

Research Article

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Structure and tensile properties evaluation of samples produced by Fused Deposition Modeling

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Abstract: This paper presents the result of a study evaluating the influence of alternative path generation strategy on structure and some mechanical properties of parts produced by Fused Deposition Modeling (FDM) technology. Several scientific investigations focused on resolving issues in FDM parts by modifying a path generation strategy to optimize its mechanical properties. In this study, an alternative strategy was proposed with the intention of minimizing internal voids and, thus, to improve mechanical properties. Polycarbonate samples made by this alternative path generation strategy were subjected to tensile strength test and metro-tomography structure evaluation. The results reveal that the structure observed on build models differs from a structure expected from path generation predicted by software Insight 9.1. This difference affected the tensile strength of samples.

Keywords: FDM; polycarbonate; deposition strategy

1 Introduction

The focus on productivity has been one of the main targets of industries worldwide since long time. To achieve higher quality, cost reduction, and greater efficiency, as well as an ability to meet environmental objectives with a consequently faster product development and a reduced time to customer, industries have attempted to apply more computerized automation in manufacturing. One of the latest

technologies to have significant stride over the past two decades is Additive Manufacturing (AM). AM technologies are able to build parts of any complicated geometry in short time without adding extra cost for tool designing and manufacturing. Another advantage is that AM technologies are able to produce functional, complex, and optimized parts. In turn, these make them an attractive option due to its low cost and ease in assembly since it consolidates subassemblies into a single unit at the computer aided design (CAD) stage, reducing the number of parts, handling time, and avoiding mating and fit problems.

Fused deposition modeling is known for its reliability and production of durable functional parts. Nowadays, due to availability of various FDM printers in wide price range, low material cost and user friendly manipulation is the FDM fastest spreading rapid prototyping (RP) technology. FDM allows building parts containing complex geometrical shapes in a reasonable time period [1]. The quality of built parts is affected by many process variables. As the relation between mechanical properties and process parameters is difficult to establish, attempt has been made to derive the empirical model between the processing parameters and mechanical properties using statistical methods [2]. Research study results [1, 3–5] have revealed that process parameters, such as building envelope temperature, liquefier temperature, raster air gap, have significant impact on mechanical properties. In addition, built parts exhibit anisotropic properties, as far as tensile strength is concerned, depending on build orientation. A parts strength in the direction parallel to the building direction is recognized as the weakest (40–60% lower compared to tensile strength in other building directions) [3].

The functional relationship between process parameters, (layer thickness, orientation, raster angle, raster width and air gap) determined by response surface methodology, shows that the optimal factor setting for increasing the flexural and tensile is same, but it differs in factor levels of raster angle and orientation for impact strength [6]. Experiments made by testing of compressive strength of ABS400, shows that the strength of the fibre-fibre bond has to be strong to achieve optimal results. This can be achieved by controlling the distortions arising dur-

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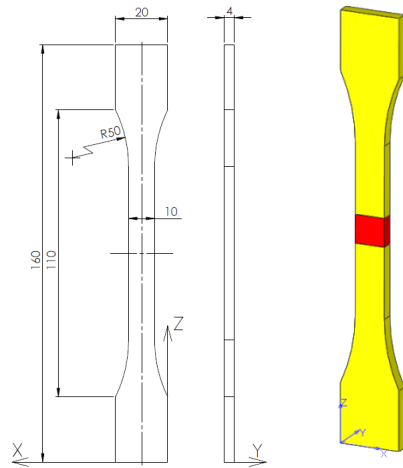


Figure 1: Tensile test specimen dimensions, building orientation and 3D scanned area (red).

ing the part build stage. The reason for the low strength can be also assigned to anisotropy, caused by the polymer molecules aligning themselves with the direction of flow when they are deposited out of the nozzle [7].

Methodology based on optical scanning technics for the analysis of geometry accuracy of shape-complicated prototyped parts provides faster and complex diagnostics and verification of accuracy [6]. However, it provides only the outer geometry of part. For the analysis of the internal structure of a prototype, it is necessary to use more sophisticated techniques. To evaluate the prototype interior structure, there is a very convenient method which allows scanning the exterior shape and the interior structure of prototypes. Metrotomography is considered as one of most suitable technologies for this task, due to the fact that x-rays easily pass through polymer structure of FDM parts and the gained data is fully 3D. The Metrotomography is a fully non-destructive testing technology, and the abilities of this technology act as an excellent tool for evaluation of FDM prototype structures [1, 10].

As apparent from the foregoing discussion, FDM manufactured parts exhibit anisotropy mechanical properties. Properties are affected and sensitive to the processing parameters because parameters affect structure and bond strengths between fibers. Also, uneven heating and cooling cycles due to the inherent nature of FDM build methodology results in stress accumulation in the built part. This results in distortion, which is primarily responsible for weak bonding and thus affect the strength. It is also noticed that a good number of works in FDM strength modeling is devoted to study the effect of processing conditions on the part strength, but no significant effort is made to develop the strength model in terms of FDM process

parameters for prediction purposes [4]. The presented research focuses on the assessment of the tensile strength of parts made of polycarbonate (PC) and fabricated using FDM technology. An alternative path generation strategy was proposed to minimize the volume of internal voids and maximize the fiber-to-fiber contact area. Improving these parameters can lead to the increase in tensile strength.

Different deposition densities, orientations, and their combinations can be applied in the process of FDM to achieve required stiffness properties of manufactured parts. Considering the different combinations of raster angles in successive layers, a large variety of laminates can be created. The application of a negative gap in raster can reduce the volume of voids [8].

2 Methods

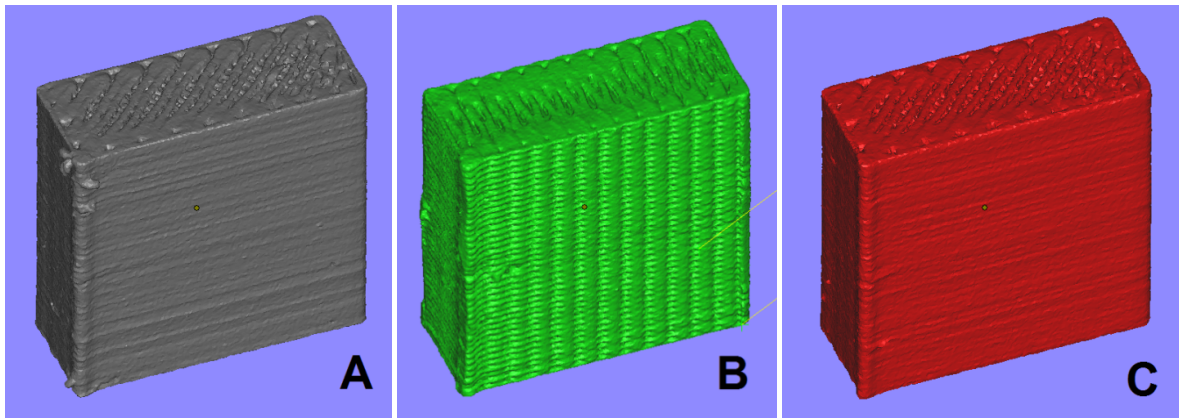
The Fortus 400mc rapid production system from Stratasys Inc. U.S.A. with Insight 9.1 software was used in the study. PC was selected as modeling material to build the samples for testing. Specimens were built on Fortus 400mc with a slice height of 0.127 mm. As presented in the Figure 1, building layers are parallel to XY plane – the plane of a building platform. The selection of the building orientation of the samples was based on the research as mentioned in the previous section.

Samples were built with three different strategies. The first type of samples (A) was prepared at default settings for 0.127 mm layer height, raster width 0.3408 mm, 45 degree raster angle and 90 degree raster angle between the following layers. The second type of samples (B) was designed with a path generation strategy that should provide larger surface contact area between following layers, thus increasing the density and strength of the part. The samples were built from two types of alternating layers. One layer was built from 0.4032 mm wide raster with a 0 degree raster angle and without an outline contour. The following layer was built from 0.4032 mm wide raster with a 0 degree raster angle (parallel raster between all layers) and with a 0.2032 mm outline contour. The third type of samples (C) was built to check the influence of the raster width, which was set to 0.4032 mm and path generation strategy as in the first type of samples. The types of samples used in experiment are listed in Table 1.

Fabricated specimens were analyzed by computer tomography to obtain a 3D model of a specimen's structure, and the gathered information was processed in VG Studio Max 2.0. The VG studio MAX 2.0 presents the structure of specimens as a cloud of points exported in 3D as a STL for-

Table 1: Path generation strategies used in experiments.

Sample type	Raster width [mm]	Raster angle [°]	Raster angle between following layers [°]	Number of outline contours	Width of outline contours [mm]
A	0.3408	45	90	1	0.3408
B	0.4032	0	0	1	0.2032
				0	0.0000
C	0.4032	45	90	1	0.4032

**Figure 2:** 3D scanned volume by Metrotom device from samples in STL format.

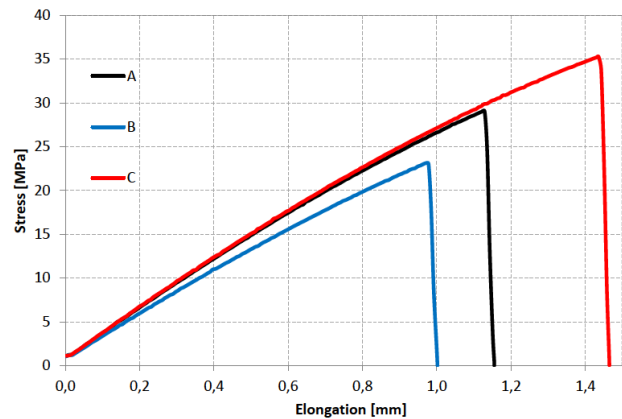
mat with high accuracy [10]. The selected volume (Fig. 1 red area) from the samples was subsequently imported and analyzed in software Materialise Magics (Fig. 2).

To determine tensile properties of prepared specimens, standardized uniaxial tensile test (STN ISO 527-2) was used. Results achieved from tensile test are described in result and discussion section.

3 Results and discussion

Results from tensile test presented in Fig. 3, clearly present significant influence of path generation strategy and raster width on the tensile strength. Sample “A” made with default raster width and path generation strategy has the tensile strength of 29.06 MPa. Sample “B” has the tensile strength of 23.08 MPa. The highest tensile strength of 35.25 MPa was observed in sample “C”. Increasing the raster width in 16% (from 0.3408 mm to 0.4032 mm) has caused a 21% increase in tensile strength. This result cannot be generalized, and the influence of the raster width has to be verified on wider range of samples.

The tensile strength observed at sample “B” is the lowest, although the proposed path generation strategy was designed to increase tensile strength. To explain the decrease of tensile strength (25.9% compared to sample “A”),

**Figure 3:** Stress-elongation curves of tested samples from tensile test.

an internal structure of samples was evaluated. Distribution, shape, and overall size of the voids were determined from the 3D STL model (Fig. 4).

The size of voids (volume) was quantified as 55.2 mm³ in sample “A”, 44.1 mm³ in sample “B” and 22.9 mm³ in sample “C”. A reduction of void volume between case “A” and “C” corresponds to the increase in tensile strength. As presented in Fig. 4, the distribution of the voids in sample “A” and “C” is uniform in whole volume. The voids present in sample “B” are not uniformly distributed and are located on the side of the sample volume where the

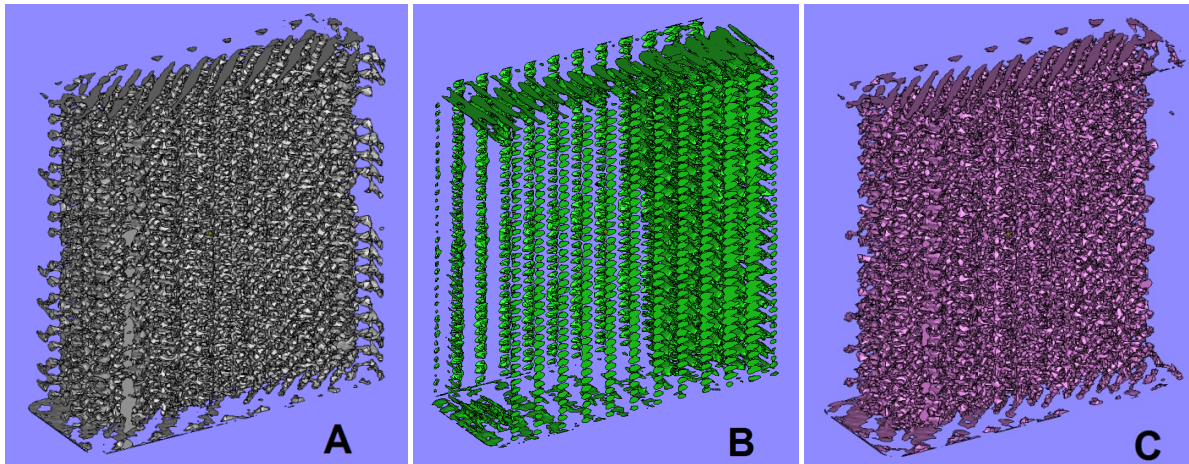


Figure 4: Distribution of the voids in the volume of samples.

layer printing starts. The total volume of the voids in sample “B” is the lowest, but the concentration of the voids at one side reduces the effective cross-section for transferring the load. About one third on the right side (Fig. 4) of the sample “B” volume is filled with voids; thus effective cross-section for load transfer can be estimated as $2/3$ of the original size. The volume of the sample “B” on the left side shows no inner voids greater than the resolution of a Metrotom scanner (0.04 mm^3). The voids on the left side are the only surface voids resulting as a difference between theoretical and scanned volume. The location of the voids in sample “B” in one area (in the place of layer building start) is very surprising and an interesting topic for further research to determine what causes this phenomena. If in the whole volume of sample “B” there were the incidences of the voids like in the left side of the sample, it can be assumed that the tensile strength would be highest, compared to case “A” and “C”.

4 Conclusions

Generating a path deposition strategy for FDM parts with default settings generates produced parts with relatively high amount of voids in the structure. This with the inherent feature of FDM technology, which creates parts with anisotropic properties, leads to relatively low tensile strengths compared to parts made of the same material grade by conventional technologies (injection molding, extrusion etc.) The proposed alternative path generation strategy shows potential of void reduction, thus improving the tensile properties of FDM parts, that is when the non-expected behavior of real layers deposition in machine is solved.

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