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INFLUENCE OF FILLING TYPE ON STRENGTH OF PARTS MANUFACTURED BY FUSED DEPOSITION MODELLING

Fused Deposition Modelling technology allows to produce elements of very complex shapes without any additional tooling, which is why it has a broad range of industrial applications. Possibility of manufacturing parts with controlled degree of internal filling allows to shorten the manufacturing time and reduce volume of used material. The paper presents influence of layer filling type on part capability of carrying loads and economical coefficients of the manufacturing process. A problem of mechanical properties is important especially in case of elements used as functional prototypes. The paper presents methodology and results of experimental strength tests of samples with various types of internal filling. As a build material for test samples, ABS material was used. Composite samples were also used – the ABS matrix produced by Fused Deposition Modelling was filled with chemically hardening polyurethane resin in a process developed by authors. The samples were subjected to destructive testing and their strength properties were compared.

1. INTRODUCTION

Rapid development of layered manufacturing technologies, or Additive Manufacturing Technologies (AMTs) along with systems for computer aided design allowed to significantly decrease time needed for a new product to appear in the market. Additive manufacturing processes allow to obtain physical, three-dimensional shapes of nearly any complexity, directly from the digital representation of a product (stored in a CAD model). There is no need of using any specialized tooling, that is why the whole manufacturing process often consists of a single operation. Additive manufacturing technologies can be used for Rapid Prototyping, Rapid Manufacturing or Rapid Tooling. They are invaluable, when there is a need of quick manufacturing of a physical prototype of a designed part [1],[2].

One of the most frequently used AMTs for industrial purposes is Fused Deposition Modelling, which is used to obtain parts out of thermoplastic materials. The most widespread build material is acrylonitrile butadiene styrene (ABS), which ensures relatively good strength and acceptable thermal shrinkage. It also allows further processing of the obtained elements (grinding, gluing,

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painting etc.). Machines for the Fused Deposition Modelling, in comparison with the other additive manufacturing technologies, have small dimensions and are easy to maintain. They are also quiet and clean, which makes them available for use directly in design studios [1],[3].

Fused Deposition Modelling is a process consisting in layered, linear deposition of plasticized thermoplastic material supplied in form of a wire by an extrusion head with nozzle of low external dimension (in BST 1200 machine used for the described research, nozzle diameter is 0,4 mm). The head can move in two axes (X and Y). It deposes material on the model table, with data about head positioning coming from horizontal cross-sections of the part, prepared on the basis of the 3D CAD model. After manufacturing of one, complete layer, the model table moves in Z direction to distance equal to selected layer thickness. Deposed material goes back to a solid state a moment after leaving the nozzle, bonding with the previously created layers. For the more complex structures, in which the next layer contour area is significantly dislocated regarding the previous layer contour, support structures are needed to prevent gravitational deformation. The extrusion head is equipped with the two nozzles, one for the build material, the other one for the support material (usually similar types of thermoplastics are used, in some machines the soluble support material is used for easier removal). Produced part is ready for use immediately after support material removal [1],[2].

2. RESEARCH PROBLEM

The FDM technology is used not only for the visual prototypes, but also for the functional prototypes, which are expected to have appropriate mechanical properties. Anisotropy of these properties is a problem known worldwide [4],[5], as is a problem of high dependency of these properties on the process parameters, such as orientation of the product in the working chamber during manufacturing or layer thickness [5]. In practice, it can result in obtaining products of totally different properties using various sets of the process parameters – the tensile strength, for example, can vary between 8 to 22MPa for the same material [6]. The dependencies are non-linear and the properties cannot be easily predicted. The thesis [7] presents methodology of preparation of the finite element analysis of products manufactured using FDM technology and determination of maximal forces which can be applied to the part without damaging it. However, cases described in the thesis concern only simple stress states, like static bending. In practical, industrial applications, parts are very often subjected to complex loads. That, combined with complex shapes and still not fully determined dependencies between process parameters and mechanical properties, makes it very hard to predict if the part will be able to operate without being damaged. The research presented in this paper is a part of a broader study, aimed at solving this problem.

Another important problem, also addressed by this paper, is an economic efficiency of part manufacturing using the FDM technology. As observed by some researchers, the FDM technology can be considered for more or less the same spectrum of applications as the injection molding process, but these two processes are entirely different in terms of costs [8]. Although for a batch of several pieces of products it is economically justified to use the FDM technology instead of injection molding, it is still not cheap. Therefore, new methods of reducing the cost and time of producing the fully valuable FDM products are being sought by researchers all over the world. Some of the frequently presented approaches include thorough control of the manufacturing process and using multiple materials during the same build [9], as this allows to obtain some reductions in manufacturing time and cost.

The Fused Deposition Modelling technology allows to produce parts with either full (solid) or partial (sparse) internal filling (Fig. 1a and 1b). Savings in the material volume necessary for the part production is a big advantage of the sparse filling, but it comes with a price of decrease in mechanical properties, which was proven in numerous studies [10].

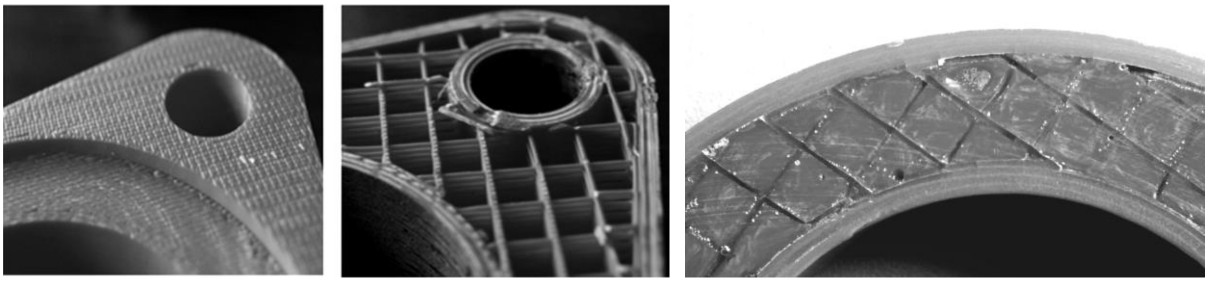

a) b) c)

Fig. 1. Filling types in FDM technology: a) full, solid filling, b) partial, sparse filling, c) sparse filling with empty spaces filled with resin – concept of the authors

In practice, the functional prototypes are mostly manufactured with the solid filling, but it is not always economically justified. In some cases, prototypes with the sparse filling will be able to carry a specific load, with maintaining a specific distance between filling threads of the material. Some previous experiments performed by the authors have shown that after a certain point, further reduction of the quantity of the internal material does not affect strength of parts significantly, especially when it comes to a complex state of stress. However, known and analyzed literature lacks data confirming these conclusions, therefore a certain part of research described in this paper was aimed at proving it.

Moreover, the authors proposed an alternative, effective way of manufacturing prototypes with the partial internal filling, in which the empty spaces are filled with a chemically hardened resin, creating a specific kind of a fiber composite. The composite has two distinct phases – the matrix produced by FDM method out of ABS material and the reinforcement in form of a polyurethane resin (Fig. 1c). Usually in case of fiber composites, internal fibers are a reinforcement to the resin matrix [11],[12]. In case of the composite invented by the authors, a contour (shell) manufactured using FDM method has a task of maintaining the product shape, while the resin ensures high mechanical properties. The resin filling also helps to reduce the anisotropy of the mechanical properties of FDM parts and diminishes the influence of the part orientation on the product strength. The idea of the composite FDM models is not quite a new one, as some researchers have tried the more classic approach of reinforcing the threads of a thermoplastic material with glass, carbon and other fibers [12]. The results of such an approach are promising in terms of increasing the strength of the FDM products. Still, the approach presented in this paper is innovative, as it uses a low-cost material (a common polyurethane resin) to reinforce an FDM part and thus reduce costs of its manufacturing.

The research presented in the paper was an experimental one – series of samples with various filling types were manufactured (of all three types – the Fig. 1a, b and c) and subjected to load. The shape of samples was more complex than the usual bending or tensile test specimen – the aim was to induce a complex state of stress in the part. At the moment, there are no mathematical models allowing to calculate stress inside the FDM part on the basis of a given load – lack of such a model is caused mostly by complexity of the internal macrostructure of parts manufactured by FDM technology. So far, there is no hypothesis which would unequivocally allow to determine the criteria of exceeding the tensile strength or yield point in complex state of stress in FDM-made products. As there are no dedicated standards of strength tests of products manufactured in a layered manner using the FDM technology, the authors designed the experimental procedure themselves. Only two values were determined for each test – maximal force (load) before the moment of fracture and maximal deformation. It is important to notice, that the planned experiment was aimed at determining the differences between samples manufactured with the various filling types, both in technical (strength) and economical (time and cost of manufacturing) coefficients of the product, therefore calculation of the absolute strength of tested products was of less importance.

3. RESEARCH PLAN

Manufacturing of samples for the tests was conducted using the Stratasys Dimension BST 1200 machine. Thermoplastic ABS material of type P400 (manufacturer designation) was used as a build material, in form of a cartridge supplied by the manufacturer. Eight series of samples were subjected to tests. Two first series were manufactured with solid filling – one of them as a standard solid filling type (designated as Solid), the other one as a sparse filling with zero distance between threads of material – this one was designed as SP0. The next two series were manufactured using the sparse filling with the tool path distance 0,15 in (3,81mm), which is a standard sparse density recommended by the machine producer, and 0,45 in (11,43mm) and were designated as SP15 and SP45 respectively. The next series was manufactured as a SP45 type, but before the processing was finished (after all the sparse-filled layers were deposed and right before 4 last solid layers closing the shell), the threads of material forming the internal filling were manually removed to obtain a completely hollow part. This series was designated as SP_empty.

The last three series were obtained by filling SP15, SP45 and SP_empty sample types with chemically hardening resin Axson F19, obtaining composite samples as a result. They were manufactured to check how filling the empty spaces of an FDM model with a resin will affect the part strength and behavior under load. The resin selected for manufacturing of the composite samples was a foundry resin Axson F19. The resin addition was realized gravitationally. The resin was added to the samples before the layer deposition process was finished – the process was stopped right before the last 4 layers (which close the shell) were deposed, at the last layer with sparse internal filling. Stopping the process was available thanks to the pause option available in the machine control panel. After using this function, the extrusion head moves outside the material deposition area and the modelling table (with the attached tray on which the model is built) moves down to the lowest coordinate in the Z axis. This allows the model to be accessed easily. Using a nozzle of 1,2 mm diameter, the empty spaces inside the ABS matrix were filled with a liquid resin. After the matrix was completely filled with the resin, the process was resumed in order to get a closed shell. After the layer deposition was completed, the modelling tray along with the composite sample was removed from the FDM machine working chamber. Because of possible deformations during separation of the model from the tray and removal of the support material, these operations were performed after full curing of the resin, which is obtained after 90 minutes for the used F19 resin.

Volume of the liquid resin was calculated before the manufacturing. Total volume of a single sample used in the research is approx. 13 cubic centimeters. The waste percentage for the used resin is about 30% (as resulting from the authors' experience with the casting process, this is determined by the resin castability) for volumes below 30cm^3. Hence, a volume of 20 cm^3 of the liquid F19 resin was prepared for the each composite sample. The liquid resin is a mixture of a base material with the hardening agent, the proportion being 1:1.

The same procedure of the resin addition was applied to all of the sparse sample types, resulting with samples designated as SP_empty_F19, SP15_F19 and SP45_F19. Each of the series consisted of 6 samples – number of a sample was added to the group designation to create a unique ID for the each sample (e.g. fourth sample of SP15 group has an ID of SP15_4).

All samples were manufactured in a horizontal orientation (0° in both X and Y axes), ensuring the best possible strength and shortest manufacturing time for the selected part geometry. The layer thickness used was 0,254mm. Samples had 18 layers in total, with the layer arrangement for each part was as following (starting from the model base):

- 8 base layers (support, not a part of the actual sample geometry),
- 4 layers with a solid filling,
- 10 layers with controlled sparse filling,
- 4 layers with a solid filling.

Trajectories of the material thread deposition in layers with controlled sparse filling is presented in the Fig. 2. During the first operation of each layer, the inner contour is deposed (Fig. 2 – green color), then the perimeter (outer surface of a part, Fig. 2 – red color) and finally the inside of a layer is filled (Fig. 2 – blue color). Tool paths for each consecutive layer are rotated by 90° regarding the previous layer. For layer number *n*, angle between tool path direction and the X axis equals -45°, for layer number *n*+1, the same angle equals +45°. Such a mutual positioning of layer fillings, named "criss-cross", allows to obtain a more durable bond between them.

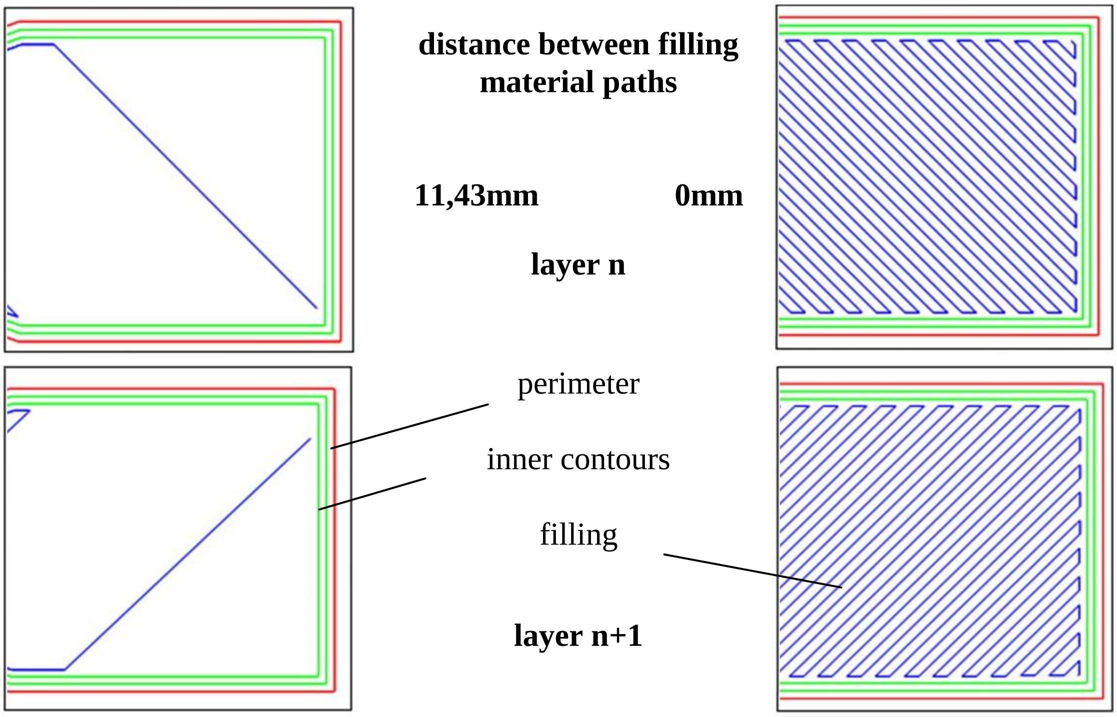


Fig. 2. Trajectory of material thread deposition in layers with controlled sparse filling

Shape of the test samples was selected in a way to achieve a complex state of stress inside a sample, both in terms of tension and bending. Dimensions of the samples and scheme of the experiment are presented in the Fig. 3.

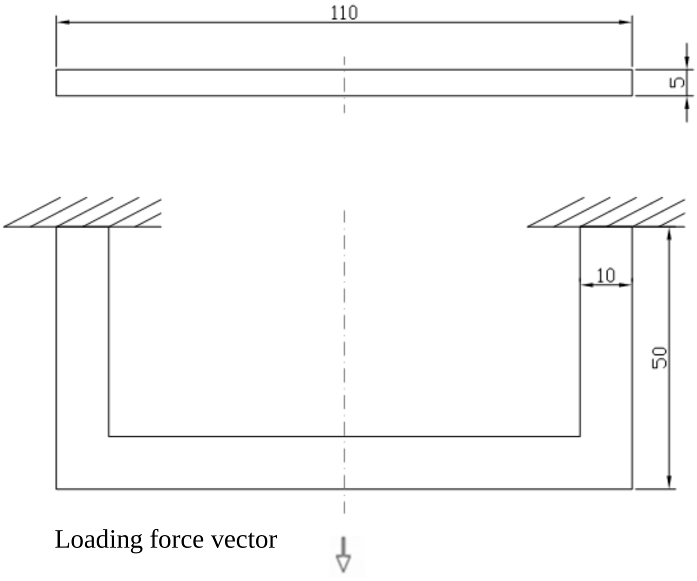


Fig. 3. Dimensions and scheme of experiment of the tested samples

Because of the sample dimensions, it was not possible to manufacture all the samples from a given series in one operation with the identical orientation – working chamber size of the available FDM machine was too small. Also, as proven in [13], planar change of location of the part in the working chamber (without orientation change) may have an influence on its shape accuracy. Earlier research has shown that the FDM process has an acceptable repeatability in terms of accuracy [3], so manufacturing each sample in a separate process is justified. Arms of the manufactured samples are actually 20mm longer than shown in the dimensions in the Fig. 3 – extended part of the arms was used for proper basing and fixing the sample in a vice, according to the assumed measurement scheme. The produced sample on the modelling tray is presented in the Fig. 4.

During the actual experiment, particular samples were gradually loaded. After each load increase, sample deformation was measured using 3D optical scanner GOM Atos I. Application of the 3D scanner allowed to perform measurements in a short time (no more than 2 seconds for a single measurement) with accuracy of ±0,02mm. In case of measurement conducted with the 3D scanner, complex standard measurement uncertainty is calculated as a vector sum:

$$u(X) \approx \sqrt{\sum_{i=1}^{m} (c_i u_i(X))^2}$$

where:
$u_i(X)$ – all identified uncertainty sources,
c_i – vulnerability coefficients [14].

In case of the used GOM Atos I scanner, taking the measuring process parameters into account (applied measuring field MV250, high-detail traversing, standard post-processing), extended measurement uncertainty is equal to 0,08mm.

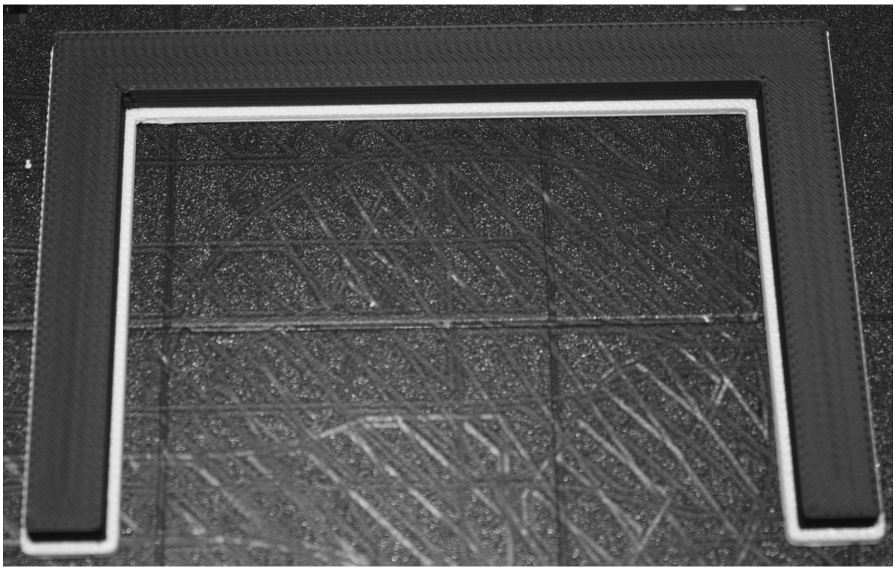


Fig. 4. Sample for research after removing the modelling tray from the BST 1200 machine (light gray contour - support material)

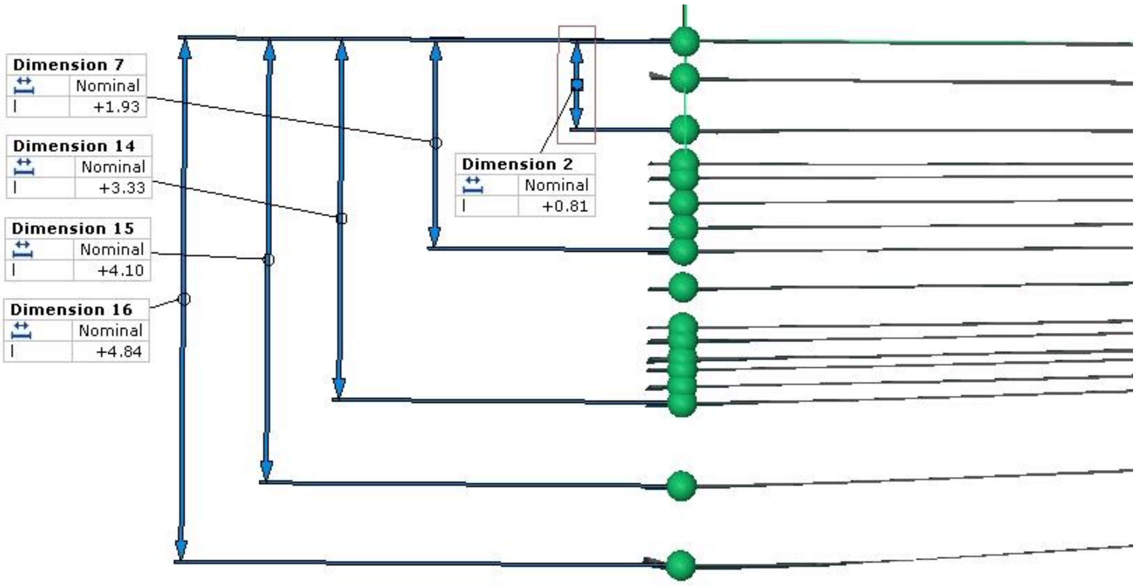


Fig. 5. Points constructed on subsequent scans, showing deformation of the sample SP_empty_1 under increasing load

Reference points in form of markers (on the basis of the markers, the algorithms of the scanner determine its position and orientation in relation to the measured object) were placed on stationary elements of the experimental workplace. Thanks to this, all measured points were placed in the same coordinate system, which facilitated determination of the samples deformation in the Z axis. The deformation was determined geometrically using the GOM Inspect Professional software. On the measured top surface of the unloaded sample, a plane was constructed along with a central point located on it. From the point, a line normal to the plane was constructed. Intersections of the line with subsequent scans were marked by points – their distance from the initial point was assumed as a sample deformation in vertical direction under given load. An example of the described constructions and measurements (the line along with the points and scans for sample SP_empty_1) is shown in the Fig. 5.

4. RESULTS AND DISCUSSION

Out of all studied samples made purely of the ABS material, the one able to carry the largest load was the sample SP0_4 – 195,2N. The weakest sample was the SP_empty_3 sample – 134,3N. In case of the composite samples (ABS matrix filled with the F19 resin), the largest recorded load was carried by the sample SP45_F19_5 – 231,7N and the weakest sample was SP_empty_F19 – 187,8N. The Figure 6 and the Table 1 present values of average destructive loads for all the studied samples. In general, the difference between the best and the worst sample in terms of the carried load at the moment of the sample destruction was 42%. Samples of the series SP0 were slightly stronger than samples from the Solid group. For all three groups of samples with the partial filling (SP15, SP45, SP_empty), average destructive load values were practically the same (differences between samples from these groups are no higher than measurement errors). Also, the samples filled with the F19 resin were mostly stronger than all the other samples.

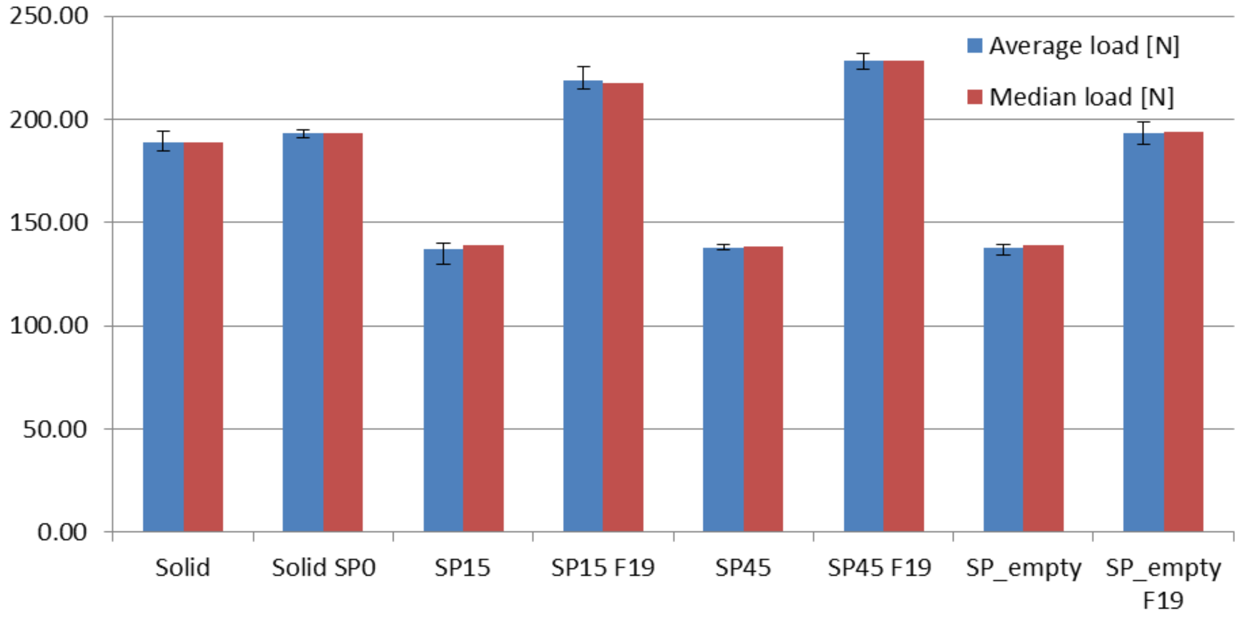


Fig. 6. Average destructive load values for the tested samples

Table 1. Results of the experiments – deformation and maximum force (destructive load)

No.	Designation	Average deformation – Z axis [mm]	Average destructive load – maximum force [N]
1	Solid	3.43	188.7
2	SP0	3.48	193.3
3	SP15	3.84	137.4
5	SP15 F19	4.56	218.9
6	SP45	3.54	138.0
8	SP45 F19	4.49	228.3
9	SP Empty	4.43	137.8
11	SP Empty F19	3.40	193.3

Samples from the series SP15, SP45 and SP empty have demonstrated practically the same mechanical properties. It means that internal filling material of these samples did not take an important part in carrying loads. Still, parts with the solid filling (SP0 and Solid) are considerably stronger than the sparse samples. Presumably, there is a certain sparse distance (lower than 3,81mm) which can be called a critical sparse value. Increasing the sparse distance above the critical value does not result in the further strength decrease. In the presented studies, all samples with the partial internal filling were manufactured using the sparse distance higher than the critical value, which has yet to be determined for the used material and process conditions. It will probably differ from part to part, as the volume ratio between solid layers and layers with the sparse filling is dependent on geometry of a given part and is lower for thicker parts (i.e. parts with the greater vertical dimension). This also leads to conclusion, that for parts with lower solid-to-sparse volume ratio, the influence of the sparse distance on part strength will be higher (i.e. the critical sparse value will be higher). Further studies are needed to confirm these statements.

Considering the composite samples, significant strength increase can be observed in case of samples from the series SP15_F19 and SP45_F19, but not for samples from the SP_empty_F19 group, which have properties similar to the SP0 and Solid samples (made purely of the ABS material). It means that presence of the material threads inside the part filled with the resin positively affects the strength of the composite parts with the ABS matrix produced by the FDM process. The highest increase of the mechanical properties was observed for samples from the SP45_F19 group – their strength was more than 17% higher than the strength of the pure ABS samples with the solid filling, which is a significant difference from the practical point of view and an important information regarding manufacturing of functional prototypes using the FDM technology. Filling the ABS matrix deposed in layers with the chemically hardening resin also helps to increase the bond between the subsequent layers, which results in significant decrease of the anisotropy of the mechanical properties of a part and reduction of probability of the layer separation under load (layer separation is a prevailing destructive mechanism in FDM parts [6]). In general, using resin to fill internal space of FDM parts practically eliminates one of biggest disadvantages of the whole technology (which is a weak bond between layers, leading to frequent part destruction by layer separation under minimum loads).

The economical aspect of the prototype production is also a very important one. the Table 2 presents information about average manufacturing time and volume of the used material for all the sample types, overall material cost was also calculated. Volumes of the P400 ABS material and manufacturing times were calculated on the basis of the values from the CatalystEX software (used to control the FDM machine). The resin volume also includes the waste material left after the process of the composite matrix filling. The support material volume was not considered, as it was exactly the same for all of the sample types. Time of manufacturing of the SP_empty sample type also includes time of removal of the internal filling material (as mentioned before, BST 1200 machine does not allow to produce entirely hollow parts, so SP_empty samples started out as SP45 samples and the internal material was removed manually during the layer deposition process). Time of filling the composite samples with the resin is also included in the table.

Table 2. Economical coefficients of the sample groups – manufacturing time, material volume and cost

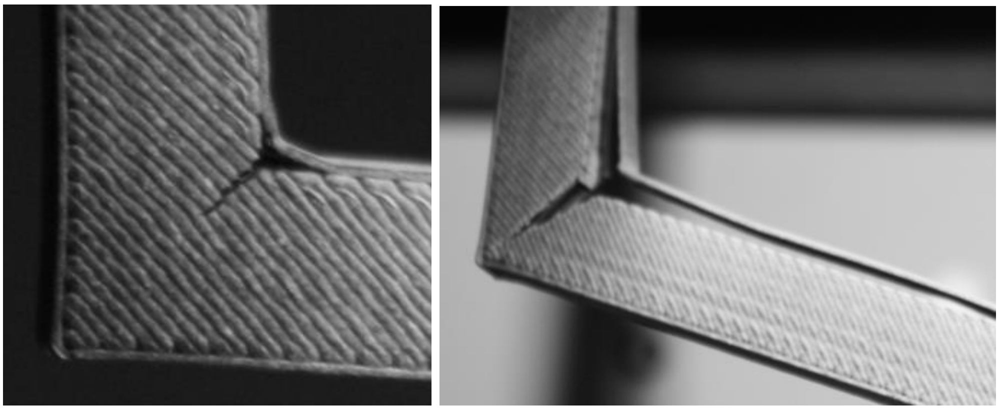
Series designation	Avg. manufacturing time [min.]	Avg. ABS P400 material volume [cm^3]	Avg. Axson F19 resin volume [cm^3]	Material cost per sample [PLN]
Solid	35.2	12.82	-	20.77
SP0	36.9	13.02	-	21.09
SP15	24.5	8.82	-	14.29
SP15_F19	31.8	8.82	20	15.79
SP45	22.1	8.35	-	13.53
SP45_F19	27.3	8.35	20	15.03
SP_empty	30.3	8.35	-	13.53
SP_empty_F19	32.2	8.35	20	15.03

Comparison of the economical coefficients from the Table 2 with the strength (Table 1) allows to make some interesting observations. If only the pure ABS samples are considered (setting aside the F19-filled samples), the relation is simple – the greater strength, the greater cost and vice versa – the cheapest sample is the weakest one.

Implementation of the resin filling method introduces a positive change to the technical-economical coefficient relation, as the F19-filled samples are both cheaper and stronger than the pure ABS parts with the solid internal filling. The composite samples from the best group in terms of strength (SP45_F19) are almost 23% faster to produce and the material used is almost 28% cheaper than in case of the strongest pure ABS samples.

In the experiment designed by the authors, the greatest stress should occur in the internal corners of the test samples (it was analytically determined by the authors before tests). The experiment has confirmed the stress distribution determined analytically – all of the test samples fractured in the corners (Fig. 7a). Most samples fractured in two or three places at once (at the corners and at the loading point – center of the sample). In case of the pure ABS samples, contour threads behaved differently than the internal filling material – they deformed and separated from the rest of the sample (Fig. 7b).

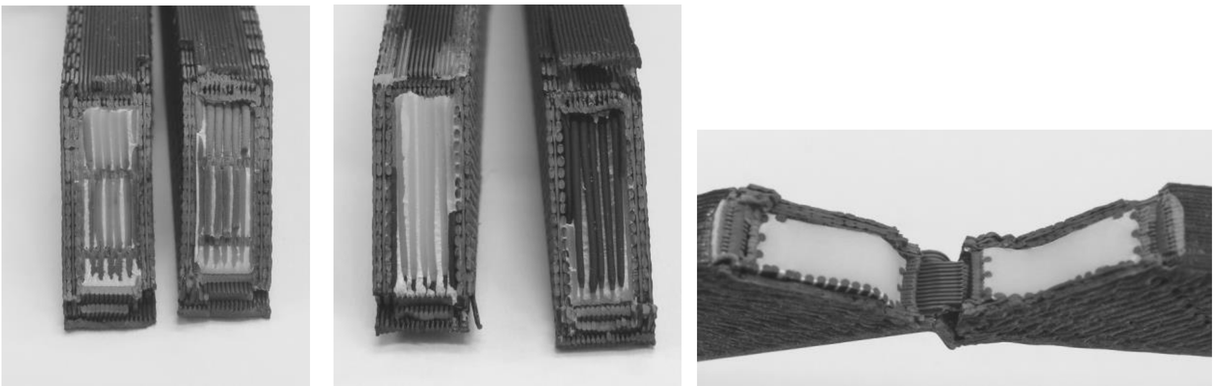
The samples with the solid internal filling (Solid, SP0) fractured entirely (to the point of separation) in the both corners, while samples of the other types fractured entirely only in one corner, the other one was deformed and damaged, but not destroyed. In case of the samples with the partial internal filling, material from the inside of the sample was separated from the rest of the sample without being destroyed (no material thread break). It confirms the conclusion about almost no participation of the sparse filling in carrying of the load (Fig. 8).



a) b)

Fig. 7. Pure ABS sample destruction – a) fracture starting point in the internal corner, b) contour layer separation

Fig. 8. Fracture in the partially filled ABS samples (sparse distance 11,43mm)



a) b) c)

Fig. 9. Broken composite samples, groups: a) SP45_F19, b) SP15_F19, c) SP_empty_F19

In the composite samples of the groups SP45_F19 and SP15_F19 (destroyed samples are shown in the Fig. 9a and 9b), the fracture line goes along the threads of the internal material. Also, layer contours have been separated from the other material threads to some degree.

5. CONCLUSIONS

The conducted research allowed to confirm the fact that the strength and the behavior of the parts produced by the Fused Deposition Technology are greatly influenced by the filling type – not as much as in comparison to the previous studies on the other parameter – the orientation, but still significantly. For the pure ABS parts, manufactured using a typical layer deposition process, degree of filling has little influence on the total strength of the part, if the distance between threads of internal material is higher than a critical distance. The critical sparse distance value (or a method to calculate it) has yet to be determined and this will be a direction of further studies by the authors.

Having this in mind, a solid/sparse ratio also needs to be considered. Parts with the sparse internal filling have a certain number of solid, monolithic layers. This number is constant – four layers per one side of the part (8 layers in total). For the tested samples, the ratio of solid/sparse layers (in terms of number of layers) was equal to 0.8. It means that for each 5 layers with the sparse filling, there are 4 layers with the solid filling. For parts with a different (larger) thickness, this ratio will change and their behavior under load will change as well. This concerns both pure ABS parts with the partial internal filling and composite parts filled with the resin. Further tests need to be performed to find out how a total number of layers will affect the product technical coefficients for all the available filling types.

The proposed innovative filling method (the sparse filling + chemically hardened resin) allows to greatly increase the overall product strength while maintaining relatively low costs of its production. Therefore, it is advisable to further investigate this method as a promising way to improve the Fused Deposition Modelling process and technical and economical coefficients of parts produced using this technology.

It is important to notice that strength of the pure F19 resin, as well as strength of the pure ABS does not exceed the strength of the obtained composite. That conclusion is true for samples where the resin mixes with threads of the internal material – both samples that were totally hollow inside and samples filled with the resin did not achieve strength higher than the pure ABS samples. Presumably, the arrangement of the material threads inside the sample also influences strength of the ABS-resin composite. It is therefore crucial to find the best combination of the sparse distance, thread arrangement (tool path angles) and amount and type of the used resin – these are further study directions considered by the authors.

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