The influence of printing parameters on selected mechanical properties of FDM/FFF 3D-printed parts

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Abstract. Rapid Prototyping technologies, especially 3D printing are becoming increasingly popular due to their usability and the constant decrease in price of printing equipment and materials. The article focuses on the study of selected mechanical strength properties of 3D-printed elements, which are not very important if the element is only a model for further manufacturing techniques, but which are important when 3D-printed elements will be a part of a functioning device, e.g. a part of unique scientific equipment. The research was carried out on a set of standardised samples, printed with low-cost standard materials (ABS), using a cheap 3D printer. The influence of parameters (such as the type of infill pattern, infill density, shell thickness, printing temperature, the type of material) on selected mechanical properties of the samples, were tested. The obtained results allows making conscious decisions on the printing of elements to be durable enough, either on a non-professional printer, or when to ordered by a professional manufacturer.

1. Introduction

Companies, forced to compete on the global market, are continuously looking for solutions that allow them to gain an advantage over competitors. The main ways of improving their operation could be optimal planning of production processes [1][2] based on simulation [3][4] and scheduling [5][6][7], automation [8][9] and robotics [10], continuous supervision of production tasks [11][12], as well as other technologies included in the Industry 4.0 strategy. One of the technologies that is gaining popularity is additive manufacturing (AM), especially 3D printing (3DP). 3D printing is an example of rapid prototyping (or additive manufacturing) technologies, that are becoming increasingly popular due to their usability and the constant decrease in the price of printing equipment and materials [13]. Most rapid prototyping technologies are still under development and characterised by high cost of equipment and materials, however, they can produce complex-shaped, high-quality, high strength elements, which can be made of different materials that have specific properties (e.g. various types of plastic, biomaterials, metal, composites and even concrete [14]). Such elements, however, are usually very expensive due to the amount of time needed for the preparation and manufacturing (3D printing of complex, even relatively small elements can take many hours, not counting the design and pre-processing stages) of the element and also the use of expensive equipment. However, some of these technologies, such as Stratasys' Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF), are so simple that it is possible to individually design and assemble low-cost 3D printers (e.g. based on open-source RepRap concept), also called personal 3D printers. These AM technologies, in which material is selectively fed through a nozzle, are classified as material extrusion technologies [13]. A polymeric material, in the form of filament, is extruded through a heated nozzle and deposited in a semi-molten state in order to create the pre-programmed shape. The whole structure is manufactured by the sequential build-up of these layers, each new one fusing with material that has been deposited previously. In the case of most professional 3D printers, the user is limited only to printing material authorised by manufacturer, whilst most personal, cheap and DIY printers can use any available materials (PLA, ABS, PET, PET-G and HIPS filaments), the only limitation is the diameter (typically 1.75 mm or 3 mm) and the extruding temperature (usually <250˚C). As a consequence, 3D-printed elements are now increasingly common and may be used not only as prototypes, but as functioning parts of devices. This allows for the relatively cheap and quick fabrication of, among others, special scientific equipment. Additionally, it is possible to obtain components with unique properties, very difficult to obtain by other methods, e.g., lightweight, hollowed-out elements with space-framed interiors. AM technologies, especially represented by personal 3D printers, are opening up new opportunities for the economy and society. The main applications of personal 3D printers can be classified as prototyping, hobby/DIY, gadget, art/fashion, scale model and household.

The quality of 3D printed parts can be assessed by mechanical or thermal properties, as well as the tactile and visual perception. Taking into account other 3D printing technologies (SLA, Polyjet), FDM parts have the roughest surface because of the relatively high thickness of layers (usually 0.1 - 0.3 mm). 3DP can be considered an evolving manufacturing technology that can reduce production costs, as well as shorten the product development cycle, in comparison to traditionally manufactured parts [15]. It also allows the possibility to manufacture more complex geometries, a reduction in the number of required parts and material waste and supervision-free processing, etc. Problems with the mechanical properties (strength parameters) of FDM 3D-printed parts usually stems, not only from the mechanical strength of material, but also from weakness points between the layers, uncontrolled shrink during the cooling process, minor discontinuities in filament extrusion, unevenness of the building platform and inaccuracies of extruder movements, etc.

Because of its growing significance, FDM 3D printing is being studied in the areas of building equipment, materials, preparation techniques, numerical simulation and is still the subject of research [16][17]. This article focuses on the study of selected mechanical properties of FDM/FFF 3D-printed elements, which are of minor significance if the element is only a prototype or model for further manufacturing techniques (e.g. moulding, injection moulding), but which are important when 3D-printed elements are planned to be parts of a functioning device. The tests were carried out on a set of standardised samples, printed on a DIY 3D printer (p3Steel - one of the RepRap design variants) using low-cost materials (PLA, ABS). The influence of parameters, such as infill pattern, direction and density, shell thickness and printing temperature on selected mechanical properties of 3D printed samples, were tested. The obtained results should facilitate decisions on the choice of manufacturing technology and parameters of elements.

2. FDM samples and 3D printing equipment

2.1. 3D printer and software used in tests

Tests of the influence of FDM 3D printing parameters on selected mechanical properties of 3D printed ABS samples were carried out using specimens prepared on modified version of P3steel 3D printer, based on the Prusa i3 RepRap concept. The main difference between P3steel and standard Prusa i3 design is high-rigidity, 3 mm thick steel frame of the P3steel printer (instead of M10 threaded rods or 6 mm plywood/Plexiglas in case of standard Prusa i3), allowing for better accuracy and easier calibration, resulting in higher print quality and repeatability.

Main parameters of the P3steel printer used in tests are as follows: XYZ 190x185x190 mm print space, single extruder able to melt any 1,75 mm filament, extrusion temperature up to 250˚C (can melt PLA, ABS, PET, PETG and similar materials), 0,4 mm extruder nozzle diameter, heated build

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platform/table (max. 120˚C) allowing better sticking of first layer to the table. The building platform top layer is a borosilicate glass, sprayed with Dimafix 3D printing glue, providing the best adhesion of the first layer of PLA, ABS and PET/PETG material to the table, observed during tests.

Printer control unit is based on Arduino Mega with Ramps 1.4 controller, programmed with Repetier Firmware. Stereo lithography (STL) files were generated using NX10 CAD software and processed using Repetier Host, allowing arrangement of parts to be printed on the build platform and its modification (duplication, scaling, rotation, etc.), responsible also for calling external slicer software (CuraEngine), generating final GCODE program for 3D printer.

Additionally, the reference specimen group were printed using Stratasys FDM 360 printer in order to compare print quality and strength of DIY printers to professional-grade 3D printer. The Insight software was used to control the process of fabricating ABS parts from the same STL file.

2.2. 3D printing specimens

The printer was calibrated to produce the best quality prints. A number of tests, which led to the samples that do not have visible defects and imperfections, including layers de-lamination, discontinuities of specimen's shell and infill, were carried out.

Samples 1BA (dogbone coupons) for tensile testing were prepared in compliance to DIN EN ISO 527-2, 178 and 179-1 standard, respectively, having dimensions shown in figure 1.

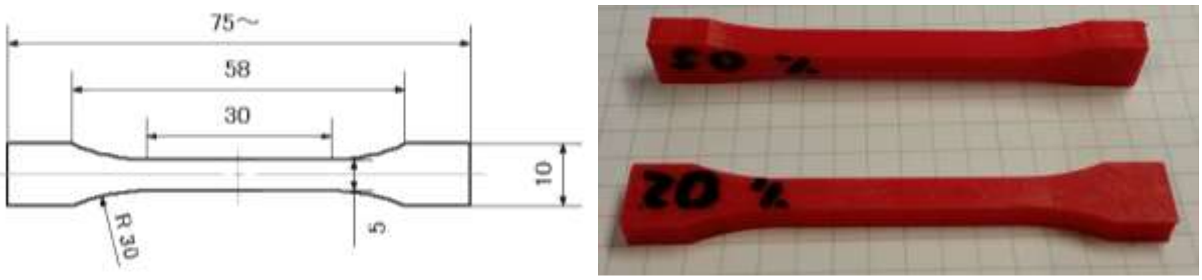

Figure 1. The 1BA ISO 527-2 sample dimensions and actual photo of 20% and 50% infill samples.

The problem considered before the strength tests was the decision whether to test only samples printed with 100% infill setting or to check also properties of specimens printed with lower infill percentage, resulting in partially hollowed-out part structure. It was concluded that, in order to show differences between the print parameters that have an impact on the print density, a standard sample intended for tensile tests of solid plastics can be used also for less dense specimens.

The reason is that non-continuous, partially hollowed-out interior of the 3D prints is not the result of manufacturing faults but planned material savings, resulting in both, partial weakening of the model and intended obtaining of lightweight object, that is nearly impossible to produce in single piece using other manufacturing methods. The degree of infill can be set, similarly to many other parameters, in the slicer software. The main reason to print less than 100% infill parts is to reduce costs (including printing time, energy and material consumption) to the extent not deteriorating drastically strength of the partial-infill sample relative to the solid ones. Among other tests, it was decided to determine the influence of decreasing average infill density and changing infill pattern, on the strength of a specimens. Another parameter important when printing non-100% infill parts is the thickness of the outer layer, called "perimeters", "shell" or "skin" in slicer software settings - it is always solid and its thickness can be defined in millimetres or number of material layers (vertically) of lines (horizontally).

3. Results and discussion

The following parameters were changed during the tests:

- perimeters - the amount of continuous external lines lying next to each other on the printed layer. They represent the outline of the outer cross-section of model on a particular layer parallel to the heating table;

- solid layers - the number of solid (100%) layers starting and ending a model's boundaries, parallel to the plane of the heating table;
- fill density - percentage of infill of the space inside perimeters and solid layers;
- fill pattern - filling technique and shape/direction resulting in less than 100% infill, e.g. rectangular grid, lines, concentric lines, Hilbert curve, honeycomb, 3D honeycomb, etc.);
- solid fill pattern - a technique of solid layers filling;
- extrusion multiplier - affects the amount (volume) of plastic extruded in the unit of distance traveled by the printhead, its default value is 1. Unlike the *fill density* parameter, it influences all types of layers and fillings at the same time.

Extrusion and heated bed (build table) temperatures (240°C and 100°C), as well as printing speed were not changed during tests, it remained constant after initial calibration and visual assessment of print quality.
Specimens were divided into 12 groups, where each group was used for verification of the effect of different parameters on the strength of 5 pieces of samples. Tensile tests were carried out at 22°C in a 50% humidity, at a 10 mm/min speed.

3.1. The reference sample

The p23 specimen group (printing parameters: perimeters 2, solid layers 2, fill density 40%, fill pattern - honeycomb, extrusion multiplier - 1), was accepted as a reference sample, used in all comparisons. These samples achieved relatively good tensile strength (exceeding 31,97MPa), being a compromise between strength and density (0.86 g/cm^3) of the sample. Figure 2 shows p23's tensile test chart (left), and cross-section (right), next to k2 100% infill specimen, printed using Stratasys FDM 360.

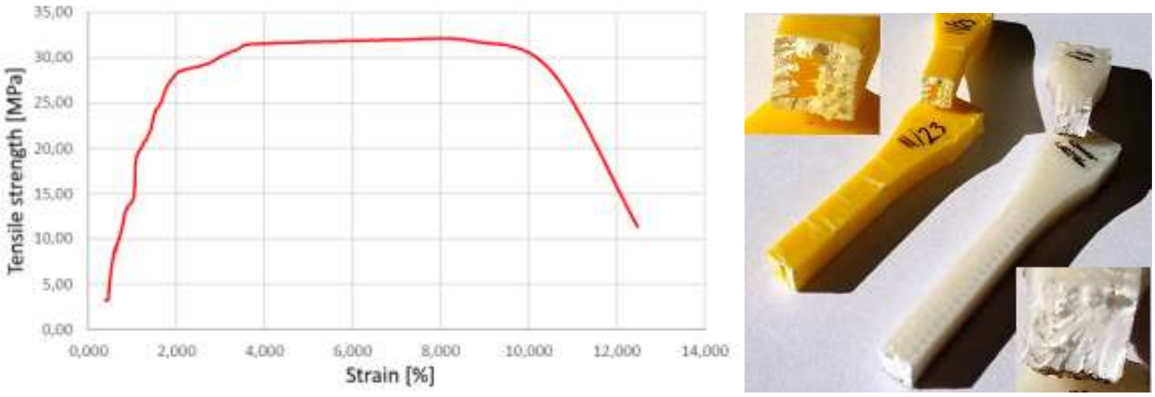

Figure 2. The p23's 40% infill tensile test chart, and cross-section, next to a 100% infill k2 specimen.

3.2. The influence of the fill density parameter

All specimen groups (p22, p23, p31, p28) used to test the influence of *fill density* parameter were printed with the same other parameters (perimeters 2, solid layers 2, fill density - variable, fill pattern - honeycomb, extrusion multiplier - 1), with the fill density respectively p22 - 10%, p31 - 25%, p23 - 40%, p28 - 60%. This parameter is responsible for the density of infill, in case of higher values affecting also infill pattern (some more complicated patterns are not available with infill >50%), having at the same time no effect on the outer layers of the print. Slicer's default value of the Fill density is usually 0.3-0.4. As shown in the figure 3, the increase of infill value reduces deformation. The strength of the sample grows with the fill density. It is also possible to note that the decrease is not directly proportional to the decrease in the strength. It can be concluded that it cost-effective to reduce the fill density to about 40-50%. At the same time it noted that for small and complex parts, it is reasonable to increase this parameter to about 0.6. Further increasing the value of the fill density parameter raises the pressure in the extruder, which forces the reduction of printing speed of simple DIY printers. Figure 4 shows specimens cross-section after tensile strength test.

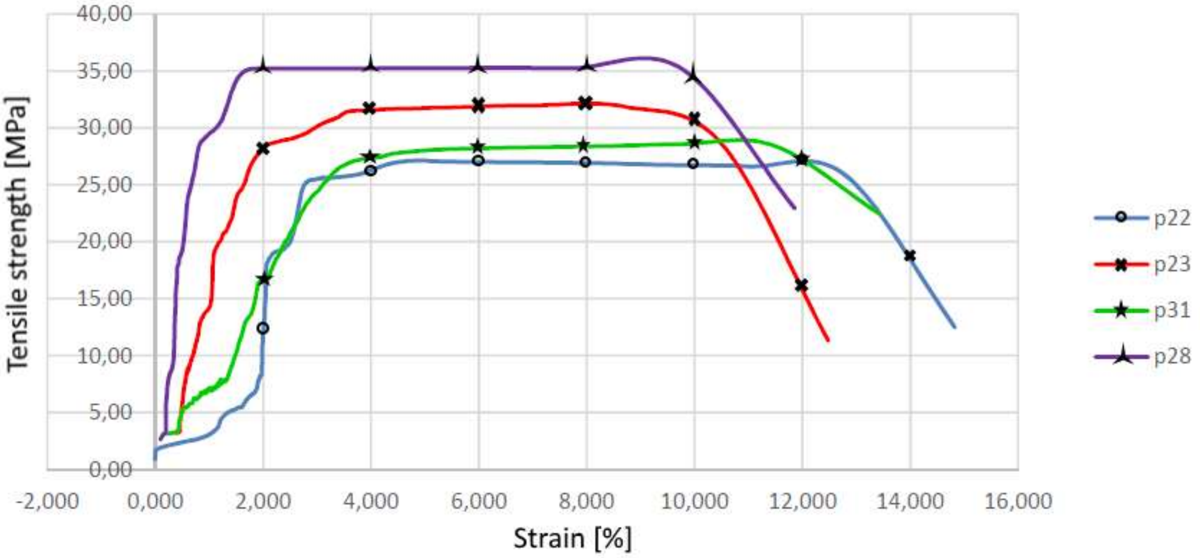

Figure 3. Stress-strain curves for specimen's fill density influence comparison.

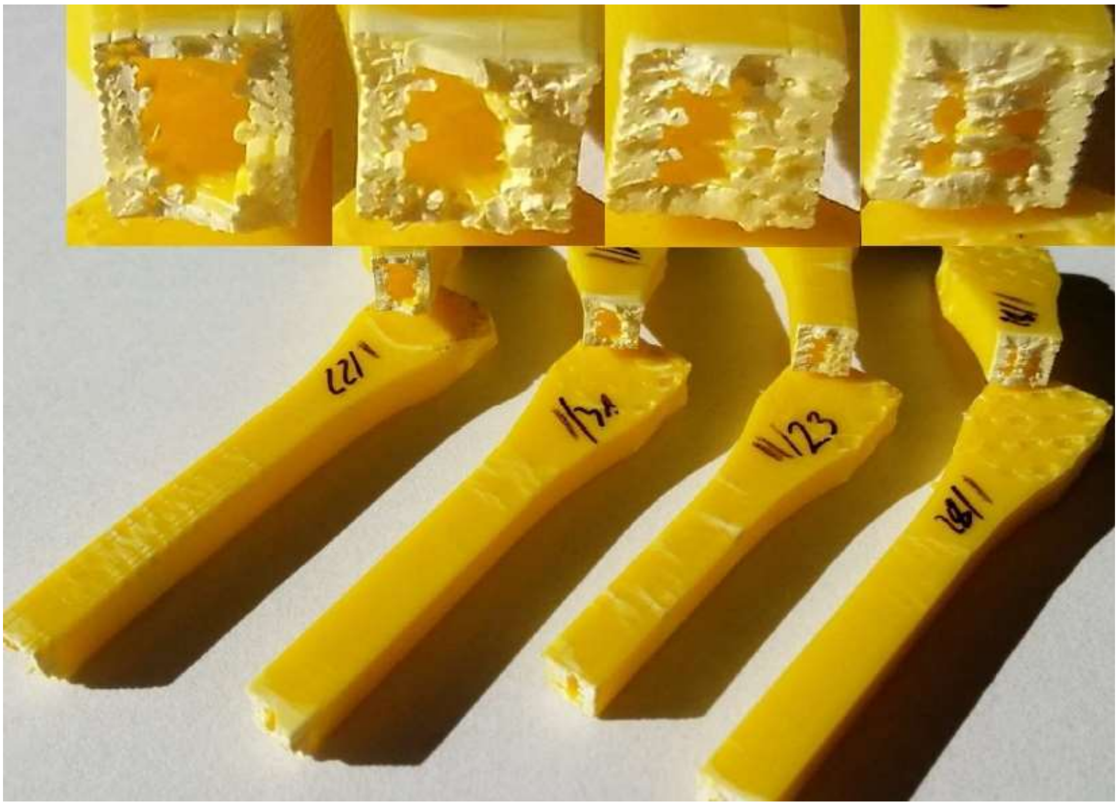

Figure 4. Cross-sections of p22, p31, p23 and p28 specimens.

3.3. The influence of the shell thickness parameter

In order to test the impact of the shell (created by perimeters/outlines in horizontal plane, and solid layers from bottom and top) thickness, the *perimeters* and *solid layers* numbers were changed at the same time, respectively for samples: p19 - 1, p23 - 2, p34 - 4, p20 - 7 [outline threads/layers]. Other parameters (fill density - 40%, fill pattern - honeycomb, extrusion multiplier - 1) were constant. As shown by characteristics (figure 5), shell thickness has a key influence on the tensile strength of the samples. When increasing values of this parameter over 4, the infill of relatively small samples is practically replaced by the solid, closely extruded filament threads. These threads have a much higher tensile strength than the standard infill pattern, resulting in overall tensile strength similar to 100% infill specimens.

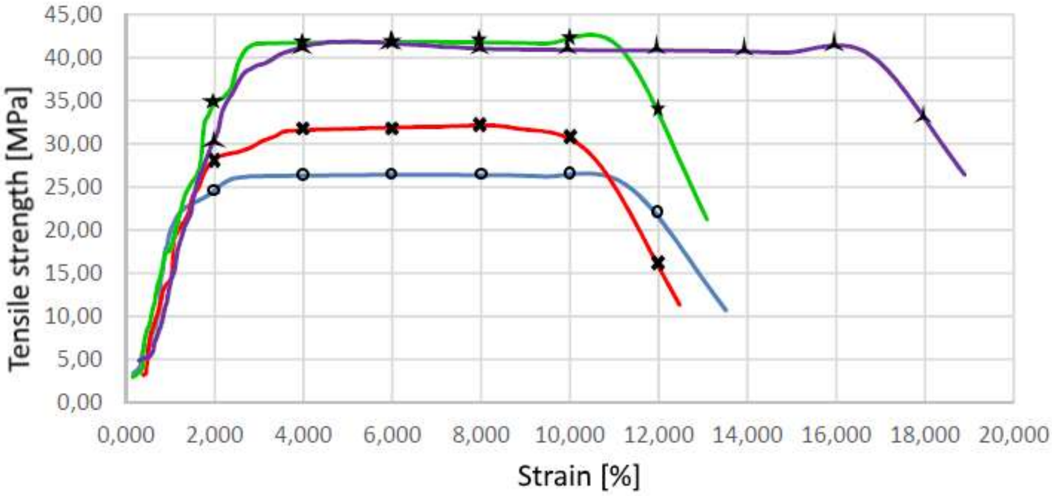

Figure 5. Stress-strain curves for specimen's shell thickness comparison.

3.4. The influence of the extrusion multiplier parameter

The extrusion multiplier parameter influences the amount of material extruded in the unit of length travelled by extruder with given speed, it's default value is 1. Unlike the fill density parameter, extrusion multiplier influences all types of layers and fillings at the same time, changing the surface of cross-section of extruded filament thread because of affecting extrusion pressure. If set above 1, it allows creating more dense prints, but too high values can sometimes cause material overflow the defined shape of printed element, resulting in lowering dimensional accuracy but stronger prints. In opposite case, with extrusion multiplier <1, the resulting print is created with less than optimal amount of filament, resulting in worse stress-strain characteristics. Lesser tensile strength of p27 specimens stems from smaller diameter of extruded material threads and consequently, smaller surface of contact between neighbouring threads. Dimensional accuracy also worsens, printed elements are a bit smaller than nominal dimensions. Photos in figure 6 shows cross-sections of p27, p33 and p23 specimens, it is visible that significant lowering extrusion multiplier results in non-connected or only partially connected threads of filament, remaining in fibre-like form.

Figure 7 presents stress-strain curves for specimens printed with: p27 - 0.5, p23 - 1, and p32 - 0,75 extrusion multiplier. The rest of parameters (perimeters 2, solid layers 2, fill density - 40%, fill pattern - honeycomb) were constant. Obtained print quality results proved that the extrusion multiplier parameter should be not changed outside {0.9-1.1} limits because insignificant reduction of material cost comes with very significant worsening of tensile strength parameters and dimensional accuracy.

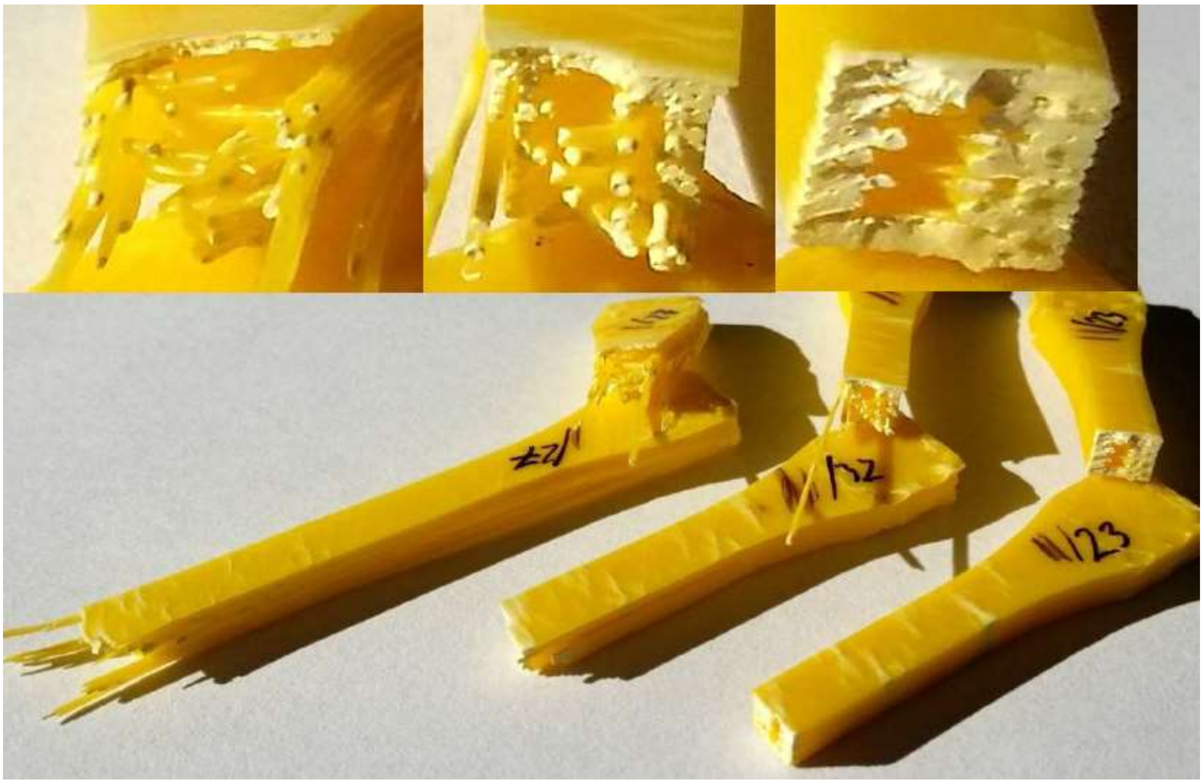

Figure 6. Cross-sections of p27, p33 and p23 specimens, threads/fibres of material visible in p27.

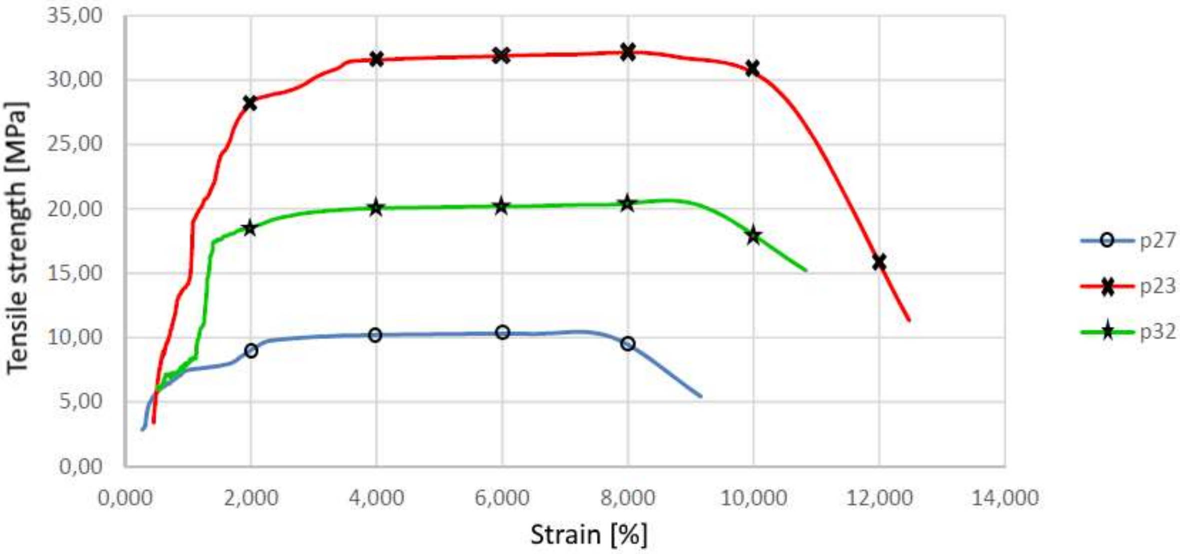

Figure 7. Stress-strain curves for specimen's extrusion multiplier comparison.

3.5. The influence of the fill pattern parameter

Setting slicer's fill density parameter to values below 100% (or 1) results in creating less dense interior of 3D printed object. The shell is made of densely laid threads of material, that should create solid entity, while interior is filled with a specific pattern of material threads (fill pattern), preventing upper, especially top layers, from collapsing inside the printed object. The infill (usually available patterns are: rectilinear, lines, concentric lines, Hilbert curve, honeycomb, 3D honeycomb, etc.) can't withstand the stress as well as the outer layers (shell). However, it allows to save time required to print, as well

as reduce filament consumption. Objects printed with less than 100% infill are lighter, what can be useful in specific conditions, while infill pattern influences also other than tensile strength parameters, like rigidity. The fill pattern parameter is controlling the shapes filling the printed solid (including intricate 3D patterns, like 3D honeycomb), while characteristic dimensions of these shapes (line spacing and directions, method of creating 3D structures) depends on the fill density parameter.
There are several types of patterns available in slicer settings, some of them (e.g. 3D honeycomb, Hilbert curve) extending printing time significantly, were omitted (considered as uneconomical).
Test specimens were printed with different fill patterns: p42 - line, p23 - honeycomb, p43 - rectilinear, p44 - concentric, and p45 - top concentric. The rest of parameters (perimeters 2, solid layers 2, fill density - 40%, extrusion multiplier - 1) were constant. After analyzing the characteristics (figure 8) it can be stated that two of them (line and rectilinear) cause a noticeable decrease in strength. Others (honeycomb, concentric and the concentric/ honeycomb combination) provide practically identical results in the tensile test. However, due to the characteristic of laying filament fill in concentric pattern, its torsional stress parameters are probably much worse. Thus, the honeycomb infill pattern can be considered the best pattern to maximise the tensile strength of 3D prints.

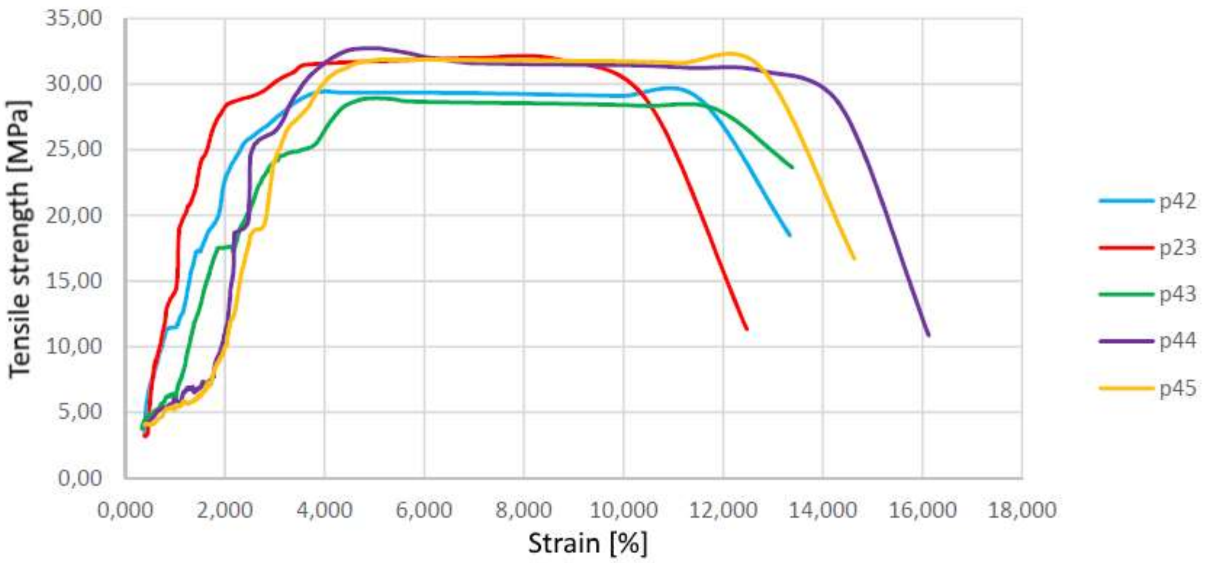

Figure 8. Stress-strain curves for specimen's fill pattern influence comparison.

4. Conclusion

FDM 3D printing is still not, and probably in the near future will not become, a technology capable of displacing traditional manufacturing techniques in mass applications. FDM technology, however, allows the obtaining of unique individual elements with satisfactory properties and, in the case of personal 3D printers, also an acceptable price. Problems with the quality of 3D printing stems mostly from changing of environmental conditions, the required high accuracy calibration of a printer (especially the build table levelling), that is a necessary condition for obtaining proper adhesion of the first layer to the table. In order to obtain correct, non-deformed prints from some materials (PLA), direct cooling of the printed item is also necessary.

As a result, the mechanical properties of ABS specimens printed using a DIY FDM printer, after some initial tuning, are generally not significantly worse than those printed with professional FDM printer. The study showed that, where the objective is to have both, a lightweight and durable element, the best set of parameters is the use of a honeycomb pattern with fill density of about 40-50%, and a shell thickness of 2-3 layers/lines. If the maximum strength is the priority, shell thickness should be increased. The use of an infill pattern other than the honeycomb can accelerate the time of printing at the expense of its strength. Tensile test has also shown that the extrusion multiplier parameter should not be set less than 0.9, because strength of the sample decreases disproportionately to filament savings. Another problem in that case is an increasing number of defects (lack of adhesion between layers, delaminating).

The results indicate the need for further research concerning e.g. simultaneous changes in many parameters and rigidity of obtained elements, which requires the development of specimens, appropriate for the specific study of 3D printed objects, as well as methods of measurement. The use of relatively small specimens does not always allow the correct determination of the impact of the examined parameters on the resulting strength and rigidity of samples - e.g. a small cross-sectional dimension of 1BA specimen does not allow the correct study of the effect of increasing the thickness of the shell and infill pattern on the strength of a sample, because the shell takes up most of the cross-section surface, practically replacing the hollowed-out pattern structure with continuous infill.

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