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INFILL AND TYPE INFLUENCE ON TENSILE STRENGTH OF PLA BIODEGRADABLE MATERIAL USING FDM TECHNOLOGY

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Abstract: Due to the increased importance shown by consumers around the world in what concerns the cost, the manufacturing time, and the quality associated with the additive manufacturing technology, more and more researchers, companies and consumers are adopting this technology and have been continuously improving it. In this paper, we analyze the behavior of PLA material during the FDM printing process and also conduct studies regarding the influence of different process parameters (pattern type, infill rate) on the tensile strength of the printed PLA samples. The paper also describes a series of defects that may occur during the process.
Key words: FDM, PLA, tensile strength, simulations, defects

1. INTRODUCTION

PLA (Polylactic Acid) is one of the most popular bioplastics used in FDM (Fused Deposition Modeling) desktop printing. The biodegradable thermoplastic material is obtained from annual plants (renewable resources) such as sugarcane or corn starch and is used for many applications where aesthetics (fine detail) is important, ranging from food-related items to medical implants. It is generally stable in atmospheric conditions but in industrial composters will biodegrade in approximatively 50 days while in water it will degrade in 48 months, [1, 2].

A very important aspect that must be taken into account in the choice of material is heat resistance. PLA thermoplastic is not very suitable for high temperature applications due to its glass transition temperature of 60°C. After this temperature, the structural integrity of the material is rapidly decreasing and the part begins to deform particularly if the part is under a load, [3].

A brief characterization of PLA material, using the data from OptiMatter, [4], depending on key decision criteria (other than speed and cost) needed in the material choice stage is shown in Figure 1. The biodegradable thermoplastic material reveals characteristics such as printing easiness, good visual quality, layer adhesion and tensile strength. Its drawbacks are its brittle behavior and low impact resistance**.** Other PLA characteristics are the fact that it is odorless, its good UV resistance, low humidity resistance and very rigid behavior. These properties are in essence neither "good", nor "bad", but they are properties that make the material suitable for some applications and not for others, [1-6].

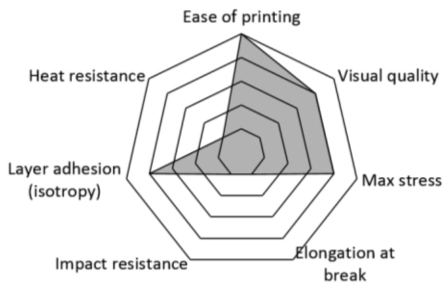

Fig. 1. 3D printing characterization of PLA, [4]

2. MATERIAL AND METHODS

The purpose of this study is to analyze the mechanical performance (tensile strength) of samples obtained by 3D printing from PLA. *PLA filament* (red color) manufactured by Raise3D™ Premium with a diameter of 1.75mm was used for this study. Some general information (average values) regarding the properties of spool studied material that has to be mentioned is tensile strength 37MPa, elongation 6%, flexural modulus 4GPa, density 1.3g/cm^3, melting point 173°C, glass transition temperature 60°C, [4]**.**

The ideaMaker software package belonging to the Raise3D Pro2 Plus printer was used to determine the different infill types.

A speed value of 0.1 mm/min was used in tensile tests. The dumb-type sample according to SR EN ISO 527-2 and ASTM D638 [5] was also used, the distance between the slots was 115mm, the data acquisition rate was 10Hz, and the test was performed at room temperature (23°C).

3. EXPERIMENTAL RESULTS

Thus, in order to view the infilling type corresponding to a certain infilling percentage, Figure 2 shows the “honeycomb”-like infilling structure and the tensile test samples (according to the SR EN ISO 527 standard, [7]) corresponding to different infill rate percentages: 25% (a), 50% (b), 75% (c), 100% (d).

Figure 2(a), corresponding to the lowest infill rate (25%) of the ideaMaker software package used by Raise3D Pro2 Plus printer, simulates the rapid prototyping process, where the "honeycomb" infill colored in yellow and the 3 'shells' (one brown 'outher shell' and two green 'iner shells') may be seen. Figures 2(b) and 2(c), corresponding to infilling percentages of 50% and 75%, respectively, reveal that the software performs the infilling simulation in the same way as for the 25% infilling rate, the difference consisting not only of the infilling percentage but also of the printing time, quantity of used material and processing cost. In the case of full sample infilling, Figure 2(d), (100%), the software no longer takes into account the selected honeycomb infilling type, automatically passing to a rectilinear infilling type (orange “solid infill”). In the case of rectilinear infill (Figure 3), the software interprets the four "honeycomb"-like infilling percentages in a similar manner. Following experiment repetition, we found that the software program started to ignore the infilling type setup at 95% infilling.

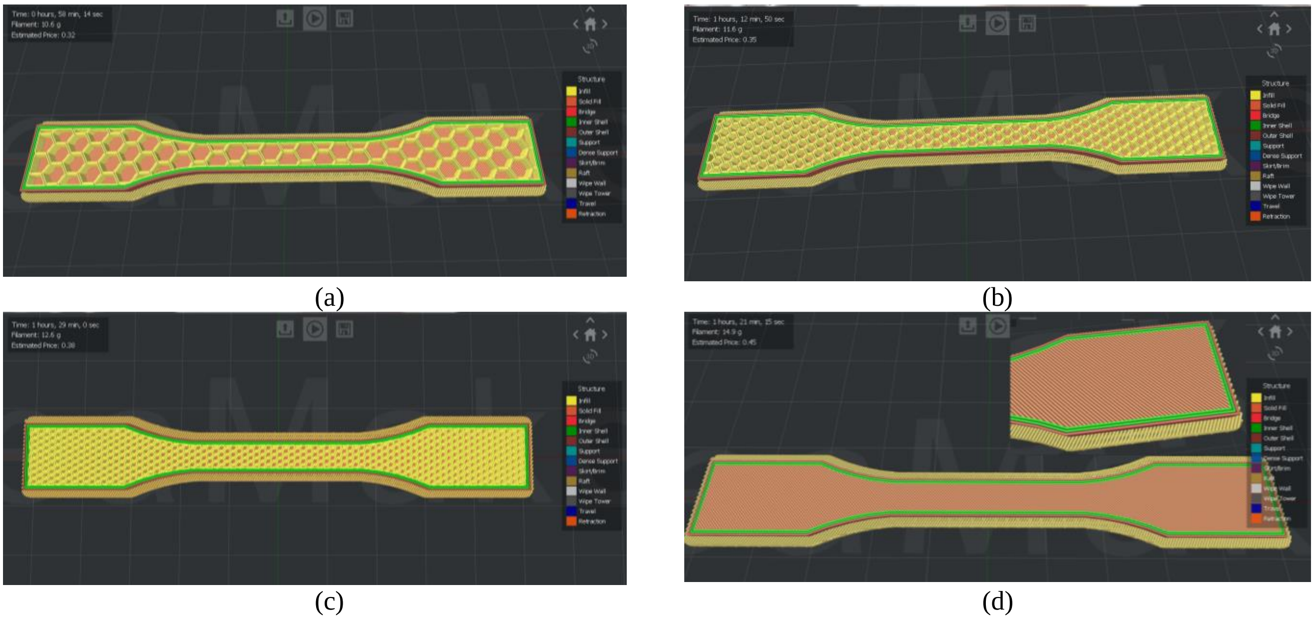

Fig. 2. Infill of PLA sample, Honeycomb type: (a) 25% (b) 50%; (c) 75%; (d) 100%

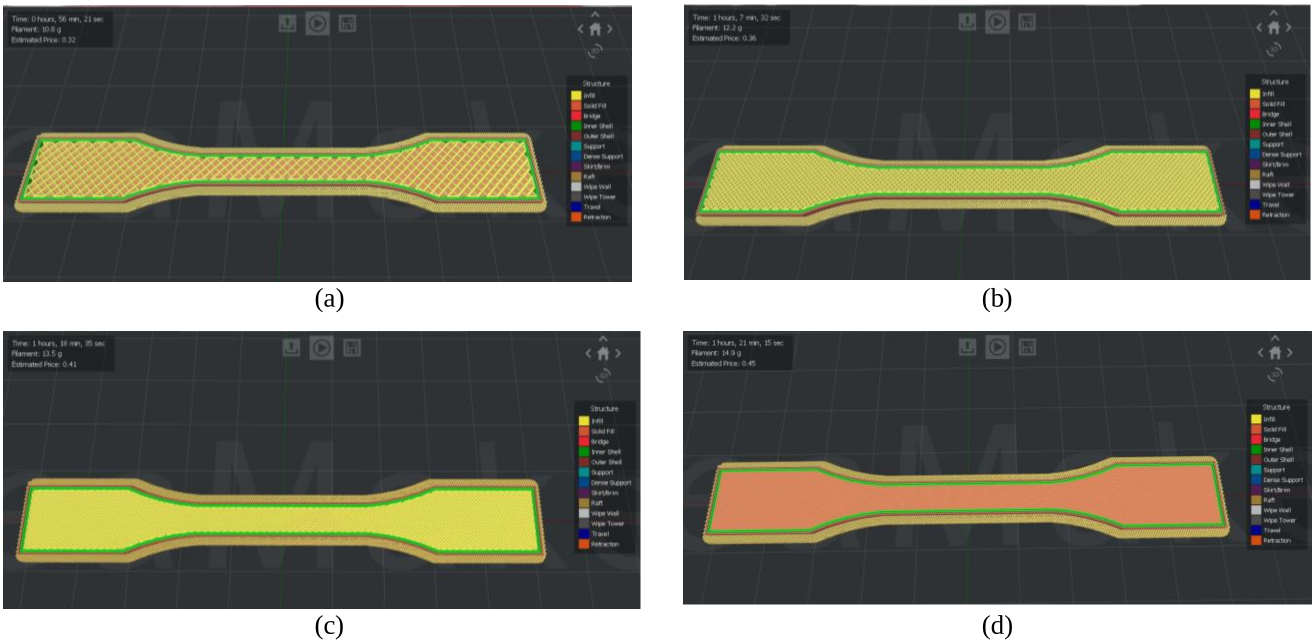

Fig 3. Infill of PLA sample, Rectilinear type:(a) 25% (b) 50%; (c) 75%; (d) 100%

The PLA samples were prototyped using Raise3D Pro2 Plus equipment developed by Raise3D. The mechanical properties of the manufactured samples obtained by FDM additive manufacturing technology depend on process parameters selection. Thus, the building orientation was flat, the nozzle temperature was 215°C, the bed was heated at 60°C, the infill rate was 70mm/s, the nozzle diameter was 0.4mm, the layer thickness was 0.2mm, the number of shells was 3, and the extrusion width was 0.5mm.
The uniaxial tensile tests were performed at the Science and Materials Engineering Faculty, "Gheorghe Asachi" Technical University of Iasi, Romania. The universal testing equipment used was Instron 3382.
The uniaxial tensile tests were performed on 3D printed models with different infill rates (50%, 75% and 100%). For each infilling rate, 3 samples were used to calculate the mean value and the dispersion of the results.
The tensile test showed an approximately proportional increase with the sample infilling percentage, Figures 4, 5 and 6. Thus, in the case of 100% infilling, the tensile strength mean value is (37.88±1.49)MPa, and in the case of 75% infilling rate, the value decreases by about 25%, namely (29.68±0.36)MPa. The decrease value is also proportional for the 50% infill rate, i.e. (24.70%±0.31)MPa.

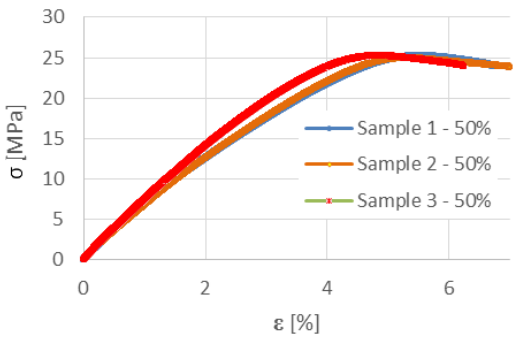

Fig. 4. Tensile strength of PLA printed sample – 50% infill rate

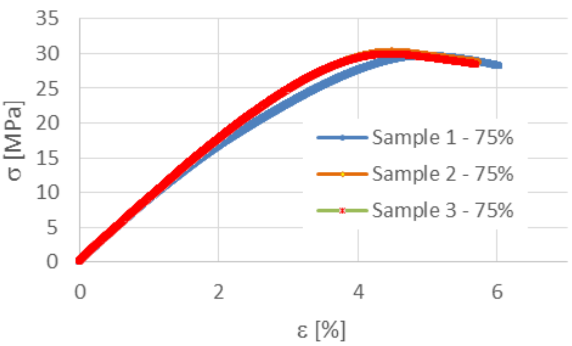

Fig. 5. Tensile strength of PLA printed sample – 75% infill rate

The mean value of tensile elongation at 100% infilling percentage is (4.47±0.22)%, at 75% infilling percentage the value is (4.75±0.11)% and at 50% infilling percentage it is (5.14±0.15)%. Having analyzed the experimental results, we can safely say that the samples manufactured from PLA material revealed a brittle behavior compared to conventional plastic material such as ABS (Acrylonitrile butadiene styrene) or PP (Polypropylene), [1, 2, 4].

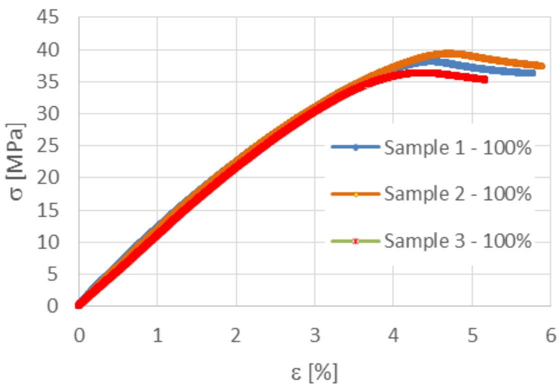

Fig. 6. Tensile strength of PLA printed sample – 100% infill rate

Considering the fact that the aim of the research is to obtain the best properties for the rapid prototype of biodegradable materials by using the FDM method, we chose to continue the experiment with an 100% infilling rate.
We also printed five samples with five different pattern types made of PLA material (red), in order to observe the orientation of the melted filament. The types of infillers were: grid, rectilinear, honeycomb, triangular and cubic. Other parameters set during the 3D printing process were 50% infill, 2 shells, 70 mm/s infill rate, 215°C nozzle temperature and 60°C heated bed.
As a result of surface morphological analysis by SEM, Figure 7, with a “honeycomb”-like infilling ratio of 50%, we found that for this type of printing the melted wire/bead follows a rectilinear pathway, also the thickness/width of the wire at the nozzle exit has a dimension of 0.4mm, but the extruder head exerts pressure on it, the wire width reaching the size of 0.5mm.
Another aspect that has to be mentioned is the chemical composition of PLA printed material, according to Zhe Wang, Zhijuan Pan et al. [8], following EDAX analysis, the biodegradable thermoplastic is 66.46% carbon and 34.54% oxygen. Also, Figure 7 shows oxygen particles distributed approximately uniformly over the entire surface of the printed sample.
The study was aimed at detecting 3D printing defects and also their causes.

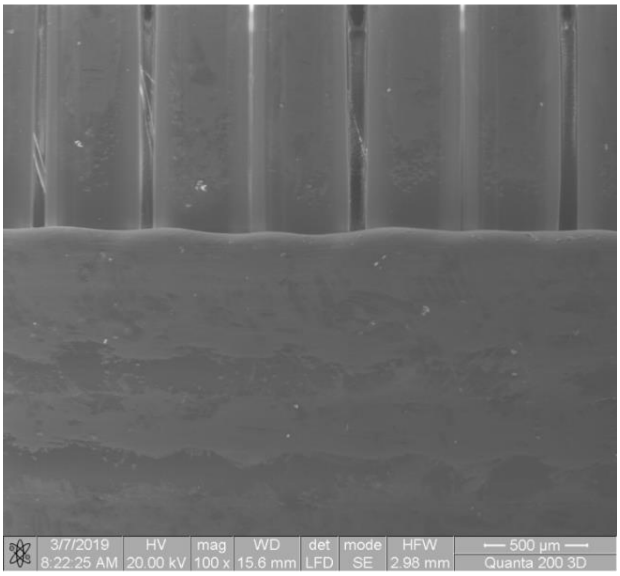

Fig. 7. SEM image of 3D printed PLA, „honeycomb" type

4. TECHNOLOGICAL PARAMETERS OPTIMIZATION

A 1.75mm diameter wire was used to make samples out of biodegradable PLA material. The technological process factors analyzed were as follows: deposited layer thickness, infill rate and printed sample orientation. A factorial experiment with three factors on two levels (2^3=8 experiments) was used, according to Table 1. Each experiment was repeated 3 times, in order to reveal the experimental process stability. Specific samples, acording to standard, for uniaxial tensile test were printed.

Table 1. Input parameters in the experimental plan

No. crt.	Parameter	Levels	
		1	2
1	layer thickness [mm]	0.1	0.2
2	infill speed [mm/min]	40	80
3	sample orientation	flat	on-edge

Following the analysis of the experimental results regarding the PLA material uniaxial tensile test, it was revealed that the technological parameter that most significantly influenced the tensile test values (tensile strength - σ, elasticity modulus - E) was the "sample orientation" on the printing table, [2].

In order to optimize the process parameters, the following criteria were taken into account: the peak of the tensile strength and the elasticity modulus. In the case of tensile strength, the following quantitative technological parameters were considered: infilling rate, v[mm/min], and printing layer thickness, g [mm]. The best tensile strength values were recorded for the on-edge "sample orientation", according to the factors influence analysis, [2].

The TableCurve3D v.4.0 application was used to determine the regression function, equation (1), which is the best representation (square of the correlation coefficient R^2=0.971) of experimental data, Figure 8.

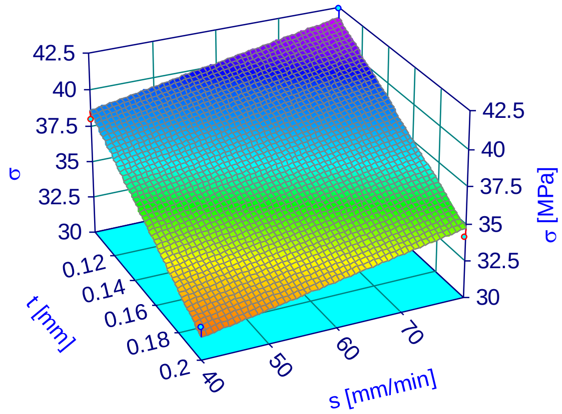

Fig. 8. The regression equation for PLA samples tensile strength printed on-edge

$$\sigma = 42.34 - 69.9 \cdot t + 0.08 \cdot s, [MPa] \quad (1)$$

The maximum value of equation (1) was obtained for g=0.1mm and v=80mm/min. For these parameters and „on-edge" printing of the sample, the σ=41.75MPa value was obtained.

In case of *elasticity modulus*, the "on-edge" position of the sample leads to the best results of the elasticity modulus.

Figure 9 shows the plan regression equation (2), which represents the influence of the infilling rate and the thickness of the layer deposited on the elasticity modulus of the 3D printing samples placed on-edge.

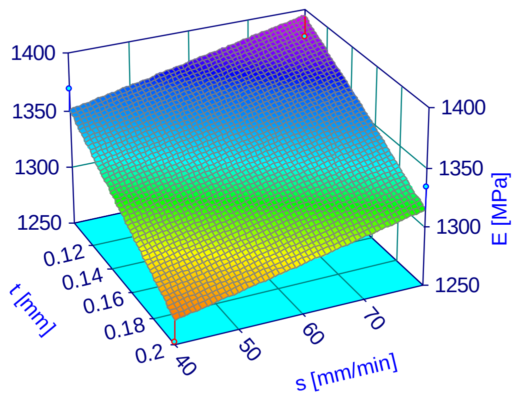

Fig. 9. The regression equation for PLA samples elasticity modulus printed on-edge

The regression equation for the elasticity modulus (R^2=0.853) is:

$$E = 1386.08 - 793.65 \cdot t + 1.1 \cdot s, [MPa] \quad (2)$$

which reaches its peak in the field of experimentation when g=0.1mm and v=80mm/min. For both these parameters and “on-edge” printing position, E=1394.72MPa.

In the case of *elongation*, the printing direction technological parameter was also considered “on-edge”, and, according to the factors influence analysis, the best results were obtained for elongation.

The plane equation (Figure 10) is for R^2=0.496, equation (3) and its peak in the field of experimentation is reached when g=0.2mm and v=40mm/min:

$$\varepsilon = 3.83 + 11.8 \cdot t + 0.00375 \cdot s, [\%] \qquad (3)$$

For the parameters above and taking into account the “on-edge” printing position, the ε=6.34% value was obtained. The deviation from the experimental data is 8.65%.

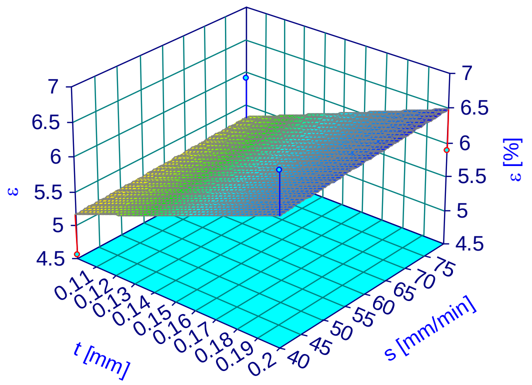

Fig. 10. The regression equation for PLA samples elongation printed on-edge

5. DEFECTS OF SAMPLES

The 3D printing process by the FDM method depends on parameters like: the physical and mechanical properties of the wire, the manner in which the model is built, the performance and state of the 3D printing equipment, the parameters of the 3D printing process and the environmental printing parameters.

The *wire diameter uniformity* used for printing is an important factor because it ensures the continuous extruder feeding. If the diameter is too small, the filament drive mechanism will not be able to guide it into the extruder and the printing process will stop. If the diameter is too big, the feed friction forces increase and the probability of wire skewing to the gear wheels of the feed mechanism also increases. This phenomenon results in the separation of the chip from the wire and the clogging of the feed zone (Figure 11).

The *thermal expansion coefficient* influences the 3D printing process by inducing tensions between adjacent layers of deposited material. The already deposited layer has a low temperature that depends on the equipment enclosure temperature. Upon depositing of a new layer, after cooling, the material undergoes a contraction that induces shrinkage tensions in the new layer.

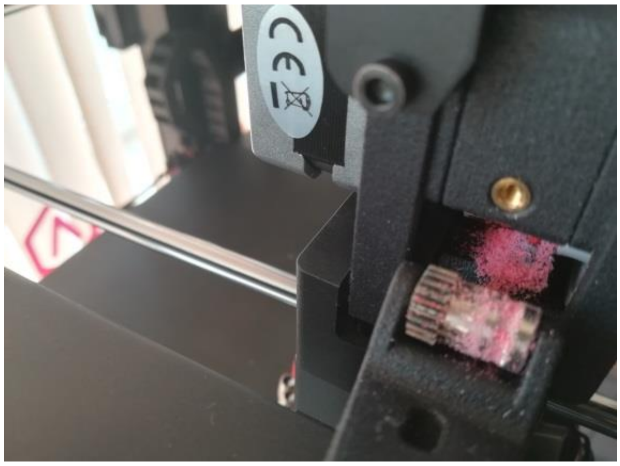

Fig. 11. Drive area clogging of the wire with the material chips

Fig. 12. Deposited layers’ delamination through 3D printing

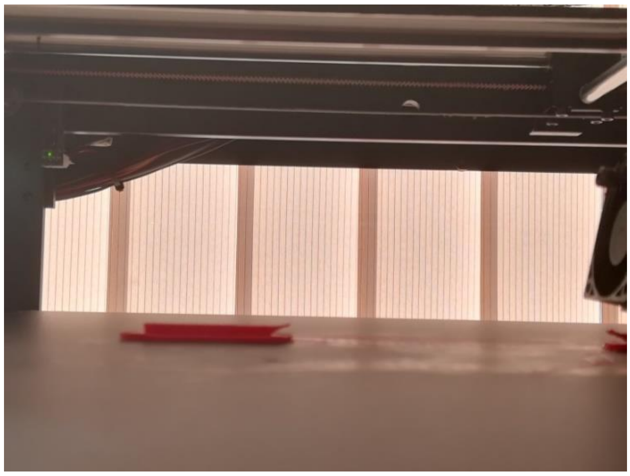

Fig. 13. Deformation by thermal shrinkage of the sample pick

If the *adhesion* between the layers (another important property of the wire material) is poor, the inner stresses and forces generated by the printing process (even if there are relatively small) can lead to the peeling/delamination of layers (Figure 12).
For certain geometries or part layouts on the printing table, thermal contraction may lead to deformations that prevent the subsequent layers to be deposited. Thus, Figure 13 shows pick lifting in the part construction due to the tensions at the shrinkage of the deposited layers. The pick comes out of the current layer deposition plane, and at the head movement, the nozzle will not be able to deposit a new layer, which will cause printing defects. One possibility to avoid these defects would be to move the printing head only in the opposite direction from the pick.

6. CONCLUSIONS

The ideaMaker software, which was provided at the purchasing of the 3D Raise3D Pro2 Plus equipment, allows setting a variety of parameters. Our paper analyzed the parameters influence on the tensile strength, such as: the type and the infilling degree of the printed part. The program allows five geometric infill patterns: “grid”, “rectilinear”, “honeycomb”, “triangular” and “cubic”. Biodegradable PLA was used as material. It was found that the equipment software no longer considered a certain infilling type for rates higher than 95%. In the case of 50% infill rate, the tensile strength was (24.70% ±0.31)MPa, at 75% (29.68±0.36)MPa, and at 100% infilling percentage the value of the tensile strength was (37.88±1.49)MPa. In the case of elongation, the infilling percentage leads to the following results: for the 50% infilling percentage the value was (5.14±0.15)%, for the 75% infilling percentage the elongation value was (4.75±0.11)% and for the 100% infilling percentage the value was (4.47±0.22)%. The traction values obtained were aproximately proportional to the increase of infill percentage. In order to maximise the tensile strength, the elasticity modulus and the elongation, regression equations were obtained.
Following the tensile strenght curves, we may conclude that in the uniaxial tensile test, the PLA material has a brittle behavior. The paper also describes some defects that may occur during the 3D printing process. Gaps in the layer deposits may occur due to the clogging with chips in the wire advancement mechanism, peeling and deformation of sharp portions of the sample.

7. ACKNOWLEDGEMENT

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