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INFLUENCE OF PRINTING CONDITIONS ON STRUCTURE IN FDM PROTOTYPES

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Original scientific paper
The main insufficiency of prototypes made by 3D printing with FDM (Fused Deposition Modelling) method is structure inhomogeneity resulting from the basic principle of this technique. The aim of the paper is to show how the structure of the FDM prototypes, by changing of processing temperature and layout on base plate, is affected. In order to define the processing temperatures influence on building structure of the FDM prototypes, various head and envelope temperatures in printing of specimens were applied. The samples were analysed by computed tomography to determine changes in layers structure, dimensions and the portion of unfilled volume in specimen. Obtained results show that material distribution in the whole volume of scanned specimens is not uniform. It was found out that structure homogeneity represented by the volume of non-filled area is affected by even the shape of fabricated part. This approach can be in the future used as a standard method for quality evaluation.

Keywords: *brand FDM, non-destructive analysis, Rapid Prototyping*

Utjecaj uvjeta tiskanja na strukturu FDM prototipova

Izvorni znanstveni članak
Osnovni nedostatak prototipova nastalih 3D tiskanjem metodom taloženja (FDM) je nehomogenost strukture koja proizlazi iz osnovnog principa te tehnike. Cilj je ovoga rada pokazati kako promjena radne temperature i rasporeda na osnovnoj ploči utječe na strukturu FDM prototipova. Kako bi se odredio utjecaj obradne temperature na strukturu nastajanja FDM prototipova, primijenjene su različite temperature glave i omotača kod tiskanja uzoraka. Uzorci su analizirani kompjuterskom tomografijom da bi se odredile promjene u strukturi slojeva, dimenzijama i dijelu nepopunjenog volumena u njima. Dobiveni rezultati pokazuju da raspodjela materijala u cjelokupnom volumenu skeniranih uzoraka nije ravnomjerna. Ustanovljeno je da na homogenost strukture koju predstavlja obujam neispunjenog područja, djeluje čak i oblik izrađenog dijela. U budućnosti se ovaj pristup može koristiti kao standardna metoda za procjenu kvalitete.

Ključne riječi: *analiza bez razaranja, brza izrada prototipa, otisak modeliranja taloženjem (FDM)*

1 Introduction

Recent advances in the fields of computer-aided design (CAD) and rapid prototyping (RP) have given designers the tools to rapidly generate an initial prototype from a concept. There are currently several different RP technologies available, each with its own unique set of competencies and limitations [1].

Using RP methods we are able to obtain real concept about a new product. RP meets the current needs in the industry to shorten design cycles and improve the design quality. The main advantage of layered manufacturing (LM) over conventional manufacturing is that complex shapes can be physically realized without elaborate tooling. However, there are some specific part shapes like thin, slightly curved shell-type structures (skull bones, turbine blades, etc.) where the application of LM is poorly suited and may result in lack of strength, stair-step effect (poor surface finish) or large number of layers, resulting in higher build time [2].

Each process has various process parameters (build direction, layer thickness, temperature, etc.) that affect the character of RP part. Among many process parameters, the component's build direction and raster angle are quite important for the FDM process [3 ÷ 5].

Fused deposition modelling (FDM) is one RP system that produces prototypes from plastic materials such as ABS (Acrylonitrile-Butadiene-Styrene) by laying tracks of semi-molten plastic filament onto a platform in a layer wise manner from bottom to top. It is known that process parameters such as the air gap between adjacent tracks, raster angle, raster width and thickness of deposited layers influence the performance of parts produced on an FDM machine [6].

In the FDM hardware, the FDM head moves in two horizontal axes across a foundation and deposits a layer of material for each slice. The material filament is pulled into the FDM head by the drive wheels. It is heated inside the liquefier in the FDM head so it comes out in a semi-liquid state. The successive layers fuse together and solidify to build up an accurate, three-dimensional model of the design.

A crucial feature of the FDM process is its potential to fabricate parts with locally controlled properties like mechanical properties, density and porosity [7]. It is even becoming possible to manufacture functional parts in addition to prototypes. In order to fully evolve the FDM into a manufacturing tool, a number of improvements are essential. The functional parts require the process improvements for greater dimensional control and better tolerances, improvements in surface finish, the variety of polymers available for use should increase and the mechanical properties of the prototyped parts should be enhanced to maintain their integrity during working. To improve this promising technology, recent years have seen a substantial amount of research in the area of FDM manufacturing process planning. Research work has included the consideration of processing parameters and their optimization [8 ÷ 12] and mechanical properties [4, 13 ÷ 16]. Some studies have been conducted to determine the optimum parameters of FDM, and performance criteria often used include build time, strength, toughness and surface integrity of the prototypes, normally for injection moulding and tooling applications [17-20]. Strength of parts made by FDM suffers from anisotropy and adhesive strength between layers (or across filaments) is appreciably less than the strength of continuous filaments - longitudinal strength [1].

One limit of using FDM for preparing prototypes of plastic parts is that these parts are typically thin walled and with the width of extruded fibre (0,511 mm) it is almost impossible to create walls thinner than 1 mm or these walls are very brittle (e.g. snap fit). Another issue with FDM prototypes is surface quality which is dependent on layer thickness (typically 0,254 mm) and build angle [21]. However, in a number of cases, proper choice of orientation of the part (build direction) in the FDM chamber may eliminate some of the above-mentioned drawbacks [5, 22 ÷ 24]. Few mathematical models have been proposed [7, 25 ÷ 27] that show promise in terms of their predictive value.

It is very difficult to evaluate the prototype interior structure. However, there is a very convenient method which allows scanning exterior shape, prototype dimensions as well as interior structure of prototypes. Computer tomography (CT) is the fusion of metrology and tomography. METROTOM is a well thought-out design with its 3D computed tomography with micro-focus X-ray tubes and detectors. CT allows you to measure the interior of a work piece: all recorded data can be applied to all areas of quality assurance and be evaluated. CT technology allows non-destructive testing of damage and porosity analysis, material inspection, defect checks, etc. Abilities of this technology offer an excellent tool for evaluation of FDM prototypes structure. Therefore, this paper provides the results of experimental determination and analysis of the structure of some simple shapes fabricated using the FDM process in regard to different temperatures of the printing head, the envelope temperatures as well as location of parts built on the platform.

2 Research background

The main insufficiency of prototypes made by 3D printing with FDM method is structure inhomogeneity resulting from the basic principle of this technique. The prototype is manufactured layer-by-layer, at which unfilled areas are likewise founded in almost each layer (Fig. 1) as well as among particular layers (Fig. 2).

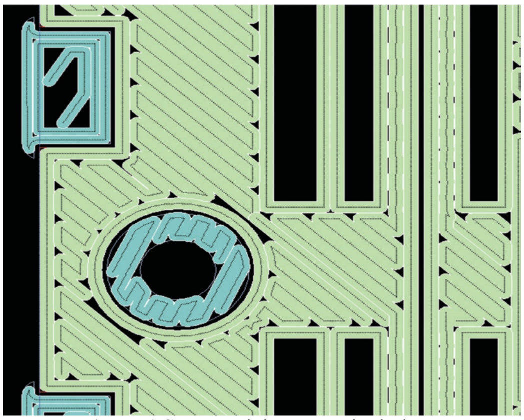

Figure 1 Structure inhomogeneity in layer

The modelling envelope temperature is regulated to aid in the bonding process. The FDM head deposits material as it follows the part geometry for each curve. It starts from the bottom curve and builds up the model to the top curve. Starting from an STL file, the geometry of a part can be read into Catalyst software and sliced at a pre-selected modelling resolution. Parameters of STL model (e.g. chord height and angle control) for RP process are very important for the accuracy of physical prototype [28].

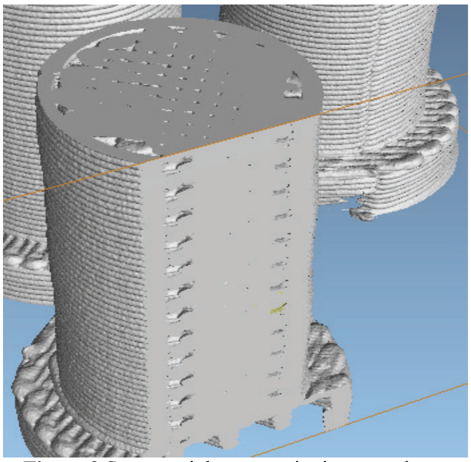

Figure 2 Structure inhomogeneity in part volume

RP processes produce models layer-by-layer. Hence, the geometric model must be first sliced into layers before the physical rebuilding process. Therefore, the slicing algorithm plays a very important role in RP systems [29]. Each slice consists of one or more curves that follow the shape of the part at that particular height. The specific height of a slice is called a "Z level". When the FDM hardware builds a physical model, it lays down tracks of modelling material called "roads". These roads (Fig. 1) follow the shapes of slice curves. In software Catalyst 4.3, each slice curve can be assigned attributes such as wall thickness and fill patterns. Roads are created as toolpaths for the FDM system. Creating roads allows the operator to view where the heads will begin and at each layer of material on the computer screen before sending the file to the FDM system.

3 Experimental work

The Dimension SST 768 (Soluble Support Technology) RP machine from Stratasys Inc. U.S.A. with Catalyst 4.3 software was used in the study. For this experiment were used two types of specimens (Fig. 3) made from commercial acrylonitrile butadiene styrene (ABS400) material. The first type of specimens with dimensions 4 × 10 × 20 mm and the second type with dimensions ∅12 ÷ ∅20 mm were used in experiment. The size of cross-section area for both types of specimens was equal (40 mm^2). As presented in Fig. 3, building layers are parallel to XY plane - the plane of building platform.

In order to define the influence of processing temperatures on building structure of the FDM prototypes, various temperatures of liquefier and envelope temperatures in printing of specimens were applied. Considering research findings [12] the envelope temperature was set to 70 °C and 75 °C, because lower temperatures would not improve the structure homogeneity. On the other hand, the servicing software of Dimension SST 3D printer does not allow setting up temperature higher than 75 °C. One of the aims of experimental research was to find out if the change of printing conditions would improve the structure homogeneity. Based on research findings [3, 5, 12, 20] and material properties of ABS polymers the liquefier temperatures were set up to 280 °C, 285 °C and 290 °C.

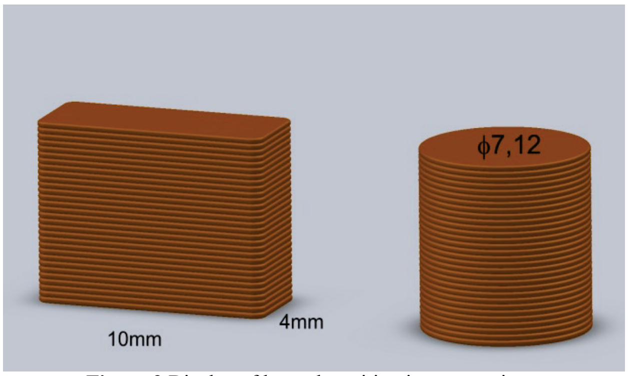

Figure 3 Display of layer deposition in test specimen

The influence of layout was tested with the rectangular specimens 4 × 10 × 20 mm (Fig. 3). According to Fig. 4 specimens were arranged on building platform with dimensions 203 × 203 mm and printed at processing temperatures (liquefier 280 °C and envelope 75 °C) recommended by manufacturer of the FDM machine.

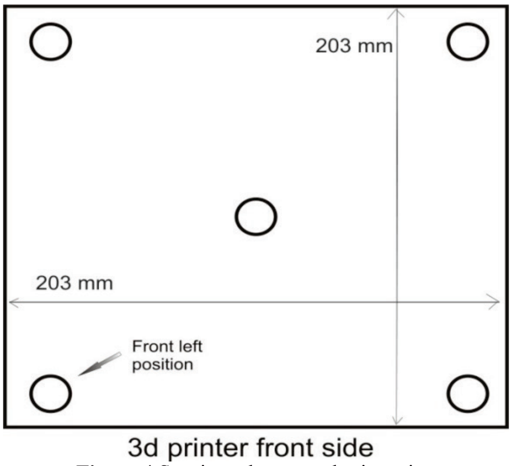

Figure 4 Specimen layout and orientation

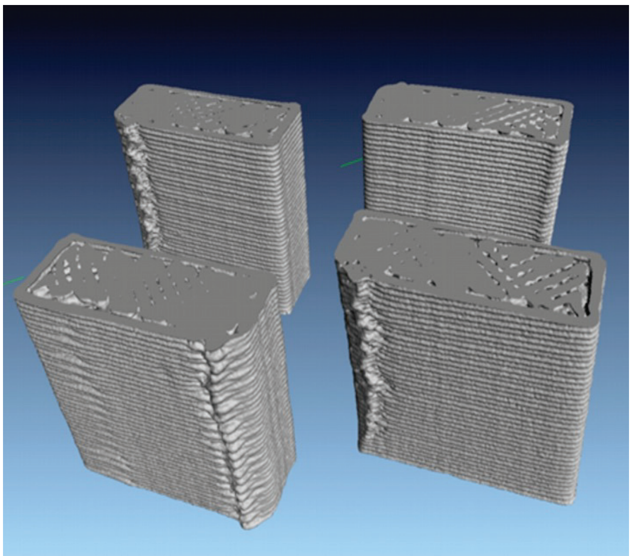

Figure 5 Cloud of points (result of measuring in Metrotom equipment)

Fabricated specimens were analysed by computer tomography to obtain 3D model of specimen's structure and the gathered information was processed in VG Studio Max 2.0. VG studio MAX 2.0 allows presenting the structure of specimens as a cloud of points (Fig. 5), and prepares cross-section pictures of specimen structure.

Achieved resolution (voxel size) of this measurement was 0,04 mm. Layer thickness of printed specimens was set to 0,254 mm, so within one layer we were able to prepare at least 6 pictures of the samples structure. In order to quantitatively analyse the volume of unfilled space in the whole volume of specimens we took eighty following snapshots in random height. After that, the obtained pictures were adjusted and analysed.

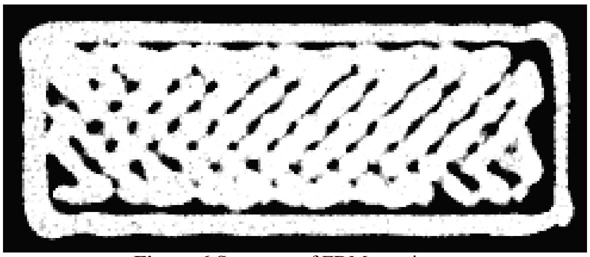

Figure 6 Structure of FDM specimen

Obtained pictures of structure (Fig. 6) were analysed with the help of ImageJ v1.4.2 software. This software allows image processing and analysis via Java plugins. The program was used in structure analysing of bitmap pictures obtained from CT. Analysed pictures were converted to 8-bit colour scale. After converting to 8-bit colour scale, the pictures were transferred to binary format and prepared to be analysed in ImageJ. Structure in binary format allows gathering the size of specimen cross-section area and the size of the area which is not filled with material. Outlines of these areas are displayed in Fig. 7. The size of non-filled area is then expressed as percentage of specimen cross-section area.

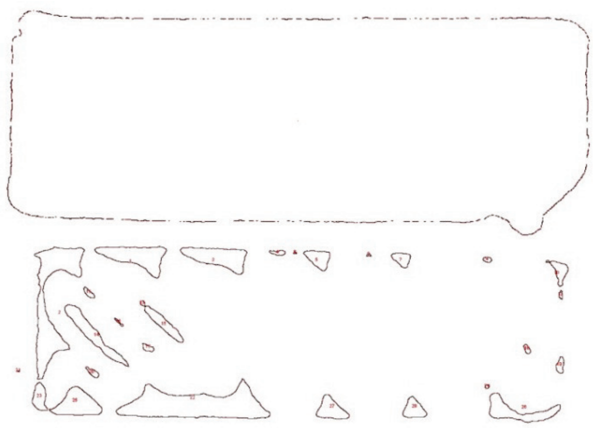

Figure 7 Outlines of the whole specimen cross-section (above) and outlines of non-filled area

4 Results and discussion

As mentioned above, there were prepared eighty snapshots in cross-section for each type (temperature range and layout) of specimens. In order to show the obtained structure only few pictures were selected as displayed in Fig. 8. These selected pictures are displayed consecutively as they were measured by CT. From Fig. 8 it is obvious that by all printing conditions there is in all specimens the area with higher density of material. This effect is in all specimens notable in the area where the printing head starts and ends printing the perimeter. In all layers printing begins in the same place, therefore on all specimens is visible tip.

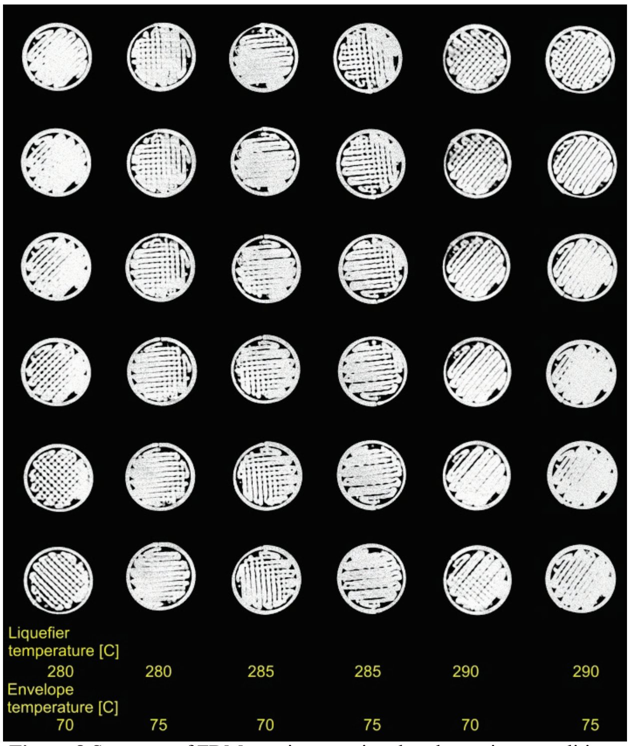

Figure 8 Structure of FDM specimens printed under various conditions

The analysis of structures and quantifying of size of non-filled area in each scanned layer was carried out in ImageJ software and the portion of non-filled volume was determined (Figs. 9 and 10). From Fig. 9 it is obvious that increasing of envelope temperature from 70 °C to 75 °C results in decreasing of non-filled volume in the sample with rectangle cross-section by about 0,8 ÷ 2,5 %. This difference decreases with rising of liquefier temperatures. Considering the influence of liquefier temperature, it is obvious that at the temperature 290 °C the volume of non-filled area is significantly lower than at the temperature 280 °C and 285 °C (Fig. 9).

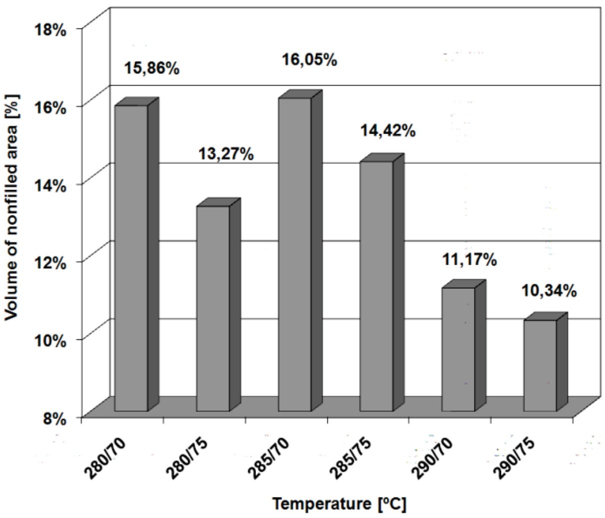

Figure 9 The influence of liquefier and envelope temperatures on the volume of non-filled area in samples with rectangular cross-section

These findings are consistent with the experimental results presented by Sun et al. [12]. On the other hand, performing volume analysis of non-filled area in the samples with cylindrical cross-section (Fig. 10), the influence of temperature change is not so significant, except for the highest temperatures combination used in this experiment, where the difference is about 3 %. As a result it is clear that not only the FDM printing condition, but also the shape of the fabricated part influences the structure homogeneity represented by the volume of non-filled area in samples.

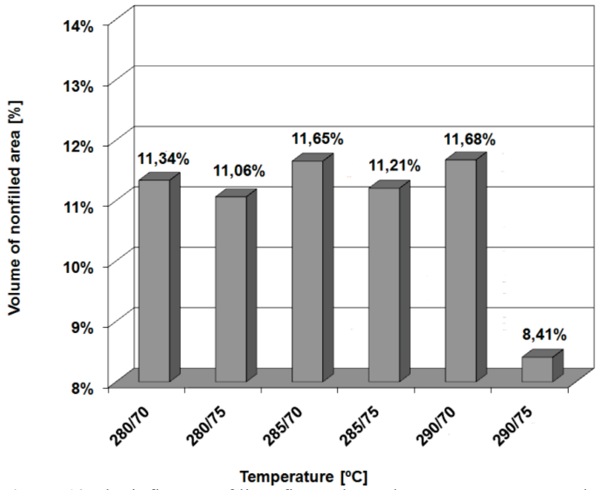

Figure 10 The influence of liquefier and envelope temperatures on the volume of non-filled area in samples with circular cross-section

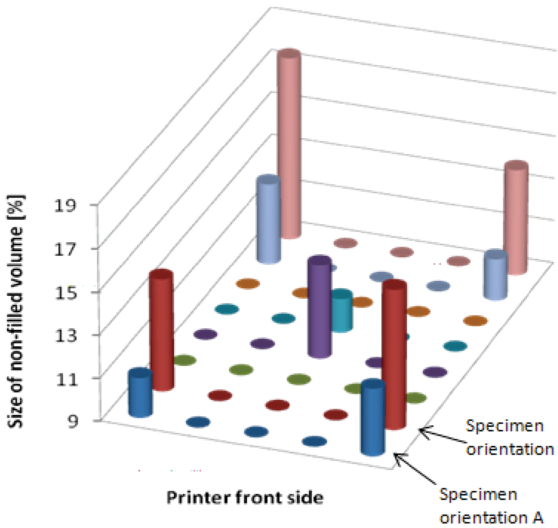

Figure 11 The size of non-filled volume in specimens (specimen layout according to Fig. 5)

Fig. 11 shows the influence of specimen layout and orientation on the size of non-filled volume in tested specimens. In all four corners of building platform these specimens with orientation A (referred to Fig. 4), have lower amount of non-filled volume as compared with "B-oriented" specimens. The difference is from 3,02 to 4,79 %. The size of non-filled volume in specimens from the centre of building platform shows that the "A-oriented" specimen has by 2,78 % higher non-filled volume in comparison with the "B-oriented" specimen. This result is in contrariety to the results obtained in specimens from the corners of the building platform. To observe and explain this phenomenon, it is necessary to decrease the gap between specimens in order to observe potential relation between the layout and the structure.

Experiment with changing of processing condition shows differences in the amount of non-filled area in samples built in the same locations. Considering these results in evaluating of layout influence on the structure homogeneity in the samples built under the same processing conditions we can propose the inference that the temperature profile inside the building chamber is not constant and is probably affected by the chamber construction, shape of the part and actual position of the printer head.

5 Conclusion

The aim of experimental research was the FDM prototypes structure analysis and evaluation of processing conditions that influence the final structure of prototype. In order to research the influences of head and envelope temperatures on final structure of particular prototype layers, the specimens were printed with various temperatures of liquefier and envelope temperatures within device allowable temperatures.

From obtained results it is obvious that material distribution is not uniform in the whole volume of scanned specimens, and higher density can be observed in the area of layer building start point. It was found out that the structure homogeneity represented by the volume of non-filled area is affected by the shape of the fabricated part. The influence of processing temperatures on structure homogeneity was less significant in the parts with circular cross-section than in the part with rectangular cross-section.

To obtain optimal processing parameters for 3D printing prototypes, it is necessary to execute further experiments, which could verify the obtained results of temperature influence on the structure of FDM prototypes.

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