FUSED DEPOSITION MODELLING VS. INJECTION MOULDING: INFLUENCE OF FIBER ORIENTATION AND LAYER THICKNESS ON THE MECHANICAL PROPERTIES

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The paper deals with comparison of tensile, flexural and impact characteristics of parts produced by injection moulding technology and Fused Deposition Modelling (FDM). The influences of various layers' thicknesses and their orientation on the final mechanical properties of printed parts were also among the evaluated factors. ABS and PC / ABS materials were selected for the study and the analysis of the internal stresses of the moulded parts exposed to the surfactant environment (acetic acid) was also included.

KEYWORDS

fused deposition modelling, Injection moulding, Acrylonitrile-butadiene-styrene copolymer, Polymer blend, polycarbonate

1 INTRODUCTION

In contemporary technical practice, 3D printed parts are getting more and more employed as structural elements in final applications. This approach dramatically shortens the time needed to obtain functional part or assembly. As a consequence, influence of various mechanical loads and long-term impact of the environment onto the final part properties and behaviour must be taken into account. Due to market demands, materials and additional techniques are constantly developed. This article is focused on study of thermoplastic materials which can be processed employing Fused Deposition Modelling (FDM). Final specimens produced by selected technologies showed outstanding mechanical properties and chemical resistivity [Gross 2014, Linda 2014]. In the frame of this paper the influence of layers' orientation on final mechanical properties was also studied.

Principle of the FDM technology is shown in the Fig. 1. During the building process input material in the form of filament is extruded via heated nozzle. Thin fibre of the melted material is then spread in the horizontal plane according to STL data. In the next step, building platform is lowered in the vertical direction in the extent of corresponding layer thickness and the whole process is repeated. Crucial aspect of the FDM process is the definition of support structures which provide additional reinforcement of the model and which protect it from collapsing. Typically, support structures can be removed in the chemical (dissolving in appropriate solution) or mechanical way.

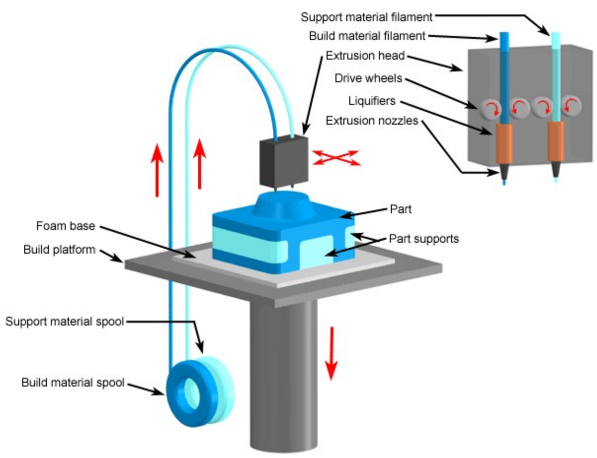

Figure 1. Principle of the FDM technology [Custompartnet.com 2015]

Drawbacks of the FDM technology are possible distortion and shrinking of the final part due to applied heat and subsequent cooling [Sun 2008]. On the other hand, such deformations can be minimized by optimization of technological parameters [Hossain 2013, Montero 2001].

Injection moulding of thermoplastics is a manufacturing process for producing parts by injecting the melted material into a mould. Plastic material is fed into a heated barrel, mixed (using a helical shaped screw) and injected (forced) into a mould cavity, where heat is removed from the melt and material solidifies. The resulting properties of the injected parts are influenced not only by the type of material but also by the technological parameters which have to be optimised [Dobransky 2007].

2 EXPERIMENTAL PROCEDURE

The analysis of polymer specimens produced by 3D printing (FDM) and by injection moulding was carried out on so-called multi-purpose test bodies type A according to ISO 3167, type 1A according to ISO 527 and test bodies shaped as a rectangular prism type 1 according to ISO 179-1 and ISO 178. The test bodies were made of ABS-M30 and blend PC / ABS (Stratasys Ltd.).

2.1 3D printing of the parts

The specimens were printed using Fortus 450mc (Stratasys Ltd.). Parts with the minimum and maximum possible layer thickness for the given material (0.127 and 0.330 mm) were produced. Various layers' orientations with respect to location of the printing head (0°, 90° and concentric layout of layers (K), see Fig. 2) were also included in this study.

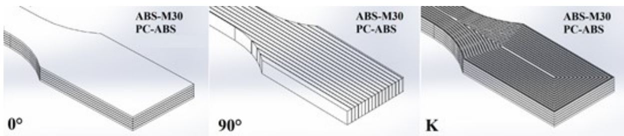

Figure 2. Fibre orientation of printed specimens

Printing of the parts made of ABS-M30 was performed at the nozzle temperature of 315°C and the chamber temperature of 90°C. Specimens made of PC / ABS were produced at the nozzle temperature of 325°C and the chamber temperature of 95 °C. Example of 3D printing output is shown in the Fig. 3.

Figure 3. Parts after printing using Fortus 450 with ABS-M30 material.

2.2 *Injection moulding of the parts*

The first step was focused on preparing of sufficient quantity of pellets from ABS-M30 and PC/ABS filaments (Stratasys Ltd.) for the production of specimens using injection moulding. Subsequently, the test bodies according to ISO 294-1 were prepared under the technological conditions listed in the Table 1. The production was carried out using Arburg 270S 400-100 injection moulding machine equipped with the screw with diameter of 25 mm, maximum clamping force of 400 kN and two-plate injection mould for the production of multi-purpose test bodies complying with ISO 3167 corresponding to Type 1A bodies complying with ISO 527, out of which type 1 bodies complying with ISO 179-1 and ISO 178 were also mechanically machined. Before the strength and impact properties of the injected specimens were evaluated, the specimens had been conditioned in a standard environment, i.e. at the temperature of (23 ± 2) °C and relative humidity (50 ± 10) % for at least 16 hours according to ISO 2580-2.

Material	ABS-M30	PC/ABS
Melting temperature	250 °C	270 °C
Mould temperature	60 °C	60 °C
Injection speed	35 cm³/s	
Holding pressure	450 bar	520 bar
Holding time	40 s	
Back pressure	20 bar	
Cycle time	60 s	

Table 1. Technological parameters for injection moulding

2.3 *Tensile properties of parts*

Tensile properties, particularly tensile strength (σ_m) and tensile modulus (E_t), were determined in a standard 23/50 environment by methods stated in the ISO 527 / 1A / 50 (in the case of tensile strength) and ISO 527 / 1A / 1 (in case of tensile modulus). Measurements were carried out on TiraTest 2300 device with the Epsilon extensometer Model 3542-010M-025-ST. The measured values are shown in Fig. from no. 4 to no. 7.

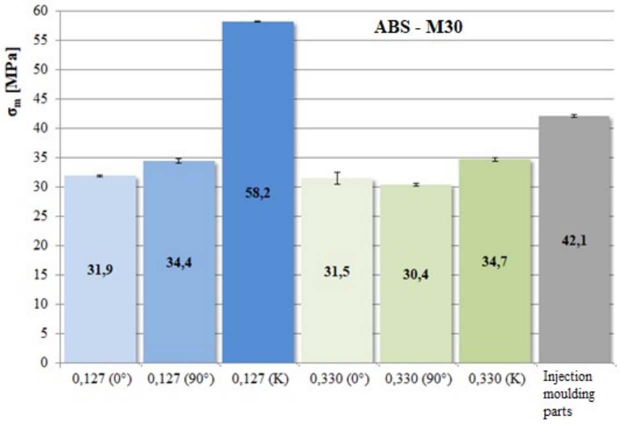

Figure 4. Tensile strength of ABS-M30 parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

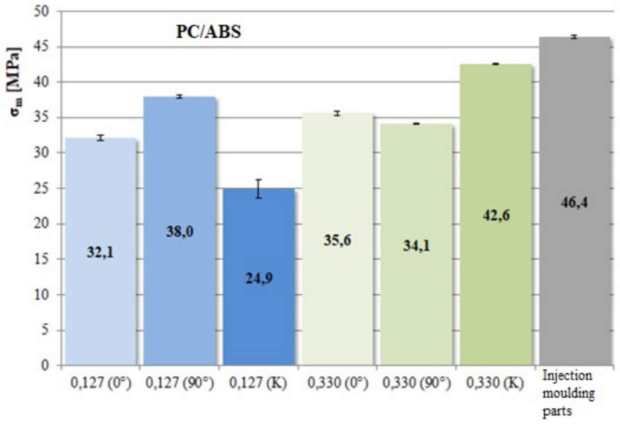

Figure 5. Tensile strength of PC/ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

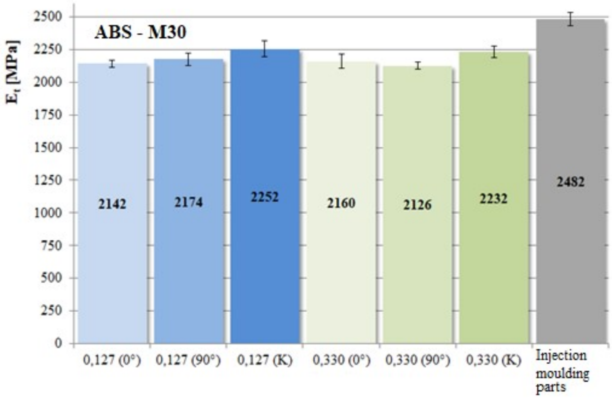

Figure 6. Tensile modulus of ABS-M30 parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

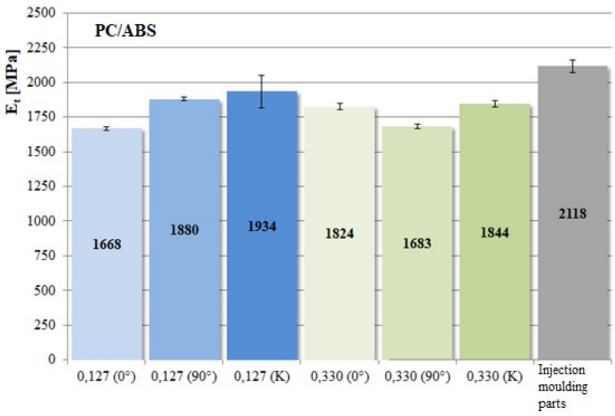

Figure 7. Tensile modulus of PC/ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

When evaluating the limit of tensile strength (σ_m) the fact can be stated, that the ABS-M30 parts did not show any dependence of the tensile strength on the layer thickness at constant orientation of layers (0°), while the tensile strength of PC / ABS samples increased by 11% with maximum thickness of 0.330 mm. On the other hand, the orientation of the layers (90°) led to tensile strength reduction by 10%, resp. 12% with increasing layer thickness for both materials. The cause can be found in the coarser structure of samples made with higher printed layer thickness. The ABS-M30 samples with concentric layering exhibited the highest strength at minimum layer thickness (0.127 mm). For samples with layer thickness of 0.330 mm (K), this increase was not recorded due to the unfilled gapes between adjacent layers occurred during the printing (Fig. 8). These manufacturing defects resulted from the concentric layering methods and led to premature failure of the test bodies. These defects were also present in samples with layer thickness of 0.127 (K) but in very small scale and their effect on the premature failure of the part was less significant. Behaviour of PC / ABS samples with concentric layer layout was also influenced by production defects - unfilled gaps between adjacent layers negatively with the exception that the manufacturing defects negatively affected primarily specimens with layer thickness of 0.127 mm (K) in contrast to ABS-M30, see Fig. 8 and 9.

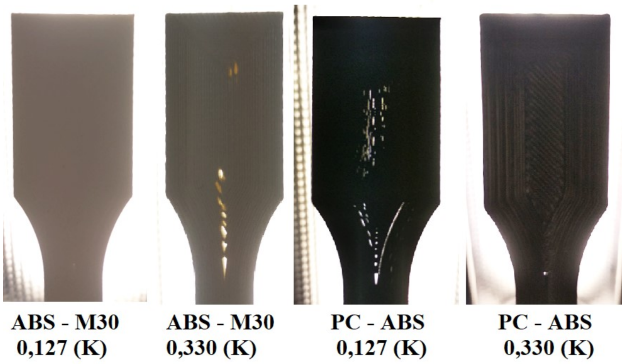

Figure 8. Different specimens' appearance with concentric layer layout

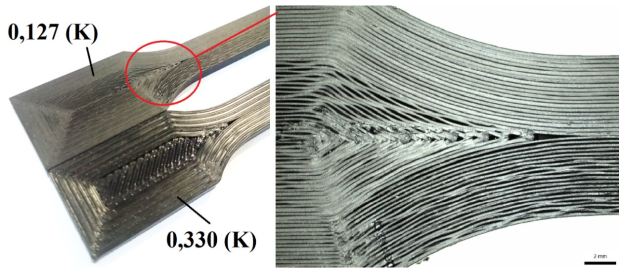

Figure 9. Appearance with concentric layer layout of specimens made of PC / ABS

When comparing samples with minimal thickness of 0.127 mm in terms of the different layer orientation, the fact is obvious that higher strengths were achieved in the orientation of layers under 90° and the highest tensile strength was detected when analysing the specimens with the concentric layouts (assuming the suppression of manufacturing defects). For ABS-M30 samples with layer thickness of 0.127 (90°), the increase was only by 8% comparing to samples with layer thickness of 0.127 (0°), while for samples with layer thickness of 0.127 (K) the increase was up to 82%, see Fig. 4. Comparing to the injected parts, the samples with layer thickness of 0.127 (K) reached the increase of tensile strength by 28%. Differences in resulting strength reached by printed parts with the maximum 3D layer thickness considering the orientation of the base plate (0° and 90°) were statistically insignificant. Tensile strength limit values among the samples with layer thickness of 0.330 (K) were similar to the differences in the behaviour of ABS-M30 and PC / ABS sample with layer thickness of 0.127 mm (i.e. 0.127 (K)) affected by the manufacturing defects described above. Based on the tensile strength results and assuming the elimination of manufacturing defects using concentrated layering (ideally by applying it to rectangular parts), the result can be stated, that 3D printed parts can achieve comparable or better limit strength compared to the injection moulded parts.

After analysing the modulus of tensile elasticity (Et) the fact can be stated, that the increasing thickness of the layer with constant orientation did not change the tensile modulus of samples with regard to the variance of the measured values. Similar trends were observed when analysing the tensile modulus of the samples with the constant layer thickness and different layers' orientation. The highest tensile modulus (stiffness) was therefore reached by the injected parts (increase by about 10% comparing to the best values reached by 3D printed parts).

2.4 Flexural properties of parts

Flexural properties, particularly flexural strength (σ_{fM}) and flexural modulus (E_f), were determined in a standard 23/50 environment using Honsfield H10kT device at a loading speed of 2 mm / min according to ISO 178. The measured values are shown in Fig. 10, 11, 12 and 13.

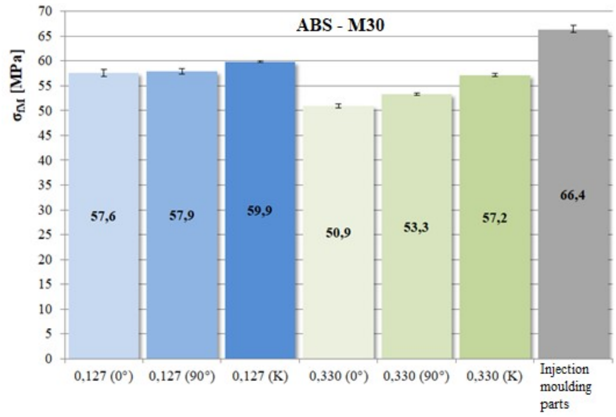

Figure 10. Flexural strength of ABS-M30 parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

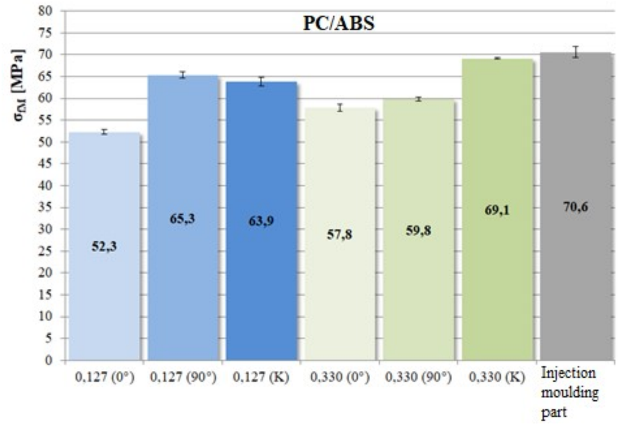

Figure 11. Flexural strength of PC/ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

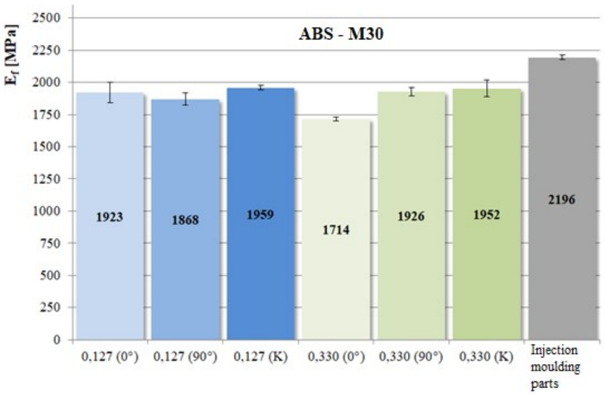

Figure 12. Flexural modulus of ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

The influence of different layers' orientations on 3D printed samples was reflected by the increase of flexural strength while the specimens thickness was constant. While this difference is statistically insignificant for ABS-M30, the flexural strength of PC / ABS with the layer orientation of 90° and a concentric layout increased by up to 25% (with minimal layer thickness of 0.127 mm) comparing to the orientation of 0°. With higher (maximum) layer thickness and concentric layering, the flexural strength increased by up to 20% and the printed specimens reached flexural strength comparable to the injected parts.
Performed trends of flexural modulus behaviour correlated with trends of flexural strength behaviour.
When comparing printed and by injected parts the fact is clear, that the best flexural properties were achieved by injection moulded parts. These values were the closest to the 3D printed samples with concentric layering. The differences in flexural strength and flexural modulus for ABS-M30, with regards to the processing technology, were (10 ÷ 14)%, resp. 11% for flexural modulus, see Fig. 10 and 12. When comparing the injection moulded parts and the 3D printed parts, the difference in flexural strength for PC / ABS with the concentric layout was 2 ÷ 9%, resp. 7 ÷ 18% for flexural modulus, see Fig. 11 and 13.

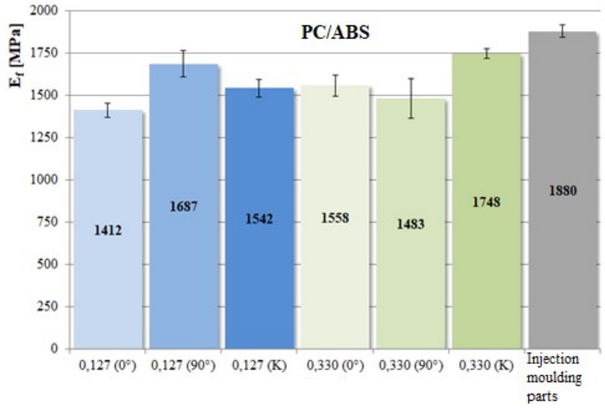

Figure 13. Flexural modulus of PC/ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

2.5 *Impact strength of parts*

Impact strength was evaluated in a standard 23/50 environment by ISO 179-1 / 1eU (Charpy) method using the Resil Ceast 5.5. and Zwick / Roell HIT50 P. All measured values are shown in Fig. 14 and 15.

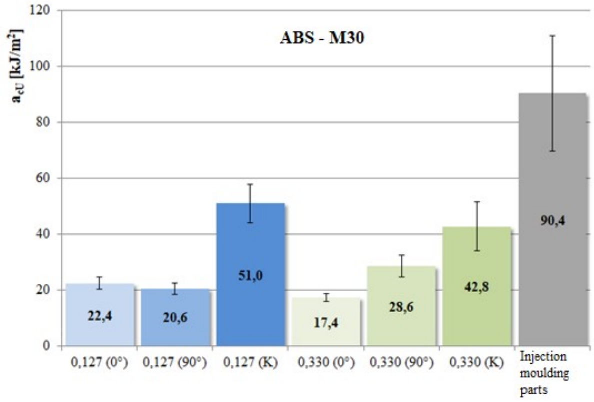

Figure 14. Impact strength of ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

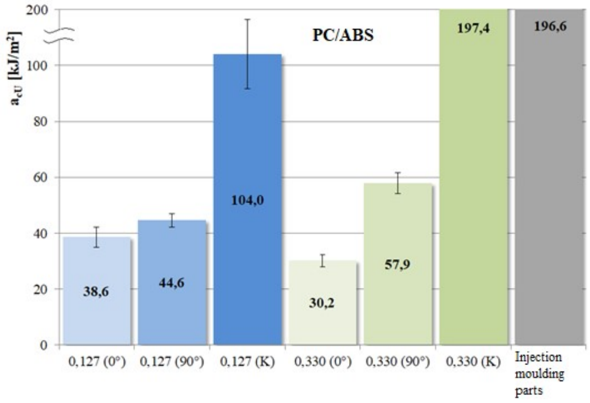

Figure 15. Impact strength of PC/ABS parts: injection moulding vs. 3D print (different fibre orientation and layer thickness)

Impact strength results indicated that the samples made by 3D printing technology with a concentric layout reached the highest impact strength, whereas the PC / ABS material showed the impact strength comparable to the injected specimens. Differences in impact strength linked to the orientation of the layers were not observed, with regards to the dispersion of the measured values when analysing the results reached by specimens with the minimum thickness of the layers. However, with the increasing thickness of the layers, the influence of layer orientation was also significantly increased. Materials with the orientation of the layers under 90° exhibited higher impact toughness than materials with the orientation of 0°.

2.6 *Residual stress of parts*

Injected parts are characterized by residual stresses (unlike 3D printed parts), that are affected by the technological parameters and process conditions. As a result of these residual stresses a failure of the injected parts may occur under considerably lower external stress.

Figure 16. Microscopic study of stress cracks on the surface of the injected part made of PC/ABS (acetic acid 99 %, T = 35 °C, t = 120 s).

Objective determination of the residual stress in the injected part is problematic as well as the methods of their quantification. In practice, indirect testing methods are used, e.g. the soaking in the surfactant environment (usually in specific liquid) is among the most widespread. The surfactant environment is capable to accelerate the occurrence of stress cracks on the surface of the manufactured parts. The higher the residual stress, the sooner the cracks appear on the produced parts. Due to the chemical structure of the ABS and PC / ABS polymers the 99% acetic acid was used as a surfactant at the temperature of 35 °C and an exposure time of 60 seconds for ABS and 120 seconds for PC / ABS respectively was used. Stress cracks on the surface of the injected parts are shown in Fig. 16 and 17. The residual stress was not detected on the 3D printed parts.

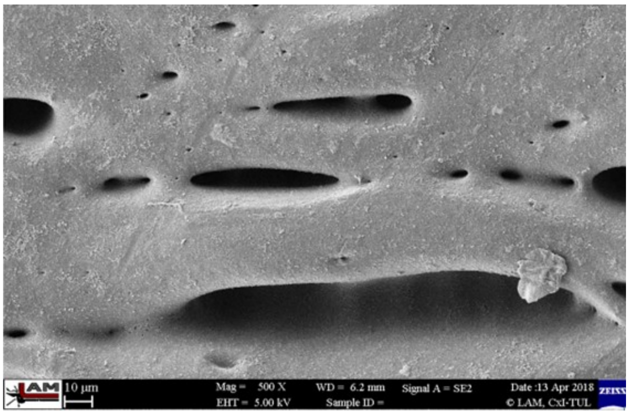

Figure 17. Microscopic study of stress cracks on the surface of the injected part made of ABS (acetic acid 99 %, T = 35 °C, t = 60 s).

3 CONCLUSIONS

The final discussion is focused mainly on the evaluation of suitable geometries and orientation of printed layers in terms of final mechanical properties and comparison to the injected parts. By comparing these two technologies, the fact can be stated, that the injected parts were homogeneous with regards to the volume and surface quality compared to the 3D printed parts, but the injected products are often affected by internal residual tension that may result in their premature failure during loading. Based on the strength and impact characteristics of the parts made of ABS-M30 and PC / ABS (Stratasys Ltd.) the result can be summarized, that in case of concentric layout of the 3D printed parts, it is possible to achieve identical or better tensile strength comparing to the injected parts, provided that the defects (unfilled spaces) that may occur between the adjacent layers produced by FDM technology (depending on the geometry of the body) are suppressed. Flexural strength, flexural modulus, tensile modulus and impact strength of 3D printed parts with concentric layering were very close to the values reached by injected specimens. However, the performed mechanical properties of specimens with concentric layering were considerably limited by structural imperfections (gaps between individual layers resulting in low homogeneity of the specimen structure), which cause premature failure of the parts under load. Due to the orientation of the layers and the nature of the specimen shape, these defects can be avoided only in case of simple geometries. For this reason, 3D printed parts with concentrically oriented layers can match the mechanical limits reached by injected parts, but this 3D printing method is not suitable for production of complex parts with integrated widths. In the case of flexural load of the part it is advisable to place the product with the view of the layers' orientation under 90° related to the main printing plane. Parts with such orientation of layers resist flexural load similarly to those with concentric layering.

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