MECHANICAL PROPERTIES OF PRODUCTS MADE OF ABS WITH RESPECT TO INDIVIDUALITY OF FDM PRODUCTION PROCESSES

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Nowadays the technologies originally developed only for prototype production are involved among modern production techniques. This trend is induced mainly by developing of new materials and very effective improvement of rapid prototyping production methods and tools. The resulting mechanical properties of the products are now fully comparable with the properties of parts produced with using the technologies modified for batch production (e.g. injection moulding or blow moulding etc.). This article deals with comparing the flexural and tensile properties of specimens produced by injection moulding technology and by FDM technology, particularly using three different 3D printers (Dimension SST 768, Fortus 450 and Rep Rap). The part orientation within the build envelope of selected FDM machines is another aspect that was evaluated and that had significant impact on part behaviour of printed parts. All the analysed specimens were made of thermoplastic ABS.

KEYWORDS

FDM, injection moulding, Dimension SST 768, Fortus 450, RepRap, ABS

1 INTRODUCTION

Additive manufacturing technology is an available tool that provides to designers very fast way how to verify new product geometries and profiles. The essential principle of this rapid prototyping technology is progressive building the final product layer by layer. Nowadays there are already more producing methods available on the market that fall into the category of additive manufacturing technology, which differ in type and form of processed material and the way of mutual connection of the individual layers. The resulting products vary in the mechanical properties (even when processing the same materials), their accuracy and surface quality. All these aspects also have a direct impact on the final price and production rate (overall productivity). Production of complex and shape limitless parts without machining or employing expensive manufacturing tools is the main advantage of rapid prototyping systems. Considering the availability this article is focused only on the most widespread prototyping technology, namely FDM (Fused Deposition Modelling). In order to produce complex shapes by additive manufacturing technology the supporting materials and structures are basically used. These structures should be easily removable and thus provide connection between the product and building platen of the 3D printers. These elements are also utilized for creation the undercuts and protrusions. Supporting structures are automatically generated by the software given for preparing the production (preprocess stage). However, the human operator may modify the placement and type of the supporting structures according to his experiences to prevent material waste and ensure time effective production of high quality parts. The removal of supporting structures is carried out mechanically or using chemical solvents. [Gross 2014]

2 FUSED DEPOSITION MODELING (FDM)

FDM method was developed by Stratasys and the most common principle is the extrusion of material in form of filaments through a nozzle, which is heated above the melting point of the processed material. Melt is then applied layer by layer, see Fig. 1. FDM is involved in the technologies of 3D printing, which produce the parts directly from electronic models from which the processing data are generated by the software tools and subsequently sent into the operating devices. The electronic models are usually in standard STL format. The main advantage of FDM technology is the rapid production of various small series without need of any other investment into the production tools. The products have relatively high accuracy and quality. With respect to production process the preprocessing stage is very fast as well. The FDM printers usually use two jets. One jet builds the supporting structures and the other is used for layering the construction materials. The main disadvantages involve the limited building area of 3D printers, problematic creation of very thin profiles (small rigidity, collapse the thin profiles during support structures removal etc.), the necessity of secondary operations to achieve a very smooth surface etc. In terms of designing limits (except the above mentioned once) design manufactured on FDM printers is not limited by general rules, which was introduced for designing plastic parts manufactured by injection moulding technology (eg. radii, drafts, uniform wall thickness etc.).[Safka 2016, Sun 2008]

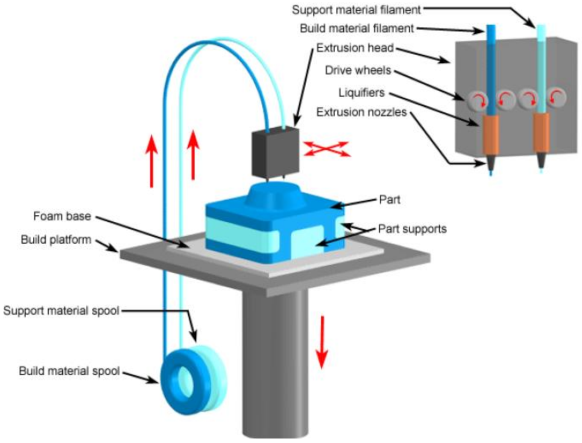

Figure 1. Principle of the FDM technology [Custompartnet.com 2015]

All models have their optimal build orientation with respect to preferred features and performances (smooth surface finish, optimal strength or fastest build time) [Garceau 2013]. When the part surface is built up gradually under very small angle relative to the printer build tray (as a very shallow slope), the visibility of each layer becomes more evident. The surface quality is also affected by the support material or can be roughened by manual removal of the support material (dissolvable supports are feasible solution) [Armillotta 2006]. The mechanical strength properties depend on the given inner part structure as a result from the build direction and the toolpath [Bagsik 2011]. The path lines for the fill can be kept parallel to each other in individual building layer. The second feature is that every layer alternates the angle of the fill lines by

90 degrees, creating a cross hatch pattern (settings utilized for reducing the print time and saving material) [Belter 2015]]. Great decrease in material consumption is also ensured by sparse fill. The solid fill is preferred in areas exposed to high stress and if the product strength is not important, then a partially hollow part is acceptable [Garceau 2013].

Many other parameters can be changed to generate a high quality product, e.g. width of the filament and the air gap between the raster in the fill pattern, which can be adjusted smaller or larger, as well as the air gap between the raster fill and the contour [Bagsik 2011].

Tensile loads should be exerted axially along the fibers [Ahn 2002]. While the unidirectional rasters (filament orientation longitudinal to the load) achieved the maximum tensile strength and effective elastic modulus, the criss-cross raster under 45°/-45° displays the largest average number of fatigue cycles to failure [Ziemian 2014].

2.1 *Rep Rap technology*

Base principles of FDM technology is also used by a large platform of the open-source 3D printers arose from the RepRap project, which is an international community project developed on the principles of open hardware approach. The RepRap printers are composed mostly of many plastic parts that can be reprinted on another RepRap. The name itself is an abbreviation for replicating rapid prototyper, which means that each RepRap is capable of self-replication and following prototype production. All documentations required for building and operating the RepRap printer including firmware and control software are released under the GNU General Public License.

RepRap technology provides a full adjustability of all technological parameters and thus complete control of each production step - the speed of laying the filaments, temperature control, rate of filament movement, etc. [Pearce 2010, Sells 2010]

3 MATERIALS

Wide range of materials can be used for building the products. In the frame of 3D printing technology the unfilled polymers are primarily used (only with a minimum content of colorants). The main reason is arresting the filling particles with bigger dimensions inside the nozzle which causes the system malfunctions (high nozzle abrasion) and low stability of the production process. However, nowadays the fillers are available (e.g., fine milled wood flour or mineral fillers) that are processable by these sensitive systems up to certain concentrations.

ABS (Acrylonitrilbutadienstyrene), PLA (Polylactic acid-polylactic acid), WPC (Wood Plastic Copolymer) BendLay, PC (polycarbonate), PA (nylon), TPE (thermoplastic elastomer), PET-G (polyethylene terephthalate - glycol), PVA (polyvinyl alcohol), HIPS (High impact polystyrene), etc. are typical plastic materials processed by 3D printers. For the purposes of this study the ABS was used and further described in detail. Acrylonitrilbutadienstyrene is a hard and stiff polymeric material that is widely used for engineering applications. ABS parts are sufficiently resistant to chemicals, heat and moisture. Various modifications of this thermoplastic were developed to increase resistance to impact stress, biocompatibility etc. The recommended minimum thickness of printed ABS is 1 mm. ABS can be sorted among low costs materials and its rheological properties allows the creation of fine and precise part contours. [Knoop 2015, Montero 2001]

4 EXPERIMENT AND RESULTS

As mentioned above, the compared specimens were made of ABS, namely ABS M30. The production was carried out in laboratories at the Technical University of Liberec where injection moulding machines and 3D printers are available. The printed products used for this study were built up on Dimension SST 768 - SW Insight software, Fortus 450 - SW Insight software and Rep Rap. Material P400 was replaced by ABS M30 and technological parameters (chamber temperature, nozzle temperature etc.) for precise production were on Dimension SST 768 optimized with using software MaracaEXU. Used technological parameters for 3D printing of ABS M30 were exported from Insight software ant they were used as basic process setting for all compared 3D printers. The RepRap printer was equipped with heated build platform with adequate temperature setting to prevent the product warpage.

The specimens produced by FDM technology were oriented under different angels related to the building platen (0º, 45º and 90º, see Fig. 2). In the frame of each analysis involved in this study five specimens were tested.

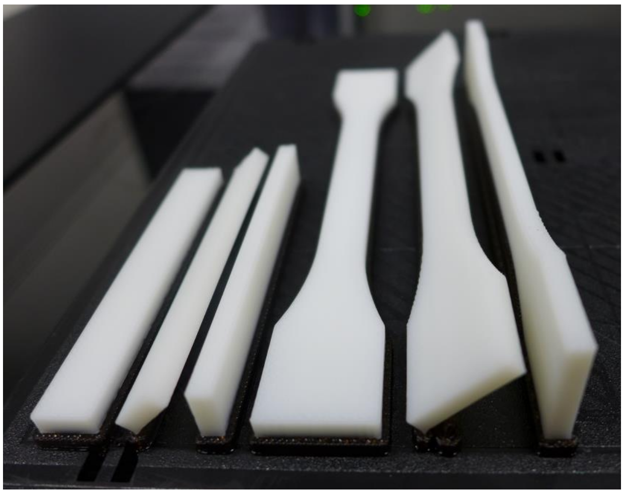

Figure 2. The bending (first three from left) and tensile specimens orientation relative to building platen (0°, 45°, 90°)

The shape of multipurpose test specimens is consistent with ISO 3167 standard and the production process parameters were adjusted in accordance with international standards ISO 294-1 and ISO 2580-2 using injection moulding machine ARBURG 270 S 400-100. The pellets were dried in a vacuum furnace Maguire at the temperature of 80 °C for 4 hours to maximally reduce the water content before injection moulding. Production process was carried out under standard conditions (23 °C and 50% of relative humidity). Individual technological parameters were selected considering the standards prescribing the production of ABS test specimens (ISO 2580-2) and the final part quality to eliminate all defects (particularly the sink marks or flashes). The technological setting of specimens production is listed in table 1 and 2.

The properties of ABS are influenced by the amount of moisture that is bonded in the material structure and that is the reason of conditioning the specimens in the defined atmosphere before conducting the mechanical tests of the hybrid composites. Conditioning guaranteed the specific moisture content that is equal for all specimens (the equilibrium state of all specimens). To achieve this state the accelerated process of conditioning was employed. The conditioning was carried out at higher temperatures according to ISO 2580-2 standard and following the requirements of ISO 19062-2 standard.

In the first step the tensile properties were analysed (namely tensile strength and modulus). The results revealed the fact that specimens produced by injection moulding technology showed the best performances, see table 3 and 4. The maximal Young modulus had the value of 2386,7 MPa. The closest values of the tensile modulus were reached by the printed specimens produced on Fortus 450. The differences were minimal and as the results imply the impact of various orientation of specimens within the building area can be neglected in the frame of the modulus analysis.

	Material [°C]	**Support [°C]**	**Chamber [°C]**	**Layer thickness [mm]**
Dimension	280	250	75	0,254
Fortus 450	285	250	85	0,254
	Material [°C]	Extruder [°C]	**Platen [°C]**	**Layer thickness [mm]**
RepRap	280	230	70	0,2

Table 1. Print setting

	4th zone	**3th zone**	**2nd zone**	**1st zone**	**Nozzle**
Temp. [°C]	235	240	245	245	250
Inject. rate	200 mm/s				
Holding pressure	52 MPa				
Cooling t.	20 s				
Cycle t.	60 s				

Table 2. Basical technological properties for moulding machine

Among the specimens produced on Fortus the best results were achieved by parts oriented in the direction of 90°. In the other orientations tensile modulus decreased by approximately 2%, respectively 7% with orientation of 0°, respectively 45°, which is not a significant drop. The products build on 3D printers RepRap and Dimension achieved comparable results. In both cases the measured Young modules represented only approximately 85% of values reached by moulded specimens. The best results were measured when analyzing the parts with the orientation of 90°. The variability of results caused by different orientations was up to 13%. A slightly larger drop in values observed during tensile properties analyses of the printed and moulded specimens was revealed among the values of ultimate strength. The maximal strength was achieved by moulded specimens and had the value of 37,66 MPa. The second best results were performed again by the parts produced on Fortus 450 and the maximal strength within this set of specimens was reduced by 5% comparing to moulded parts. The impact of product orientation within building area on the total strength was minimal which confirmed high stability of production process. The lowest tensional strength was observed when analyzing the specimens built on Dimension. Significantly stronger specimens were produced on the RepRap. The preferred orientation of products within the building area should be again 90° for all evaluated 3D printers.

	Orientation 0°	**Orientation 45°**	**Orientation 90°**
Dimension	1646 ± 90	1710 ± 47	1829 ± 9
Fortus 450	2137 ± 26	2257 ± 11	2294 ± 21
RepRap	1668 ± 385	1712 ± 164	1900 ± 35
IM	2387 ± 23	X	X

Table 3. Tensile Young modulus in MPa (IM - injection moulding)

	Orientation 0°	**Orientation 45°**	**Orientation 90°**
Dimension	20,4 ± 0,8	22,6 ± 0,2	25,4 ± 0,3
Fortus 450	33,2 ± 0,3	34,2 ± 0,3	35,6 ± 0,1
RepRap	27,5 ± 6,7	30,0 ± 1,3	32,7 ± 0,9
IM	37,7 ± 0,4	X	X

Table 4. Tensile strength in MPa (IM - injection moulding)

In the next step the flexural characteristics were analysed, i.e. flexural strength (σ_{fM}) and flexural modulus (Ef). The flexural properties showed very similar trends as those described in the frame of tensile behaviour characterization. However, the differences among the measured values were more distinctive then in the case of tensile properties. Maximum flexural modulus had the value of 3814,5 MPa and was reached by moulded specimens. The best results among the printed samples were again reached by the specimens built up on the Fortus 450. However, the stiffness decreased by more than 40%. The data again revealed the impact of different orientation of the specimens within the building area. The specimens oriented under 0° and 45° showed the additional drop of the flexural modulus by approximately 14%, respectively and 23% within the testing set created on Fortus 450. The flexural modulus measured during analysis of specimens created by systems RepRap and Dimension decreased by nearly 60% comparing to values reached by moulded parts. And even for these technologies the best results were observed when analyzing the samples under orientation of 90°. In the case of Rep Rap the specimens orientation brought additional decrease in the stiffness by approximately 13%, respectively 10% for orientation under 0°, respectively 45°. The results measured during analysis of specimens built up on Dimension were the worst. The last analyzed characterization was the flexural strength. The results obtained during the analysis of specimens created by Fortus 450 with orientation of 90° reached the same values as the moulded parts. In the frame of testing set built up on Fortus 450 change of orientation the specimens within building area induced the decrease in flexural strength by approximately 5% in both compared cases. The strength reached by specimens built up on RepRap decreased by approximately 22% and the final flexural strength of samples built up Dimension reached only 68% of the best values. Even in these cases, the highest strength within the analyzed sets was performed by specimens with the orientation of 90°. The variability of the results induced by the orientation changing was lower within the set created by Dimension, concretely the drop by about 9% for orientation of 0° and by about 15% for orientation of 45°comparing to optimal orientation of the specimens within the building area. What the flexural strength is considered, the worst process stability was recorded when analyzing the set built up on RepRap. With the orientation of 0°and 45° the strength was reduced by approximately 16%.

	Orientation 0°	**Orientation 45°**	**Orientation 90°**
Dimension	1432 ± 32	1222 ± 56	1670 ± 21
Fortus 450	1936 ± 15	1731 ± 19	2247 ± 28
RepRap	1338 ± 70	1389 ± 38	1544 ± 50
IM	3815 ± 56	X	X

Table 5. Flexural modulus in MPa (IM - injection moulding)

	Orientation 0°	Orientation 45°	Orientation 90°
Dimension	36,7 ± 0,9	34,1 ± 0,7	40,0 ± 0,9
Fortus 450	55,6 ± 0,5	55,3 ± 0,2	58,1 ± 0,8
RepRap	38,4 ± 1,7	39,1 ± 0,5	46,1 ± 0,6
IM	58,7 ± 0,23	X	X

Table 6. Flexural strength in MPa (IM - injection moulding)

5 CONCLUSIONS

The submitted study deals with the evaluation of the impact of different 3D printing technologies based on FDM principles on the mechanical properties of the plastic parts. All the compared specimens were made of ABS M30 including moulded parts, which were used as a reference representing the standards achievable by serial manufacturing processes. As the representatives of additive manufacturing technologies the 3D printers Dimension SST 768, Fortus 450, Rep Rap were chosen. The effectiveness and process stability was derived from changes of tensile and flexural mechanical properties, concretely tensile and flexural strength or modulus. Also the orientation of specimens within building area was taken into account (orientation under 0°, 45° and 90°).

Generally, the fact can be stated that in the frame of analyzed properties the moulded specimens showed the best performances. The main reason is limited consistency of the printed parts internal structure and thus the reduced ability to transmit external loads. On the other hand these disadvantages may have a positive impact on improving impact resistance of the parts, because the layered structure will probably have a better ability to absorb the kinetic energy of pulses.

From the above mentioned data can be clearly derived that if the product is primarily subjected to tension stress, the parts created by FDM technology achieve approximately the same level of mechanical properties as the moulded parts. These assumptions are applicable only for parts that are without critical dimensions (too thin walls, etc). When applying bending stress the values measured during the analyses of printed sets were comparable with the data reached by moulded parts only for bending strength. The bending stiffness of printed specimens decreased at best case by about 40%, which was caused probably by presence the large sliding surfaces between the individual layers creating the final product. All the results also confirmed the assumption that the orientation of the product within the building area of 3D printer is one of the crucial factor affecting the final mechanical properties of printed parts. The smallest variability among the results performed by specimens of individual sets was observed for parts build on Fortus 450, which indicates very precise control of process parameters and stability of entire production process when changing the part orientation. Generally the fact can be stated that best results were reached with the orientation of 90° in all evaluated cases. This orientation should be promoted according to direction of applied stress load. In the frame of this study the best alternative to the moulded parts was represented by products built up on Frotus 450.

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