Title:
Precision and Strength Comparison of Various AM Technologies in View of their Applicability in the Automotive Industry

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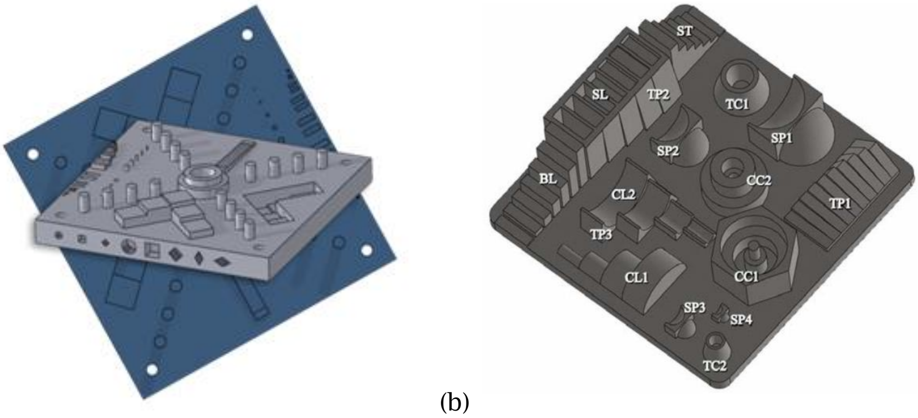
Introduction:
In view of the wide range of Additive Manufacturing (AM) technologies available, it has become essential to distinguish suitable machines and materials for specific intentions. Architecture focuses on building thin walls and huge models, medicine focuses on biologically friendly materials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



(a) (b)

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

The paper deals with a comparison of the manufacturing accuracy of various Additive Manufacturing technologies. Firstly, a special specimen 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 specimens made by various machines. The second main part of the paper focuses on the mechanical investigation of a selection of tested materials/technologies. In the conclusion, study tables, including the precision and strength parameters, are presented.

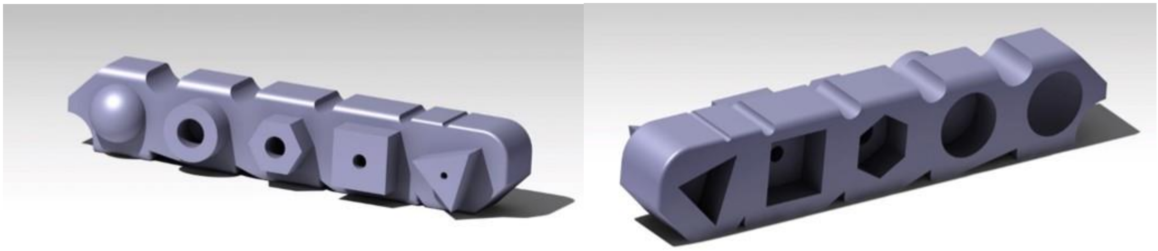


Fig. 2: A specimen designed especially for the presented comparative study.

Specimen 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 sample design point of view and looks into another important aspect of 3D printed components – their assembling.

	Δ1	Δ2	Δ3	Δ4	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
MakerbotPLA_XY	0,17	0,17	0,38	0,13	0%	11
MakerbotPLA_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

Tab. 1: Resulting comparative study of all combinations of technologies and orientations.

Previous works were focused on the evaluation of dimensional precision using similar artifacts to verify it. Fig. 1 shows artifacts from some previously published studies. The main goal there was to compare features of various dimensions. Various protrusions or holes with dimensions from only several tenths of a millimeter up to several dozen millimeters were built. The main advantage of using consolidated design of a test artifact is to compare results with other workplaces using the same base. However, for this project it was necessary to design a sample of a small volume having fewer protrusions and holes, in order to minimize evaluation time. The proposed artifact is shown in Fig. 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.

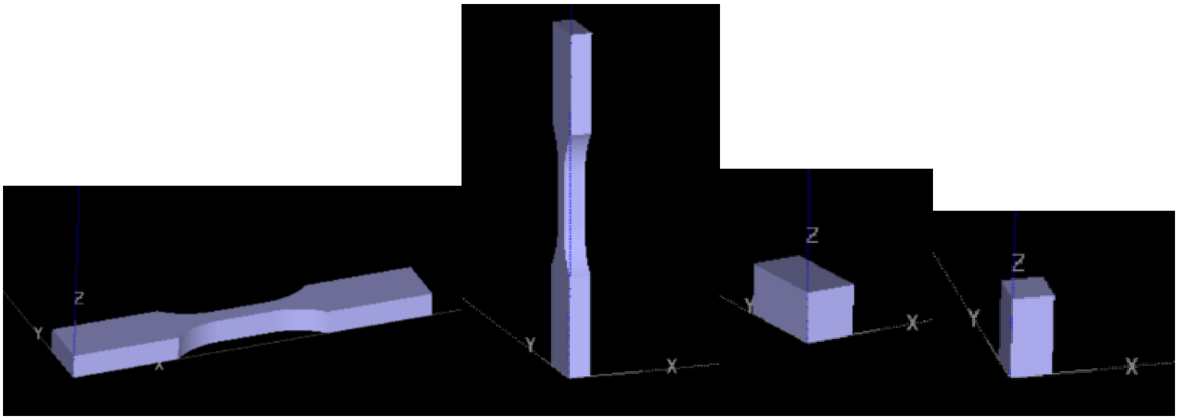


Fig. 3: Orientation set-up of printing for tensile and compression specimen.

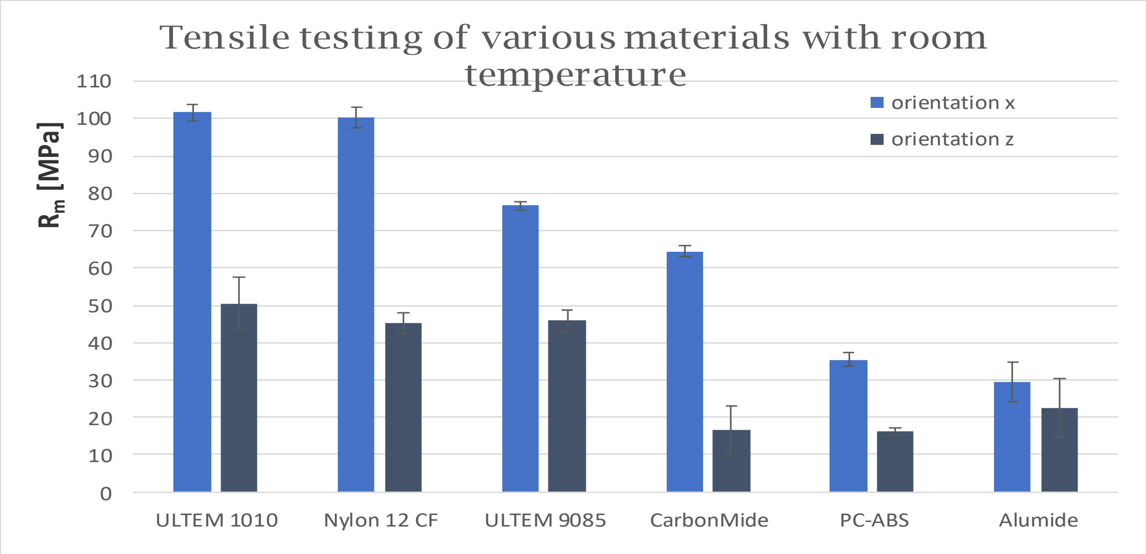


Fig. 4: Comparison of tensile testing results with scattering.

<u>A Precision Comparative Study:</u>
The dimensional accuracy assessment of the specimens' geometry was performed using an ATOS Compact scan 2M optical 3D scanning device, which is suitable for a high precision quality check. This is estimated to be accurate to about 0.002mm in optimal light conditions.

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 45 specimens, which were digitized, compared to a CAD model and then the deviation was reported. Table X shows only some of the geometrical features examined. Δ_1 measures the perpendicularity of a block plane, Δ_2 measures the radius of an edge fillet, Δ_3 measures the cylindricity of the outer cylindrical feature, and Δ_4 measures the radius of the outer spherical feature. Tab. 1 also shows a comparison of assembling possibilities. There were always 2 or 3 specimens within a specific orientation group and their protrusions and holes were fitted together using a different shape. 0% means no protrusion fit to a corresponding hole and 100% means all the protrusions fitted into their holes. The comparison specimen was designed with 0.00mm clearance.

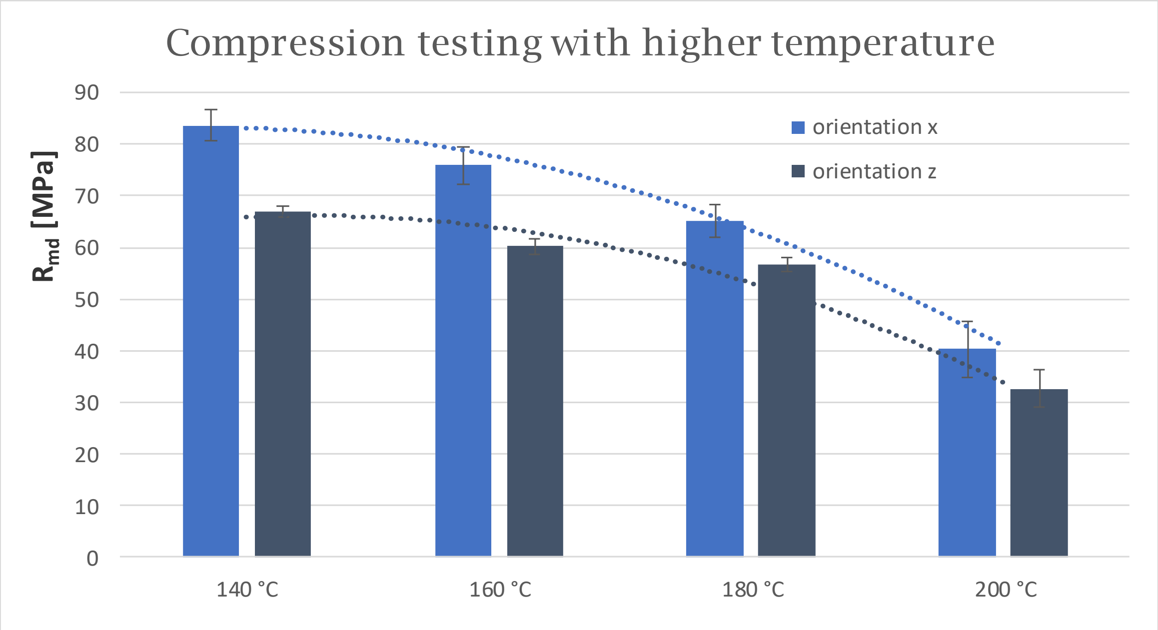


Fig. 5: Decreasing tendency of compression tested ULTEM 1010 specimen with scattering.

<u>Tensile and Compressive Testing of Selected Materials:</u>
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 a geometry of tensile and compressive specimens. 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 Fig. 3.

Many studies have already been carried out, mostly by manufacturers of the filament or other printing materials. However, the research presented here offers a few improvements. One improvement is to link experiments with the precision study. 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.

Results and Discussion:
This paper briefly presented a wide comparative study of applicability of components fabricated using AM technologies, which uses high-strength plastics or composite materials. A part of tensile and compression studies is shown in Fig. 4 and 5. 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 and composite material ULTEM 1010 and NYLON 12 CF. 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.

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