The effect of the 3D printout filling parameter on the impact strength of elements made with the FDM method

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Abstract. The paper discusses the aspects of potential use of 3D printing technology in the process of manufacturing elements with different layer fillings. In 3D printing technology, the denser the percentage of filling a material, the higher the mechanical strength of a given element. However, in the literature on the subject, the dependence on these parameters for additive technology has not been unequivocally determined. Therefore, the aim of the study is to find a correlation between the internal structure of the elements understood as a percentage of filling the material produced by 3D printing technology and the impact strength achieved by these elements. To carry out the research process, sets of polymeric samples were prepared using 3D FDM printing. The shape and dimensions of the samples were determined in accordance with the PN-EN 10045-1 standard. The samples were made by means of the Printo H3 device with a closed working chamber, using ABS polymer filament. The samples were filled with a percentage interval of 10%. Impact strength tests of polymeric samples were carried out on a Charpy hammer stand adapted for this purpose. In this way, the results concerning the breaking energy were collected for particular groups of samples. The collected data allowed us to determine the relationship between the percentage of filling the sample and the energy absorbed by the sample. The results provided the basis for conclusions and recommendations regarding one of the most important technological parameters – the percentage of printed element filling.

1. Introduction

Plastics are a relatively new group of materials which have become highly popular in recent years. They are important for the manufacture of lightweight structures and components. Their special properties, such as corrosion resistance, low density, low cost, flexibility of machining, good mechanical properties in relation to weight, good tribological properties make them alternative materials to traditional metal and ceramic materials [1]. The properties of plastics are modified by the use of various additives [2, 3] to obtain various composite polymeric materials. This broadens the scope of their engineering applications in various branches of industry, opening up a whole range of possibilities for individual adaptation of materials to specific purposes [4, 5, 6, 7, 8, 9].

Plastic products (components) are manufactured using various methods, e.g. extrusion, injection moulding, casting or machining. An additional method that has appeared in recent years and is being dynamically developed is 3D printing technology. It has gained acceptance and popularity in production [10], educational and home applications. FDM printers are the most common type of equipment for manufacturing components. This is a method in which the thermoplastic polymer film is plasticised and
applied in layers until an object is created. The basic advantages of FDM printing include: relatively low cost of manufacturing an element, lightness and speed of production without the need to use a mould, wide range of printing parameters, the possibility of obtaining complex shapes and structures, elimination of machining or additional finish processing, etc. Currently, the number of polymers used for 3D printing is limited due to the special properties needed for successful printing. These are: relatively low glass transition temperature, melting point and low tendency to shrink after solidification. The most commonly used materials for 3D printing are acrylonitrile butadiene styrene (acrylonitrile butadiene styrene), acrylonitrile-butadiene-styrene (ABS) and polylactic acid (PLA). It is caused by their technological properties – dimensional stability and low glass transition temperature. Other printable polymers include polycarbonate (PC), polyvinyl alcohol (PVA) and polyetherimide (Ultem). Year by year the development of new polymeric composites with a wider range of physical properties is visible, which increases their applicability in 3D printing. These are polymeric composites in which the matrix material is a printable polymer. This is dictated by the fact that it is compatible with 3D printers. There are many examples of successful implementation of such material modifications for the use in FDM [11]. Mechanical properties of 3D printing technology products depend mainly on the properties of the substrate material [12]. In addition, these properties are also affected by the parameters of the printing process itself, i.e. density and pattern of material filling, angle of printing elements, the thickness of layers, etc. Due to the fact that the use of this technology increases in the most diverse areas, it requires continuous improvement of knowledge and technology. Therefore, these issues attract increased attention from scientists and researchers [13]. In their work, Mitrović et al. [14] attempted to establish a functional relationship between the angle of printing 3D ABS samples and the tensile strength under static axial load conditions. In turn, simulation and experimental studies of deformation and cracking behaviour of the crystal lattice of printed 3D samples under uniaxial tensile load were carried out by Xu et al. [15]. Two types of printed elements were considered: elements printed horizontally and vertically. Whereas, mechanical properties of 3D printed composite samples reinforced with continuous carbon fibres were characterised in the paper by Werkena et al. [16].

The aim of this study was to find a correlation between the percentage filling of the material of the 3D print samples and one of the mechanical properties parameters – impact strength.

2. Object and research methodology

The impact tests were carried out with the use of 3D printing technology. The samples were printed on a Printo H3 device (figure 1) with a closed working chamber using the FDM method. For printing, a thermoplastic filter made of acrylonitrile-butadiene-styrene (ABS) with a relative density of 1.06 and melting point >80 °C was used. Varying percentage of internal filling of the sample material was applied. The minimum filling density was 10% and the maximum of 100%. The density was increased by 10% in relation to the previous one.

Figure 1. View of a 3D Printo H3 printer.

Digital 3D models of samples were made in Autodesk Inventor according to PN-EN 10045-1. It contains detailed data concerning the preparation of samples for the testing process. 3D models of
55x10x10 mm samples with two types of notches (V and U-shaped) with a depth of 2 mm were prepared (figure 2).

![Image of notched specimens]

Figure 2. Dimensions of notched specimens: a) Type U, b) Type V.

The geometry models developed are saved in *.STL files so that they can be exported to a slicer program. Cura version 2.3.1 was used, and configured with the 3D printer used. After loading, the model was placed in the working space of the printer table with the notch facing up and the dimensions interpreted by the program were checked for correctness. The grid pattern of sample filling was selected due to the fact that it is most frequently used in the printing of elements. With these settings, a sequence of instructions was generated for the printer in the form of separate g-code files for all sample options (different fill levels and different notches). The data estimated by the program for each printout, such as object weight and print time (without taking into account the warm-up time of the printer elements) were saved. Figure 3 shows an overview of the grid distribution for 3D models with different fillings, which was generated by the program. The blue lines on the view indicate the idle movements of the printer head. The distribution of the filled grid is the same for samples with V and U notches.

![Image of 3D models with different fillings]

Figure 3. 3D models with the following filling values: a) 10%, b) 20%, c) 30%, d) 40%, e) 50%, f) 60%, g) 70%, h) 80%, i) 90%, j) 100%.
The 3D printing process was carried out using the parameters presented in Table 1.

**Table 1. Summary of the most important parameters of the sample printing process.**

| Parameter name                  | Value                                      |
|---------------------------------|--------------------------------------------|
| Layer height                    | 0.2 mm                                     |
| First layer height              | 0.2 mm                                     |
| Number of wall outlines         | 2                                          |
| Pattern of filling              | GRID                                       |
| Material filling density        | from 10% to 100% (every 10%)               |
| Head temperature                | 235 °C                                     |
| Table temperature               | 95 °C                                      |
| Retraction distance             | 4 mm                                       |
| Retraction speed                | 60 mm/s                                    |
| Total print speed               | 50 mm/s                                    |
| Filling print speed             | 60 mm/s,                                  |
| Outside wall print speed        | 25 mm/s                                    |
| Cooling of the printout         | off                                        |
| Supports                        | none                                       |
| Raft                            | none                                       |
| Scale of the object             | 100%                                       |

The impact tests were carried out using a Charpy pendulum hammer. A hammer with a rated initial energy of 1.5 kpm was used. Using the following conversion factor: 1 kpm = 9,806 J, the rated initial energy of the hammer was determined as 14,709 J. The laboratory stand consisted of a pendulum with a nominal arm length of 380 mm (from the beginning of the arm to the middle point of the hammer), at the end of which there was a hammer with a nominal mass of 2,035 kg. The stand was equipped with an analogue scale that enabled the reading of the energy absorbed by the breaking of the sample and the angle of the arm's inclination after breaking. The maximum swing angle of the arm when released was 160° and corresponded to the free fall of the hammer without the specimen. The scale was attached to the fixture body in such a way that it was possible to change its position if the scale zero point needed to be moved. Figure 4 shows the Charpy hammer stand with a visible scale.

![Figure 4. Charpy's hammer used to break the samples.](image)

The base of the device was a cast-iron block which allowed it to maintain the stability of the position of the device during the tests. The equipment was used to break samples made of various
materials, including metallic materials. The specimens were placed in such a way that the hammer struck from the opposite side of the notch. The device was activated by manually unlocking the hammerlock with a lever.

3. Results

The results of the research allowed to determine the correlation between the internal structure of the elements (understood as the percentage of material filling) made with 3D printing technology using the FDM method and ABS polymer filament, and the mechanical properties parameter – impact strength.

The results from the tested processes conducted for selected samples are presented in Table 2.

| Sample determination | Sample filling [%] | Fracture energy [kpm] | Fracture energy [J] | Hammer angle after fracture [°] |
|----------------------|-------------------|-----------------------|---------------------|--------------------------------|
| 1pV10_02             | 10                | 0.07                  | 0.68642             | 148                            |
| 2pV10_02             | 10                | 0.075                 | 0.73545             | 147.5                          |
| 3pV10_02             | 10                | 0.07                  | 0.68642             | 148                            |
| 4pU10_02             | 10                | 0.08                  | 0.78448             | 147                            |
| 5pU10_02             | 10                | 0.08                  | 0.78448             | 147                            |
| 6pU10_02             | 10                | 0.07                  | 0.68642             | 148                            |
| 7pV20_02             | 20                | 0.06                  | 0.58836             | 149                            |
| 8pV20_02             | 20                | 0.07                  | 0.68642             | 148                            |
| 9pV20_02             | 20                | 0.07                  | 0.68642             | 148                            |
| 10pU20_02            | 20                | 0.07                  | 0.68642             | 148                            |
| 11pU20_02            | 20                | 0.07                  | 0.68642             | 148                            |
| 12pU20_02            | 20                | 0.08                  | 0.78448             | 147                            |

Samples from a single test series show similar results when broken. Small differences in impact strength occur between specimens with the same percentage filling but with a different notch shape. Figure 5 shows averaged data for the groups of samples tested.

Figure 5. The relationship between grid density and average energy absorbed by the specimens in a fracture test.
The scraps of samples after the tests differed from each other. Samples with lower grid density had irregular edges at the breaking point. Denser filled samples had a regular fracture edge. Some of the samples did not break completely in two. At the point of impact, a joint consisting of not completely torn first layers of material on the side of impact remained. On this basis, such scrap was characterised as stratified scrap. White discolourations were visible on the specimen material, probably in the places with the highest material stresses. Scrap from the test specimens is shown in figure 6.

Figure 6. Sample scraps a) 12pU20_02, b) 21pV40_02, c) 47pU80_02, d) 49pV90_02.

Figure 6a shows a scrap specimen with visible jagged edges at the breaking point. Figure 6b shows a completely broken scrap. Figure 6c shows a specimen with an irregular rupture of the inner mesh of the filling. Figure 6d shows scrap metal with a visible regular edge of the broken specimen. This condition of scrap indicates that in many cases the specimen was first bent before breaking. The fracture occurred only after crossing the yield point. In addition, the delamination, which results in non-separation of the specimen into two separate elements, confirms the high anisotropy of the specimens. The collected data were used to determine the impact strength of the samples. For its calculation, formula No. 1 was used.

\[ KC = \frac{K}{S} \]  

(1)

where: KC – impact strength, K – impact work, S – starting surface at the notch location.

The impact strength of all the other samples was calculated in the same way, the selected calculation results are presented in Table 3.
Table 3. Summary of impact strength values for selected groups of samples.

| Sample determination | Sample fill [%] | Impact rate \([J/cm^2]\) | Average impact rate for the series \([J/cm^2]\) |
|----------------------|-----------------|-----------------|---------------------------------|
| 1pV10_02             | 10              | 0.858025        |                                 |
| 2pV10_02             | 10              | 0.9193125       | 0.878454167                     |
| 3pV10_02             | 10              | 0.858025        |                                 |
| 4pU10_02             | 10              | 0.9806          |                                 |
| 5pU10_02             | 10              | 0.9806          | 0.939741667                     |
| 6pU10_02             | 10              | 0.858025        |                                 |
| 7pV20_02             | 20              | 0.73545         |                                 |
| 8pV20_02             | 20              | 0.858025        | 0.817166667                     |
| 9pV20_02             | 20              | 0.858025        |                                 |
| 10pU20_02            | 20              | 0.858025        | 0.898883333                     |
| 11pU20_02            | 20              | 0.858025        |                                 |
| 12pU20_02            | 20              | 0.9806          |                                 |

The results for the analysed series of samples in the form of the functional dependence of average impact strength and grid density are presented in figure 7.

The impact energy absorbed by GRID filled specimens varies disproportionately to the filling density, with no clear increase in energy absorbed as the filling grid density increases, with the exception of 100% filled specimens, which exhibit superior strength to any other specimen.

4. Conclusion

Within the framework of the work, the production parameters were determined for two basic groups of samples – with the U notch and V notch. For each variant samples were prepared, which were produced using the 3D FDM printing method. In total, 60 samples were produced and tested for impact strength. On the basis of the collected data the following conclusions were drawn:

- Most of the impact energy was absorbed by 100% filled specimens, the average values for this series are respectively: 1.92 J/cm² (V notch), and 1.96 J/cm² (U notch).
- The curves of the relationship between the filling density and the impact strength obtained for the V notch and U notch are similar in shape but differ in values at certain points.
• It is likely that parameters other than the filling density of the grid such as the local arrangement of the grid at the impact point, the pattern of the grid, the distribution of the external elements of the object (base and wall) are decisive for the impact strength of the specimen.
• The weight of the specimens increases proportionally with the density of the filling.
• The linear relationship between the fill density and the weight of the specimens allows for an estimation of the grid density at which the specimen was filled.
• FDM printed parts are highly anisotropic.
• The best ratio of mass to the energy absorbed during the impact was achieved with samples filled with 10% (U notch) and 30% (V notch).
• The best weight/impact ratio of fully fractured specimens was achieved with 20% (U notch) and 60% (V notch).
• No proportionality was found between the weight of the specimen and the impact strength of the specimen.
• Samples with the same notch were not visually different in any way.
• The breakage of V-notched samples was much more frequent than that of U-notched samples.
• All samples with a filling density between 40% and 70% V notched were completely broken.

The data collected relate to one of the many materials available in the ABS category. This group of materials from other manufacturers can show different results. In addition, samples were produced with a specific 3D printer, and printouts from other printers may show different results. Further differences may be due to different software used to generate a sequence of instructions for the device and different print parameters. All of the limitations should be kept in mind when interpreting the data collected.

5. Future works
On the basis of the assembled data and the conclusions, possible fields of research expansion in the future were also identified. These are presented below:
• Giving up U-notch samples in favour of more V-notch ones. V-notch specimens were more reliable (more fully fractured specimens).
• Employing a hammer with lower impact energy, because only 12% of the initial energy of the test stand in question was used.
• Examining more points on the graph, increasing the filling density with a smaller stroke, every 5% or even every 1%.
• Examining other filling patterns.
• Examination of samples with different orientation of the layers in relation to the direction of impact.
• Examination of other types of materials.
• Investigating the influence of other parameters, such as layer height, or the number of contours.
• Carrying out tests at different temperatures of the tested elements.
• Fractographic analysis of selected samples.

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