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Mechanical properties of ABS samples manufactured under different process conditions

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Abstract.. The purpose of this study is to determine the effect of manufacturing conditions on the mechanical properties and structure of ABS parts. Two sets of samples with the same geometric characteristics were produced by Fused Deposition Modelling (FDM) and injection molding (IM). The molding pressure and cooling rate were found to have a significant effect on shaping the mechanical properties and structure of ABS products. The manufacturing method and adopted process parameters have a significant impact on the degree of packing of macromolecules in the volume of the product, and thus determine its density. Selected mechanical properties were determined and compared with their specific gravity. The research was carried out using tools and machines, i.e. injection molds of unique design and standard measuring stations. Tensile and bending strengths and Young's modulus were related to the density of products obtained under different process conditions and having gradient and solid structures. The results provide useful information for engineers designing products using FDM technology. Relating tensile and flexural strength and Young's modulus to the specific gravity of the product. It was found that the value of product properties is closely related to various process conditions, which further provides a true description of the products.

Key words: FDM, Injection Molding, Mechanical properties, Microtomography, ABS,

1. INTRODUCTION

Universality of additive technologies that make use of a filament is now being applied rapid prototyping, manufacturing of functional objects in automotive industry [1], airspace industry [2] and medical aplication [3, 4], medical aplication [3, 4], pharmaceutical [5], packaging [6] and their automation [7]. Fused Deposition Modelling (FDM) and related methods (i.e. Fused Filament Fabrication) similarly make use of an insert material in a wire-form that can be manufactured from thermoplastics [8, 9 and 10]. Additive manufacturing technologies with the use of a polymer filament are put under research in terms of their mechanical properties. The influence of the applied materials examined by teams of Stern [11], Parast [12] and Ninikas [13]. Process parameters were studied teams Alafaghani [14], Dev [15], Yankin [16]. The effect of orientation during printing on mechanical properties has also been confirmed [17, 18]. The impact of the nozzle diameter on the structure and performance properties is also important in the production of objects with a favorable structure [19, 20]. Marciniak with team verified surface modification on the quality of the produced parts [21]. The measurement accuracy of the obtained parts was also studied, using standardized samples and control geometries as examples [22].

One of the growing problems in recent times is the increasing amount of waste from the 3D printing process, such as broken parts or failed prints [23, 24, 25]. Secondary use of recycled materials is also investigated in additive technologies[26, 27, 28]. It has been confirmed that a re-use of the material provides an opportunity to obtain entirely functional elements. Maidin team [29] proposed a new approach to research on 3D printing, i.e. while the printing device is placed in the chamber and a vacuum is created, the mechanical properties of the samples increase by 14%.

Injection molding is the most common method for producing components from thermoplastics. The essence of injection molding is the heating of a portion of the starting material, usually in a form of granules, to a plastic state and then injecting it under high pressure into a closed mold whose cavity reflects the shape of the manufactured element. After the injection, the material solidifies, due to the temperature drop. After the material solidifies, the finished element is removed from the injection mold. From the research carried out by Sykutera team [30], it was concluded that the most important parameters are pressure and temperature. This technology differs from FDM particularly by the insert material (i.e. a granulate) and by a high process pressure used in injection, the latter of which is necessary to insert a polymer alloy of high flow resistance to a mold cavity.

Teams Askanian [31] and Behalek [32] compared injection molding to Fused Deposition Modelling, in the the research verifying the process parameters such as number of layers, the direction of paths being applied and the degree of filling. Owing to the parameters that can be standardized in IM technology, the material properties of various thermoplastics can be determined. In the standard IM, owing to injection and packing pressure, solid molded parts can be obtained. As it follows from the research teams by Marciniak [33] and Rodríguez-Reyna [34], in FDM technology the structure of manufactured objects is gradient, whose actual functional charateristics is more dificult to determine than in case of composites.

A method to determine the actual properties of details manufactured by FDM is applying parameters that refer to the specific gravity [35, 36]. The parameters applied to the specific gravity are likely to demonstrate the appropriate approach to assess mechanical properties of products which are not characteristic of a solid material structure, obtained in the mentioned before technologies. According to Szewczykowski and Skarżyński [37], the assessment of mechanical properties with a reference to the specific gravity seems to be correct; as in additive techniques and in porous injection molding the structure of obtained parts is porous or openwork.

The aim of the research is to perform a comparative evaluation of the selected mechanical and structural properties of ABS samples obtained in various process conditions. The comparison between additive manufacturing and injection molding results from the fact that IM seems to be the most beneficial and popular method of manufacturing thermoplastic products of complex shapes.

2. METHODOLOGY

The samples were prepared by two methods that differ in the value of molding pressures and cooling conditions. The high-pressure injection molding (IM) and Fused Deposition Modelling (FDM) technology were used. In the case of the FDM, the samples are formed at low pressure in contrast to IM. The basic research material for both technologies was ABS-P430™ terpolymer manufactured by Stratasys (The USA) in a form of filament with a diameter of 1.68 mm, designed to manufacture products in the FDM additive technology (see Figure 1).

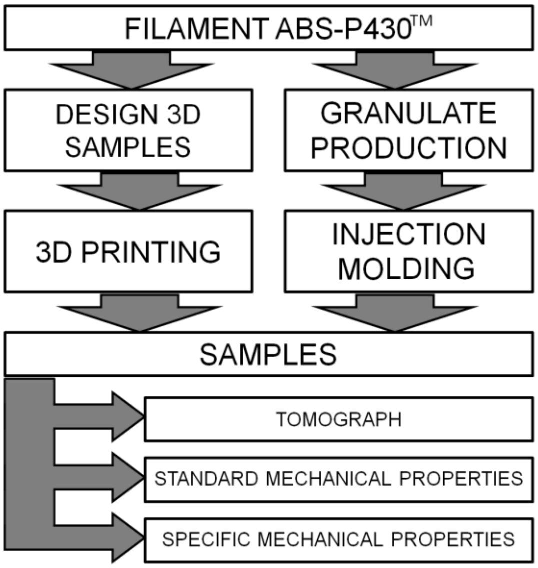

Fig.1. The process of identifying mechanical properties of test samples obtained from ABS filament in FDM and IM technologies

A. Sample preparation at high pressure molding

The process of injection molding was preceded by auxiliary processes. The ABS-P430™ filament was cut in a TS-10 lab granulator manufactured by IMPiB (Poland). The obtained granulate with a repeatable length and a repeatable diameter was dried for 4 hours at a temperature of 60°C in a KMF 115 thermal chamber manufactured by Binder (Germany). The molded pieces in the form of standardised dumbbell-shaped samples (standard PN-EN ISO 527 – sample type 1BA, dimensions 75x10x2.2 mm) were manufactured in a hybrid e-Victory 110 injection molding machine manufactured by Engel (Austria), with a clamping force of 1100 kN. Oryginal double-cavity lab injection molds manufactured by the Bydgoszcz University of Science and Technology (Poland) were used to prepare the samples. In the following parts of this manuscript, the samples described above are designated as A. The index "1" stands for the samples used in a tensile strength test. Assigned for bending strength tests in accordance with PN-EN ISO 178:2003 standard (signified as A2-samples) and impact strength according to PN-EN ISO 179:2010 (signified as A3-samples), molded pieces in the form of a beam (dimensions of 80x10x4 mm) were cut out from the dumbbells. These molded pieces were obtained in the ergo ech 50-200 system injection molding machine with the clamping force of 500kN, manufactured by Demag (Germany) and with the use of second injection mold manufactured by the Bydgoszcz University of Science and Technology (Poland). The technological parameters adopted for injection molding have been presented in Table 1.

TABLE1. Parameters used for injection molding of test specimens

Parameters	Injection machines	
	Engel (samples A1)	Demag (samples A2, A3)
Injection pressure, MPa	26.2	57.9
Injection time, s	0.32	0.56
Holding pressure, MPa	20	31.2
Holding time, s	6	21
Melt temperature, °C	250	250
Mold temperature, °C	50	50
Cooling time, s	25	20

B. Sample preparation at low pressure molding

To prepare samples by FDM in a thermal chamber, a Dimension Elite tool has been used (Stratasys, the USA) with the parameter settings presented in Table 2. The supporting material was P 400R Soluble Support filament (Stratasys, the USA). Three types of samples with shapes and dimensions corresponding to the ones of the molded pieces were manufactured. The print was performed in the following three options: Solid, High Density and Low Density. Owing to this, samples of variable density were obtained and, in the following parts of the paper, there are identified as B1 (FDM Solid), B2 (FDM High Density) and B3 (FDM Low Density).

TABLE 2. Parameters for additive manufacturing of test specimens by FDM

Parameters	Stratasys Dimension Elite
Nozzle temperature, °C	275
Chamber temperature, °C	75
Nozzle diameter, mm	0.35
Thickness layer, mm	0.1778
Filling type (machine settings)	Solid, High Density, Low Density
Orientation angle relative to the Y axis, °	0

C. Tests of physical and rheological properties

A basis to prepare the samples was a 3D model of a test specimen with the geometrical properties (i.e. section and length) identical to the samples obtained from injection molding and used to determine strength in the static tensile test (the section of samples was 5x2.2mm) and impact and bending tests (the section of samples was 10x4mm).

The density of ABS terpolymer samples was measured by a hydrostatic method and investigated with the use of AD50 lab balance manufactured by Axis (Poland). Methanol of a density of 792 kg·m^{-3} was applied as a liquid. Tensile and bending tests were conducted on the Z030 testing machine manufactured by Zwick/Roell (Germany) in accordance with PN-EN ISO 527 and PN-EN ISO 178 standards. Tension velocity was estimated at 50 mm·min^{-1} and the elasticity of elongation was conducted at the velocity of traverse move of 2 mm·min$^{-1.}$ The obtained values of maximal stresses and Young's modulus were referred to the specific gravity of the samples, which next allowed to estimate the specific strength and specific Young's modulus in tension and bending tests. According to the bibliography, the acquired values were given in kilometers. The specific strength (Nm/kg) (similar specific modulus) of the samples was calculated, which was understood as the ratio of the mechanical tensile strength of the material (N/m^2) and the apparent density (kg/m^3). The resistance to dynamic load of the samples was tested on the HIT50 impact testing machine manufactured by Zwick/Roell (Germany), whereas the impact of the samples without notches was tested by Charpy's method, in accordance with PN-EN ISO 179. Moreover, the resistance of the samples to impact tension was determined in compliance with PN-EN ISO 8256, but the notches had not been previously cut on either side of test samples. Therefore, the external layers of FDM samples were not violated. According to the algorithm controlling the order of applying consecutive layers in Dimension Elite machine, the two external layers of the produced samples are characteristic of maximal density. The number of tests assumed to be conducted in order to determine mechanical properties was 10.

Rheological properties were determined for the following three types of specimens: a) filament ABS P430™, b) material from the 3D Printed ABS P430™ and c) material from the molded parts ABS P430™. Mass and volume melt flow rate were determined in accordance with PN-EN ISO 1133, using Aflow Plastometer (Zwick/Roell, Germany).

D. Structure research

The results of mechanical tests were accompanied by the tests of the sample structures. The distributions of voids throughout the samples' volume were prepared. The images of the product structures that were obtained by FDM and injection molding were determined by a Bruker SkySkan 1173 computer tomographer manufactured by Bruker (Belgium). The following scanning parameters were adopted: source voltage of 50 kV, source current of 160 µA, image pixel size of 7.94 µm, exposure of 500 ms, rotation step of 0.2°, frame averaging of 3, random movement of 40.

The glass transition temperature of the samples was determined by differential scanning calorimetry method using DSC 214 Polyma (Netzsch, Germany). This way, the influence of cutting and plasticizing processes in the injection barell on the possible mechanical and thermal degradation of ABS macromolecules was analyzed.

3. RESULTS

A. Results of material tested

The cutting process of a filament and its secondary processing by injection molding have not caused any significant degradation in the polymer structure (e.g. shortening of a macromolecule chain length). This can be evidenced by insignificant differences in the values of the melt flow rate and the glasshouse temperature (see Table 3).

TABLE 3. Test results of the Melt Flow Index and Differential Scanning Calorimetry

Material: ABS P430™	MFI		Glass transition temperature, °C
	MFR, $\frac{g}{10\ min}$	MVR, $\frac{cm^3}{10\ min}$	
Filament	37.52 ± 0.88	38.47 ± 0.38	105.8
3D printed	37.95 ± 0.48	39.61 ± 0.68	105.4
Injection molded	39.48 ± 0.84	41.62 ± 0.71	105.3

B. Results of mechnical properties

For all samples under analysis, similar changes of σ(ε) have been observed. Nevertheless, it has also been noticed that the maximal permissible stress values were achieved in the static tension tests of molded pieces, as presented on Figure 2.

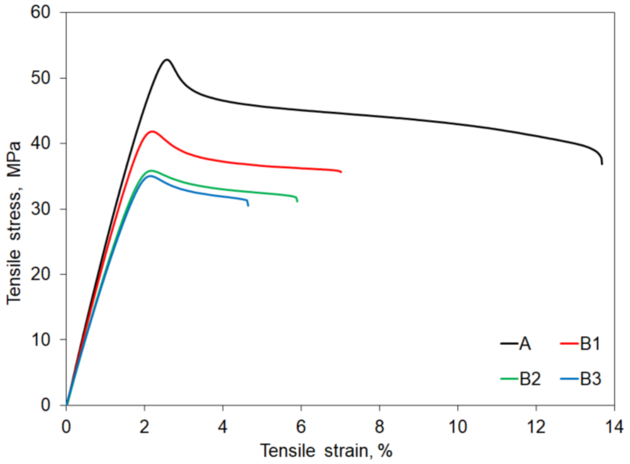

Fig.2. The course of changes of the tensile stress and the unit elongation for the test samples A and B

The average value of a maximal tension at the yield point for IM was at a very high level, slightly exceeding the values for the standard types of ABS terpolymer [31]. It has been concluded that the way of applying layers in FDM considerably affect the tensile stress and Young's modulus (as shown in Table 4). The best results were achieved for the samples of the highest density (i.e. B1). It has also been noticed that deformability of the samples produced by additive manufacturing (range 2.14% to 2.20%) was lower than the ones of injection molded pieces (2.58%) (see Figure 2). The major difference in the elongation was observed between the molded pieces A and B3 samples (low density). This justified the decrease of elasticity of the specimens and indicated the influence of process conditions on this material feature.

TABLE 4. Tensile, flexural and impact strengths of the test specimens obtained by IM and FDM

Spec.	Tensile test		Flexural test		Impact strength	
	Young's modulus, MPa	Tensile stress, MPa	Young's modulus, MPa	Flexural stress, MPa	Charpy impact, kJ/m²	Tensile impact, kJ/m²
A	2581 ± 40	51.1 ± 1.6	2397 ± 162	73.2 ± 0.3	81.5 ± 21.7	87.3 ± 10.1
B 1	2390 ± 40	40.8 ± 1.3	2018 ± 118	57.5 ± 1.3	43.2 ± 16.2	47.6 ± 5.8
B 2	2082 ± 84	33.9 ± 1.7	1061 ± 466	16.6 ± 0.6	15.9 ± 1.7	61.3 ± 10.5
B 3	1998 ± 62	32.7 ± 1.5	1453 ± 285	16 ± 0.59	15.2 ± 1.8	45.6 ± 5.4

The influence of high pressure on a melted polymer in injection molding enabled to obtain an ABS sample of the maximal Young's modulus value (Table 4). For the printed samples (B) the value of this property was lower. It was probably the areas of voids occurring in the printed test samples that caused the decrease of this property which was the biggest, the lower was the density of the layers applied. It is worth noticing that for the B1 samples, Young's modulus was lower by 7.4 per cent in comparison to the molded parts (A).

Applying of the material in other process conditions (B2 and B3) resulted in a further decrease of this property by 20 per cent, as referred to as E_{tA}. Undoubtedly, using process condition B1 for ABS processing resulted in manufacturing products of a high tensile strength and Young's modulus characteristic of engineering thermoplastics. A similar tendency can be observed in the analysis of bending strength tests. However, the bending strength of A samples was higher by 21.1 per cent and Young’s modulus was higher by 15 per cent when compared to B1 samples (see Figure 3, Table 4). For the samples B2 and B3, a considerable decrease of bending stress values (by 77 and 78 per cent, respectively) and the E module (by 55 and 38.8 per cent, respectively) were observed. Increase of Young's modulus value for the samples B3 indicated the role of voids when interacting on these samples with a bending strength. These empty spaces located between the paths of the melted ABS could function similarly to the elements of products manufactured to increase stiffness (overpressing of walls, ribs, flanges, etc.). The strength properties of B2 and B3 samples were considerably worse, hence they are not recommended to be applied in construction elements. Moreover, it can be noticed that ABS samples printed in FDM technology overloaded by bending perpendicularly to the applied layers, were far more fragile than the molded parts (A) (see Figure 3).

The process conditions had a considerable influence on the impact strength of the specimens. The ABS macromolecules which were better-packed throughout the whole volume of molded pieces (i.e. A) affected their significant resistance to an impact load. The B samples were characteristic of a significant decrease of this parameter, determined both in Charpy's test and in the tension impact test (reduction of the values by 47 and 45.5 per cent, respectively, in comparison with A). The analysis of the results indicates that resistance to the impact load of B2 and B3 depends on the direction of force (see Table 4). As far as impact load test by Charpy's method caused a further decrease of the impact to the value of only 15-16 kJ·m$^{-2,}$, the further impact bending of the samples did not cause any further decrease. For the B2 samples, it even showed an increase to 61.3±10.5 kJ·m$^{-2,}$ when compared to the B1 sample.

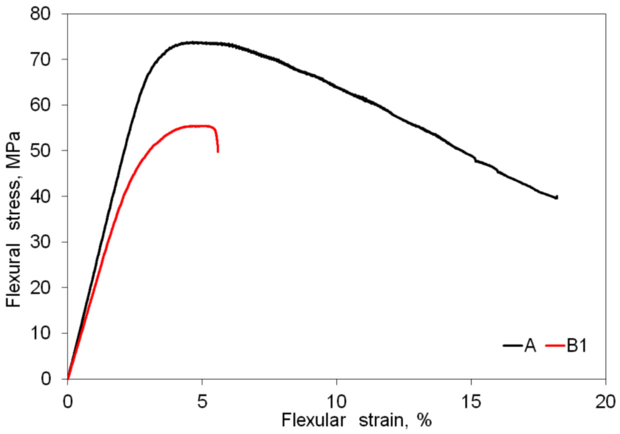

Fig.3. The course of changes of bending stress and deformation for the samples A and B

To conclude the above presented part of the discussion, the molded parts (A) are characteristic of better mechanical properties. It was also found that there is a correlation between the direction of applying the external load and the direction of applying the melted material paths in FDM technology. This affects strength and impact.

This is evidenced by the radar chart presenting the results for the B specimens and molded pieces (A) manufactured at high pressure (reference point), as it can be seen on Figure 4. It can be noticed that though strength properties in the bending test for B1 products are indeed worse than for the A molded pieces, they are good enough to be recognized as constructional elements. A method of a manufacturing of specimens modifies the behavior of ABS samples in impact load to a considerable extent. A method of applying consecutive layers seems to establish a proper way to improve the impact and to determine guidelines for manufacturing products of the desirable and expected mechanical properties.

C. Discussion of results

The behavior of samples described above is also confirmed by the microtomographical analysis. In the A specimens, structural areas of voids (in the form of air bubbles located in the core) have not been found. The cross sections of B samples showed the air pores of variable dimensions (marked in black in Figure 5), located in different way depending on a method of layering. For B1, relatively large pores located not far from outside layer that were predominant.

They arose as a result of changing the direction of the applied paths of melted plastics (as on Figure 5). Both for B2 and for B3, the large pores in the core part of the samples have been also observed. For the samples of the lowest density, the average height of void areas was equal to a fourfold height of a single layer, i.e. 0.68 mm. For the B2, the voids in a core part of samples (i.e. 6 or 7 layer) had the height a two times smaller. The crucial issue for the behavior of B samples in mechanical tests was the fact that there were numerous small pores randomly located throughout the products. The pores were a result of incomplete linking of the melted path of a filament with the neighboring paths, particularly the ones that had been previously applied in the lower layers. It can be concluded that the injection and packing pressure in the IM process causes the elimination of voids in a volume of molded parts and reduces the distance between macromolecules (i.e. it increases their packing). As a result, the strength properties of these samples are most advantageous.

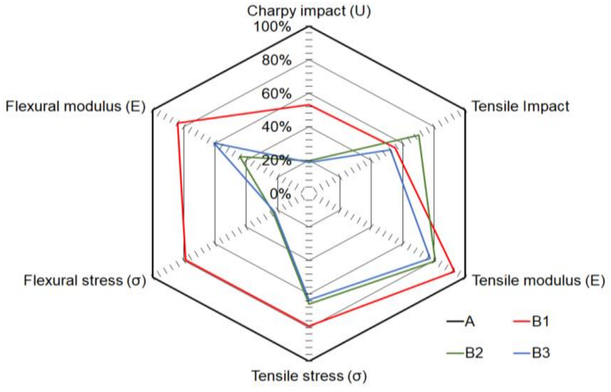

Fig.4. Comparison of mechanical properties of B and A samples

Despite the research conducted in a thermal chamber (for the B samples), the voids were observed at the limits of subsequent paths, as it was already confirmed in the previous paper [19]. Thus, a method of applying the layers has a significant impact on the mechanical properties of the B samples. This could be particularly observed in tension impact tests, where the notchless B samples cracked. When compared to the A samples, the fracture energy in the tensile impact test for the B samples significantly decreased.

The research results presented in this paper seem to inspire to undertake the activities to identify an individual methodology for the realisation of mechanical tests of the porous samples. Undoubtedly, in this type of a porous structure, the cracking appears in the areas of the highest concentration of voids and in the areas where these structures are major. In a microtomography, it has been confirmed that ABS molded pieces are of solid structure and with no voids (see Figures 5 and 6).

It has also been found that the pores content in the whole volume of the material increases, as the density of the B samples made in the FDM technology decreases (as can be seen in Figure 6). The indirect method to determine the changes occurring in the structure of B samples is the analysis of their density. It has been concluded that B samples are characteristic of a lower density value than the A samples (see Figure 7). The lower the density of the applied layer, the lighter and more

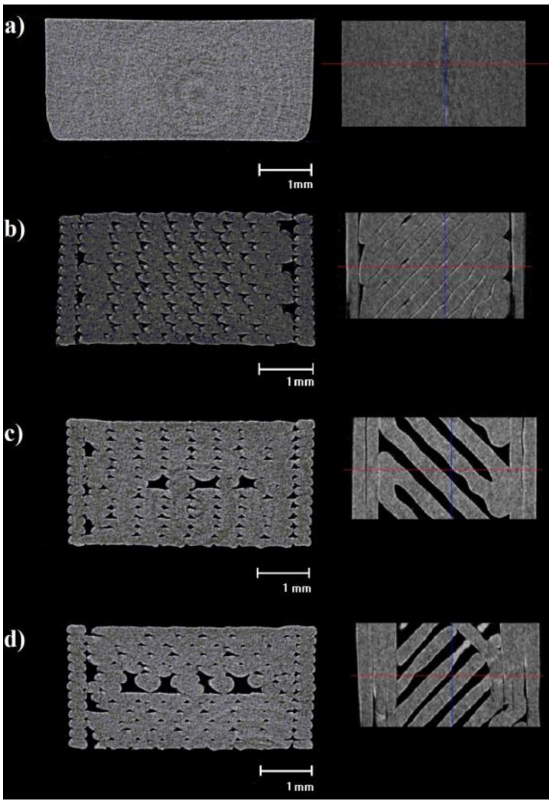

Fig. 5. Tomograph images presenting intersection of ABS products: a) A piece, b) a B1 sample, c) a B2 sample, d) a B3 sample with visible areas of construction voids (in dark colour)

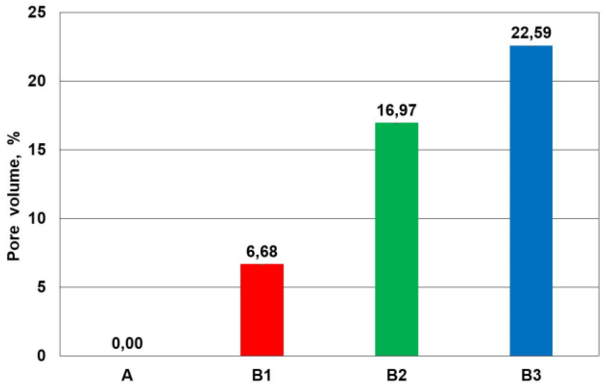

Fig. 6. The pore volume throughout the volume of ABS specimens

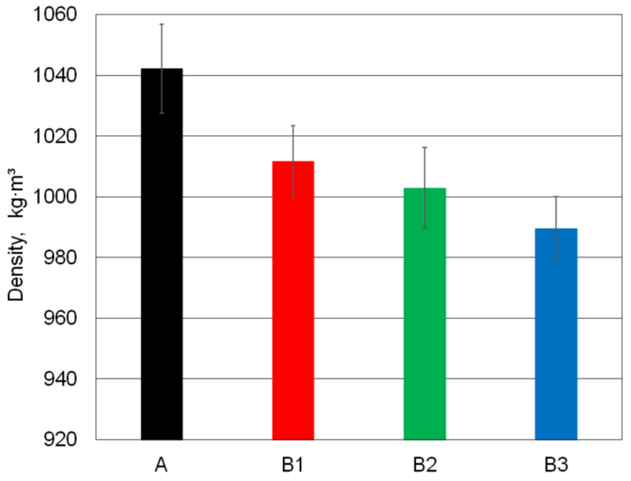

Fig. 7 Influence of manufacturing technology and layering method in FDM on the density

porous the B samples are. This confirms the previous microtomographic analyses.

Referring the density reduction of samples B described above to their mechanical properties, it can be concluded that specific strength of A samples is higher than the one of the printed samples, and the difference between A and B1 values is about 20 per cent. A similar relation was observed in the absolute values of R_m (seen in the radar chart). Simultaneously, it can be noticed that the difference between the specific strengths of B2 and the one of B3 is not significant. The similar results were observed for the specific Young's modulus (Figure 8b)

As can be seen in Figure 8, a high repeatability of results is maintained, which is evidenced by the low values of the standard deviation for all presented process conditions.

4. Conclusion

It can be concluded that for both static and dynamic loads of the samples manufactured in the FDM technology, there occurs a significant difference between the maximal strength values, depending on the direction of a load application.

A load perpendicular to the surface of the applied layers results in the cracking of the samples with a relatively low stress value. Test samples are characteristics of far better strength properties in the tension strength tests, realised both statically and in the tensile impact .

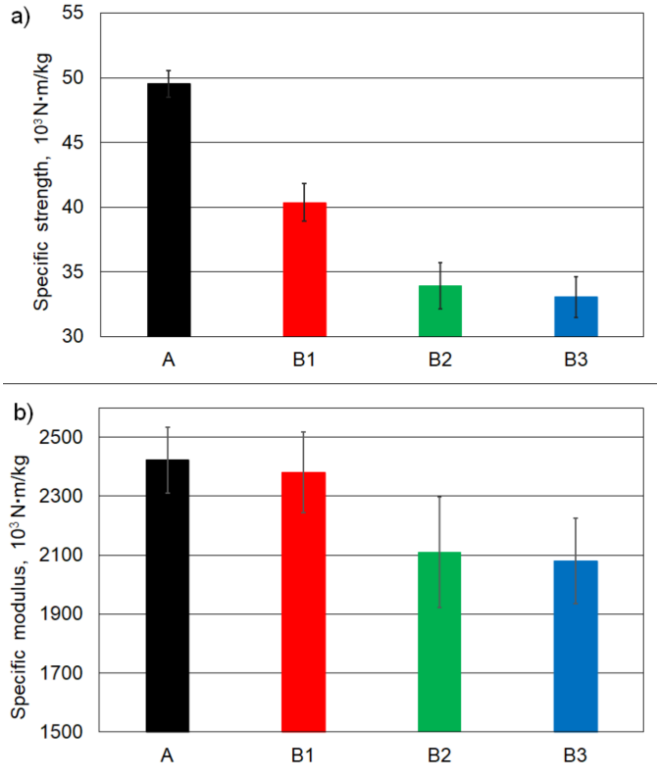

Fig. 8 The influence of manufacturing technology on the values of specific strength (a) and the specific Young's modulus (b)

The research results have confirmed the findings published in the accessible research papers on the comparison of mechanical properties of the B and A samples so far. The samples manufactured under high process pressure are characteristic of better mechanical properties. A way to increase properties for the B samples is developing a better algorithm for the layering of a filament, which leads to minimise the empty spaces throughout the volume of a product. This particularly applies to the areas of voids located near the outside surfaces, as it is them to behave as notches in the material structure. The solution to this problem is looking for changes in 3D printing head design. It was found that the specific strengths for the B3 and B2 specimens are similar, which seems to be beneficial from the point of view of both the economy of the material use as well as of the manufacturing of the structural products with the lowered density.

The following stage of the research will focus on minimizing large voids in the material structure and on better interpenetration of neighbouring filament paths.

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