which is suitable for a high-accuracy quality check. This is estimated to be accurate to about 0.002mm in optimal light conditions. Overall deviation map is shown in Figure 5 comparing less accurate artifact with the one more accurate, while the same legend is used. Deviations $\Delta 1$, $\Delta 2$, $\Delta 3$ and $\Delta 4$ demonstrates some of investigated in the study, which are compared in Table 2.

Several geometrical features were examined and linked to various geometries commonly used in practice. Altogether, 18 different features such as cylindricity, planarity and various dimensions were measured using GOM Inspect software a professional 3D scanning tool.

Various devices were used to fabricate approximately 80 artifacts, which were digitized, compared to a CAD model and then the deviation was reported. Table 2 shows only some of the examined geometrical features. $\Delta 1$ measures the perpendicularity of a block plane, $\Delta 2$ measures the radius of an edge fillet, $\Delta 3$ measures the cylindricity of the outer cylindrical feature, and $\Delta 4$ measures the radius of the outer spherical feature. The resulting ranking of accuracy was made based on an average deviation of 18 features. Table 2 also shows a comparison of assembling possibilities. There were always 2 or 3 artifacts within a specific orientation group and their protrusions and holes were fitted together using a different shape. 0% means no protrusions fit to a corresponding hole and 100% means all the protrusions fitted into their holes. The comparison test artifact was designed with 0.00mm clearance.

Technology & orientation	$\Delta 1$	$\Delta 2$	$\Delta 3$	$\Delta 4$	Assembling	Ranking
PLAPrusa_XY	0.04	0.10	0.07	0.17	100%	12
PLAPrusa_YZ	0.07	0.09	0.17	0.10	57%	14
PLALeapfrog_XY	0.26	0.03	0.42	0.05	0%	26
PLALeapfrog_YZ	0.07	0.15	0.49	0.09	13%	22
ABSLeapfrog_XY	0.24	0.12	0.27	0.08	0%	23
ABSLeapfrog_YZ	0.07	0.21	0.28	0.04	0%	21

ABSFortus_XY	0.06	0.07	0.06	0.04	87%	2
ABSFortus_YZ	0.19	0.09	0.19	0.04	97%	10
ABSFortus_ZX	0.07	0.08	0.22	0.04	100%	1
PCABS_XY	0.11	0.13	0.19	0.06	87%	8
PCABS_YZ	0.16	0.16	0.23	0.11	33%	17
PCABS_ZX	0.08	0.37	0.23	0.01	30%	10
Ultem_XY	0.10	0.24	0.10	0.14	70%	10
Ultem_YZ	0.16	0.05	0.31	0.17	33%	11
Ultem_ZX	0.08	0.44	0.29	0.08	23%	9
VeroWhite_XY	0.08	0.18	0.14	0.06	57%	4
VeroWhite_YZ	0.08	0.08	0.18	0.04	43%	3
PLAMarkerbot_XY	0.17	0.17	0.38	0.13	0%	11
PLAMarkerbot_YZ	0.31	0.10	0.25	0.03	0%	7
DigitalABS_XY	0.09	0.03	0.22	0.05	0%	5
DigitalABS_YZ	0.04	0.26	0.12	0.08	60%	8
Rubber-like_XY	0.24	0.19	0.25	0.10	100%	4
Rubber-like_YZ	0.06	0.21	0.27	0.08	100%	3
Alumide_XY	0.12	0.22	0.10	0.13	100%	5
Alumide_YZ	0.13	0.08	0.19	0.02	17%	1
Alumide_ZX	0.09	0.26	0.21	0.05	83%	1

Table 2: Resulting comparative study of all combinations of orientations and technologies.

5 TENSILE AND COMPRESSIVE TESTING OF SELECTED MATERIALS

The final stage of this wide study was to demonstrate the most important static mechanical properties of selected materials, thus enabling further accurate estimation of their applicability. Based on their data sheets, high strength materials were chosen. Before any testing was carried out, it was necessary to prepare the geometry of tensile and compressive samples. These experiments are well-known and most widely used, therefore a common ASTM standard was used - ASTM D 638-02a for the tensile and ASTM D 695-02a for the compression test. A geometrical model was chosen from these standards and is shown in Figure 4. Both compressive and tensile specimens were oriented in two possible ways to examine the best and the worst orientation.

Many studies have already been carried out, mostly by manufacturers of the filament or other printing materials. However, the research presented here offers several improvements. One improvement is to link experiments with the comparative study. Hence, technologies which were chosen for the strength testing fulfilled the best dimensional accuracy. Another one is the selection of printing orientation and fiber arrangement in FDM technology. The final improvement is to associate some experiments in a higher temperature environment, up to 200°C.

Three explanatory tests are published here. Firstly, Figure 6 shows two tensile diagrams with comparison of different orientations made of Alumide. Here are shown raw data from an average tensile experiment and diagram shows significant difference in case of FDM technology when layers are pulled apart in normal direction. Hence, the orientation XY reached higher ultimate displacement and force compared to the orientation ZX. Similarly, three other materials were

tested for tensile and compression in a batch of 10 samples. Since ULTEM 1010 samples reached the best results, they were chosen for testing in higher temperatures.

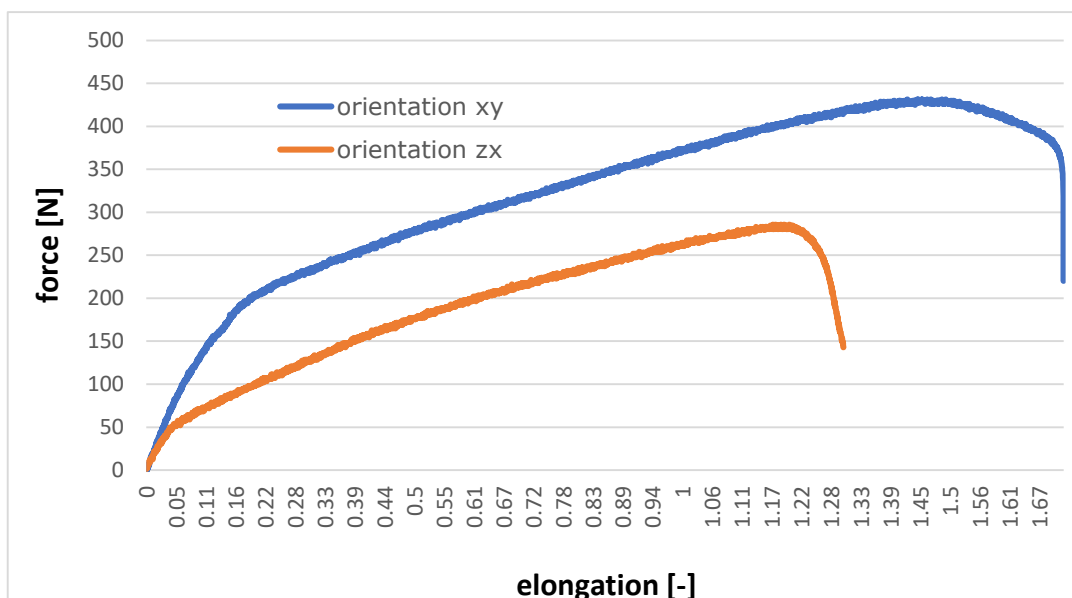


Figure 6: Tensile test of two average exemplary samples having different orientation of printing made of Alumide.

Secondly, Figure 7 shows general comparison of all samples tested with tensile load complemented with scattering boundaries. The average value was calculated from tensile strength of a set of 10 samples. Following data describes a comparison of tested samples with manufacturer data sheet values. In case of ULTEM 1010, ultimate tensile strength is 81MPa for the orientation XY and 48MPa for the orientation ZX, while average tested values were higher – 101.7MPa for XY and 50.5MPa for ZX. ULTEM 9085 has the ultimate strength 69MPa for the orientation XY and 42MPa for the orientation ZX. Average values of ultimate strength measured during testing were 76.7MPa for XY and 45.8 for ZX. In case of PC-ABS and Alumide, only one value of tensile strength is in datasheet using the test method ASTM D638, 41MPa for PC-ABS and 48MPa for Alumide. These were not reached, and measured values are for PC-ABS 35.5MPa in XY and 16.3MPa in ZX, for Alumide 29.4MPa in XY and 22.48MPa in ZX. Alumide concluded with the smallest difference between orientations, the main reason is a better interconnection between layers in comparison to FDM technologies, where the interface between layers is more significant.

Finally, Figure 8 and 9 show comparison of tensile or compressive tested samples, which were elaborated in a special chamber heated up to 140°C, 160°C, 180°C and 200°C. Characteristics declaring high temperature resistance in material datasheets are based on ASTM D648. However, the testing procedure is not corresponding with possible conditions in future projects. Hence, an original process of strength testing was developed. Dashed line in Figure 8 and 9 outlines an ultimate strength in different temperatures.

6 CONCLUSION

This paper briefly presented a wide comparative study of applicability of components fabricated using AM technologies, which uses high-strength plastics or composite materials. When the measured accuracy and assembling possibilities are combined, the best technology resulted in

Fortus 250mc and EOS P380. It can be concluded from the study in Table 2. On the other hand, Alumide artifacts built by EOS P380 were not satisfactory when assembled, since the outer surface was too ragged. Assembling of Alumide artifacts is shown in Figure 10. EOS machine was no longer considered as the best solution for structural components, since it needs postprocessing for the outer surface. On the other hand, the most accurate Fortus 250mc is used daily at the Laboratory of Generative Engineering Design for small series of surface-based components.

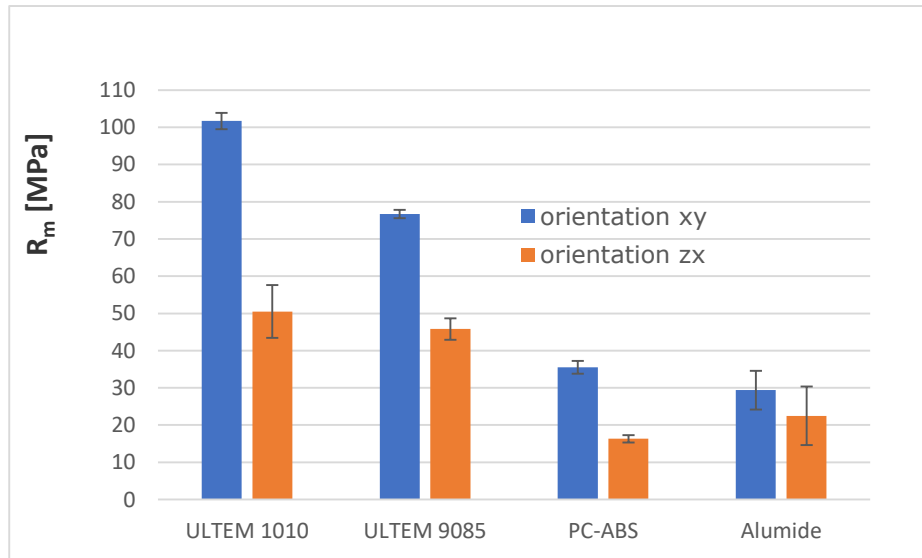


Figure 7: Comparison of tensile testing results in room temperature with scattering.

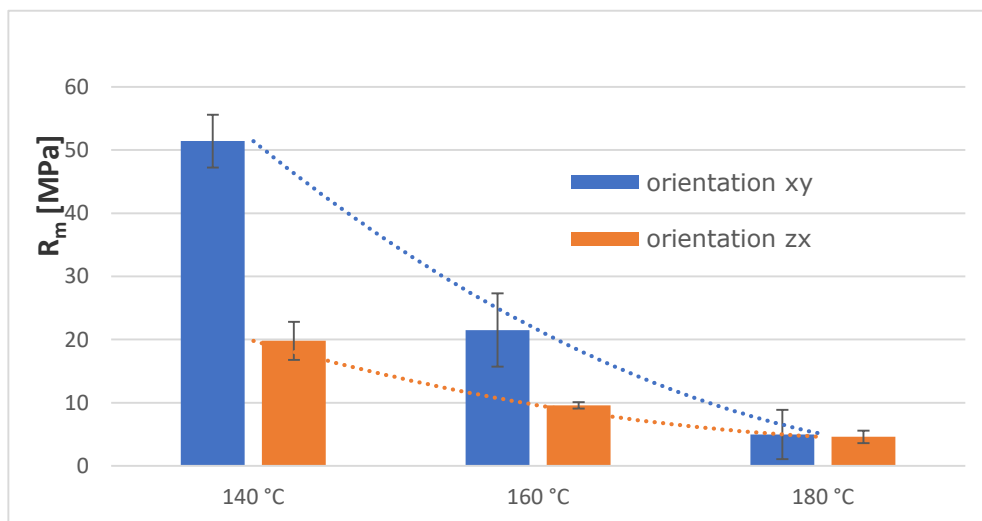


Figure 8: Comparison of tensile testing results of ULTEM 1010 in higher temperatures with scattering.

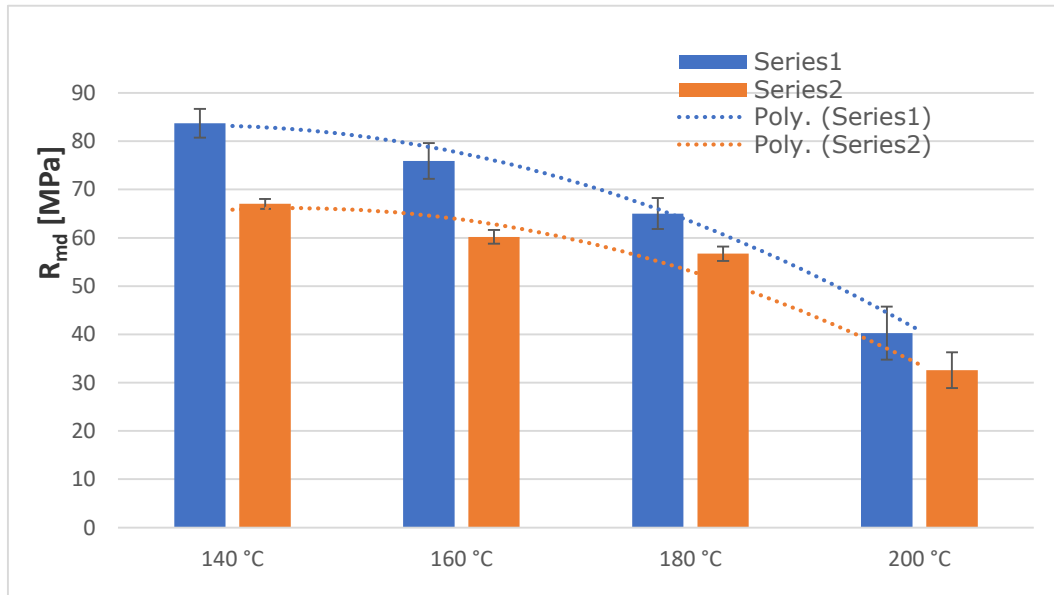


Figure 9: Comparison of compressive testing results of ULTEM 1010 in higher temperatures with scattering.

A part of tensile and compression studies is shown in Figure 6, 7, 8 and 9. As it was expected, orientation is far more crucial for an FDM technology in comparison to powder in case of Alumide material. Significantly best tensile strength was achieved with a special FDM plastic material ULTEM 1010. This study has already affected procurements at both cooperating workplaces. It is planned to extend this study with new technologies and design an algorithm for finding the best combination of material and orientation of each new component to be printed.

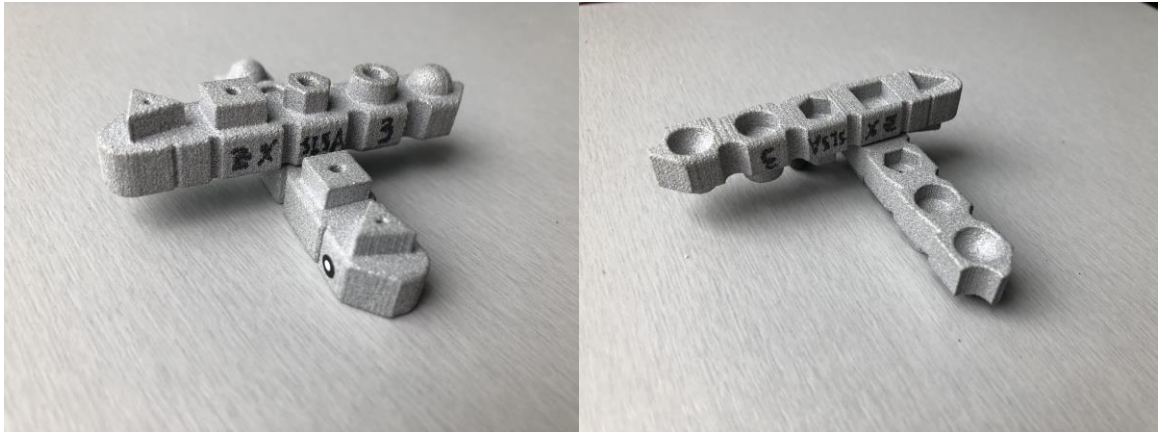


Figure 10: An illustration of assembling two Alumide artifacts fabricated using the orientation ZX.

An ongoing project is focused on real implementation of 3D printed components in a dual-mass flywheel. Sliding shoes made for this assembly need to withstand high frequencies, impact load and even more than 80°C when operated. Figure 8 shows degradation of properties during tensile load, however these sliding shoes will only be compression stressed.

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