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# THE INFLUENCE OF 3D PRINTING PARAMETERS ON THE MECHANICAL PROPERTIES OF REINFORCED PLA – A REVIEW

BY

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**Abstract.** Due to the multiple advantages of 3D printing, it is used in many industrial fields, from robotics to the food industry, from the automotive industry to the aerospace industry. The results in the paper refer to parts obtained by 3D printing (longitudinal and transverse) from PLA reinforced with wood fibers of 100%, 200% and 300% widths compared to the parts obtained by pressing. The behavior of reinforced parts of the PLA with wood fibers and a bio-additive were also studied. There were no noticeable differences in tensile strength when printing in the transverse direction from the parts obtained by pressing, and in the case of longitudinal printing the behavior is similar. Instead, there is a significant decrease in traction resistance to transverse printing compared to the longitudinal one. The variation in the width of the printed part influences the mechanical behavior in the sense that in the parts printed at 0º a more ductile behavior was recorded with its increase. The adhesion between wood fibers and matrix can be improved using a bioamide, and the addition of only 1.3% of the bio-additive led to an increase in traction resistance due to improved adhesion between wood fibers. There was also a slight increase in the rigidity of the parts

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due to the increase in Young's module. The impact resistance was much higher in the case of notchless sample because, as is natural, they can absorb more energy compared to notched sample.

**Keywords:** 3D printing, PLA bio-composites, wood fiber, reinforced PLA.

## 1. Introduction

According to the International Organization for Standardization (ISO)/American Society for Testing and Materials, the process of joining materials layer by layer from 3D digital model data or computer-aided design (CAD) models is called additive manufacturing (AM) or 3D printing (ASTM) 52900:2015 Standard (Bejan, 2019).

The continuous pace of development of 3D printers has made it possible to print layers, thereby paving the way for the development of applications in the biomedical field (Gaoa *et al*., 2015). Existing 3D printers can print complex three-dimensional cues in almost any material, from nylon to glass to titanium. This actually broadens the use of parts obtained through 3D printing to other areas of use such as the aerospace industry, the automotive industry, the food industry, the architecture and construction industry, the fabric and fashion industry, the electrical and electronics industry etc.

The most widely used 3D printing technology is FFF (Fused Filament Fabrication), due to a small investment, the use of relatively inexpensive material with appropriate properties and the reliability of this technology (https://sim.tuiasi.ro/wp-content/; Carneiro and Silva, 2015; http://ww.trosol.com/fortus/WP).

FFF's 3D printing technology consists of passing a plastic filament through an extruder where it is brought into a melting state, following the deposition, layer upon layer, with great precision in order to obtain the final 3D product (1). The print head, or extruder, is heated to melt the plastic filament, and its displacement is made both in the horizontal plane and vertically, under the coordination of a numerically controlled mechanism directly by the CAM application of the printing equipment. During the movement, the print head (4) deposits a thin row of extruded plastic which, upon cooling, immediately hardens, with adhesion to the previous layer taking place to form the final 3D model (Fig. 1). Due to the risk of deformation of parts due to the phenomenon of sudden cooling, 3D printers with a closed printing chamber, heated to high temperature, were designed and executed. In the case of complex geometries for the parts to be obtained or the parts in the console, the FFF technology prints, in the first phase, a laying base for the sample, which will then have to be removed by manually executed operations (Berce, 2014).

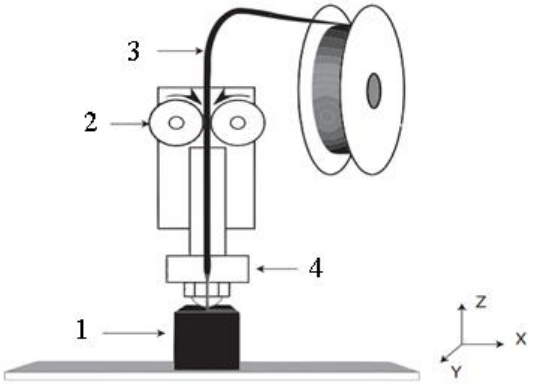



Fig. 1 – General image of the 3D printer using FFF technology:
1-printed piece; 2-rolls; 3-is the filament; 4-printing head.

The most used plastics used in additive manufacturing are polyamide, ABS, LayWood, PLA but also a series of composite materials reinforced with carbon fibers, fiberglass etc., (Gurmeet, 2020; Mazzanti, 2019; Nedelcu *et al*., 2020; Mazurchevici *et al*., 2019; Ciofu *et al*., 2019).

In FFF technology, PLA(Polylactic Acid) and ABS(Acrylonitrile Butadiene Styrene) have been the most historically used polymeric materials (Mazurchevici, 2020). However, new materials have gained much more ground in recent years, those relating to PET(Polyethylene terephthalate), Nylon, TPU Flexible(Thermoplastic Polyurethane), PC(Polycarbonate), PETG(Polyethylene terephthalate glycol), PEEK(Polyether ether ketone,) PEI (Polyetherimide), and the significant differences in their properties are presented, so that users can quickly decide which polymer to use (Mazurchevici 2020; www.blog.3ddot.ro/introducere-in-fdm).

PLA is a biodegradable plastic that can be used in resin form for digital light processing/stereolithography (DLP/SL) processes, and in filament form for FFF processes. Available in a variety of colors, including clear, the material has proven to be a useful option for certain industrial applications. PLA has the greatest commercial potential due to its aesthetic appearance, mechanical strength, thermal resistance, plasticity, biocompatibility and light machinability (Awal *et at*., 2014; Huda *et at*., 2008). It is used in a wide range of applications, e.g. sheets, textiles, packaging, medical supplies, for surgical purposes, food and bags, automobile parts and mobile phone cases etc. (Awal *et al*., 2014; Masud *et al*., 2007). The general application of PLA products may be limited because they are brittle in thicker materials and are more expensive than petroleum-based polymers such as polypropylene and polyethylene (Liu *et al*., 2005). However, the price of PLA is currently falling due to the increase in PLA production. In addition, PLA can be modified with plasticizers, which can improve the processability of biocomposites. The mechanical and thermal

properties of PLA biocomposites can be improved by adding fibers and fillers. Wood fibers are often used with thermoplastic polymers. Incorporating wood fibers into biocomposites reduces the final cost of the product because they are inexpensive and readily available in nature. In addition, wood fiber also has the characteristics of low density, high specific stiffness, renewable and biodegradable (Awal *et al*., 2011; Awal *et al*., 2010; Awal *et al*., 2012).

## 2. Influence of processing parameters on the mechanical properties for wood fiber reinforced PLA

The purpose of this study is to present an analysis of the influence of FFF parameters on the microstructure of a wood biocomposite and its consequences on hydro-mechanical properties.

Thus, a filament with the name "Fine wood filler", produced by ColorFabb, with a diameter of (2.85 ± 0.1) mm, was used, being a mixture of poles (lactic acid) (PLA) and poly matrix (hydroxyalcanoate) (PHA), reinforced with recycled wood fibers, in a percentage of (15.2 ± 0.9)%, which falls within the range given by the manufacturer (10-20)% by weight. A monomaterial was chosen to improve recyclability at the end of life and also to reduce delamination between double layers when hygromorphic biocomposites are printed (Correa *et at*., 2015; Duigou *et al*., 2015).

Setting printing parameters at 3 mm thickness: nozzle temperature and hot plate temperature are set to 210°C and 70°C, respectively, and printing speed is set to 18mm/s affects the properties of wood biocomposites.The width of the sample (Fig. 2) can vary from 100% to 300% of the 10 mm of the sample, and influences the overlapping of the layers, and implicitly the cohesion of the printed part. Samples were printed using a raster angle at 0° (longitudinal) or 90° (transversely) along the x-axis, without outline (Fig. 2), (Quanjina *et al*., 2020; Peltola *et al*., 2014; Faludi *et al*., 2013).

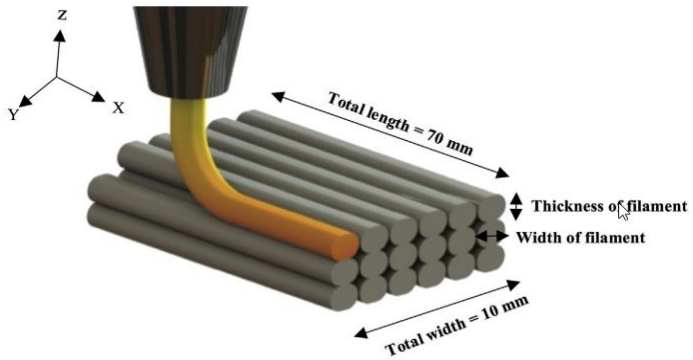



Fig. 2 – Schematic representation of printed sample geometry for tensile tests and actuation (Duigou *et al*., 2015).

Tensile tests were carried out on samples printed at 0° and transversely (90°), samples with three layers of biocomposite (≈1 mm) in the dry state and saturated with water. Young's modulus was estimated using an MTS Synergy RT1000 tractor with an extensometer. The tensile strain rate was set at 1 mm/min and five samples were systematically tested per assay (Sobczak *et al*., 2011; Duigou *et al*., 2015). The mechanical behaviour and properties are shown in Fig. 3.

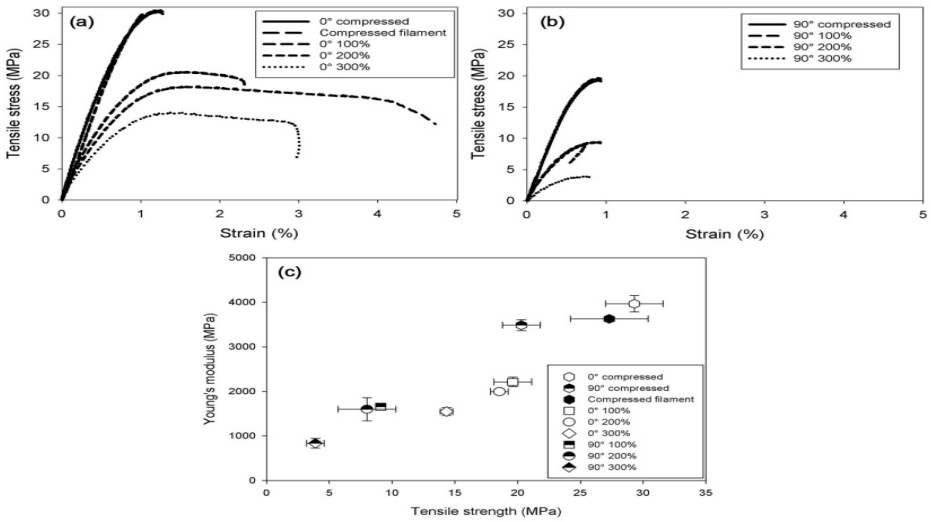



Fig. 3 – Tensile behaviour of the wood biocomposite achieved by FFF according to the printing width (100, 200 and 300%) for: (a): longitudinal printing direction (0°); (b) 90° in relation to the longitudinal direction. (c) Young modulus according to tensile strength for different directions and print widths (Duigou *et al*., 2015).

As can be seen in Fig. 3, the tensile behaviour of the 0° printed/compressed filaments and of the compressed filaments are clearly similar, with an almost elastic linearity until the fragile rupture occurs (Fig. 3a). Also, the elastic behavior is very similar (Fig. 3c), and the pieces printed at 90° with additional compression do not show any change in the fragile behavior (Fig. 3b).

However, this was reduced by about 20% and 35%, respectively, compared to their longitudinal counterparts (Fig. 3c). Therefore, it can be assumed that the orientation of wood fibers in the polymer matrix is determined by the extrusion process (production of the strands) rather than the FFF process itself, mainly due to the lower shear stresses that occur. Even with lower tensile strengths (σdatasheet = 46 MPa and Edatasheet = 3290 MPa), the achieved mechanical properties are within the range of stiffness specified in the datasheets. Thermal degradation induced by the processing stage could explain

this difference. Properties obtained for the printed/compressed 3D samples and compressed filaments are in the polypropylene (PP)/wood range of 30% (https://www.pcbway.com/rapid-prototyping/3d-printing; Jianu *et al*., 2020) and high density polyethylene (HDPE)/wood 40% (Berce, 2014), but are lower than PHA/wood by 20% (E = 3820 ± 70 MPa and σ = (65.80 ± 1.39) MPa (http://creativecommons.org/licenses/by/3.0) and PLA/wood by 20% (Wikipedia. Composite material, 2012), all manufactured by extrusion (Peltola *et al*., 2014; Sobczak *et al*., 2012; Faludi *et al*., 2013). Such differences can also be explained by the biochemical composition, the microstructure of the wood used, the geometry of the filler (fibers, powder) and the processing parameters (shear rate, temperature). The printing thickness is related to the step used by the printer, the length of the filament, the number of passes for printing the part, the yield and finally the printing time (Table 1).

**Table 1**

*Print parameters depending on the print width (Duigou et al., 2015)*

| Printing width | 100% | 200% | | 300% |
|---|---|---|---|---|
| Printing pitch (mm) | 0.322 | 0.558 | | 0.837 |
| Flow ($mm^3/s$) | 1.567 | 2.715 | | 4.072 |
| Number of passes | 310 | 179 | | 119 |
| Printing width (mm) | 0.367±0.01 | 0.557±0.025 | | 0.823±0.025 |
| Overlap (%) | 13.9±3.2 | -0.2±4.3 | | -1.6±3.0 |

When printing a pattern with a print width of 100%, the actual value of the obtained print width is larger than the print step, which means that the microstructure with an overlap of 14.0% is more cohesive than the prepared pattern with the print width set to 200 300%. In fact, the latter samples did not overlap (along the entire length of the sample), resulting in a limited contact area between each printed filament. Consequently, the porosity is greater, as shown by SEM images and density measurements (Fig. 4). The porosity measured in the printed samples was very high compared to the compressed samples (Fig. 4b, c and d), increasing from 14.7 ± 1.4 to 15.5 ± 2.9 and increasing to 21.8 ± 1.2% for samples with final print widths of 100, 200 and 300%, respectively, in the 0º direction. All patterns are printed in the 0º direction. Scale bars in Fig. 4(a-c) represent 100 μm. All samples were printed along the 0º orientation. Figure 4a shows the initial biocomposite filament with a porosity of about 16.5%. The initial porosity of the samples was reduced by printing along the long axis along the 90° direction, to values of (8.4 ± 1.7)%, (11.1 ± 3.1)% and (14 ± 1.2)% relative to the printing direction of 0°, 100%, 200%, or 300% print width.

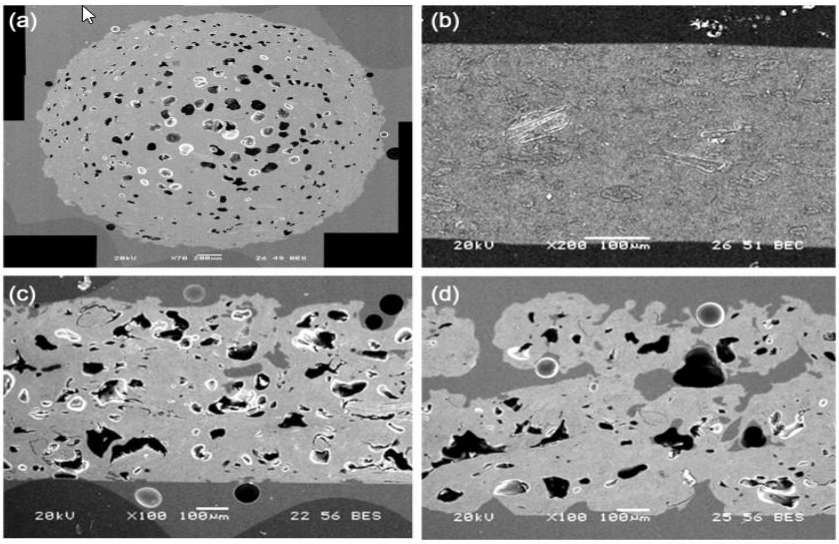



Fig. 4 – SEM cross-sectional images: (a) raw filament, (b) compressed printed samples, (c) samples with 100% printing width and (d) 300% (Duigou *et al*., 2015).

These differences can also be explained by the better compaction of the molten filament, due to a faster passage between each filament, due to the geometry of the sample (L = 70 mm and W = 10 mm), which allows for better mobility of the polymer chains. The variation in the width of the printed part (100, 200 and 300%) induces a major change in the mechanical behavior in samples printed at 0 and 90° (Fig. 3a and b) compared to the parts compressed in contrast with the samples printed at 90°, the samples printed at 0° show a more ductile behavior with the increase in the printing width, with a nonlinear relationship between tension and deformation up to the breaking area. Compared to compressed samples with the same direction of printing (0° and 90°), tensile strength is reduced by 30% and 50% for biocomposites printed at widths of 100% and 300%, while Young's module decreases by 50% and 65% (Correa *et al*., 2015; Migneault *et al*., 2015) This observation can be clearly explained in terms of the microstructure resulting from 3D printing (Fig. 4c a), that is, the high porosity favors the damage of the parts.

Adhesion between fibers and substrates can be improved using bioamides. Another role of bioamides is to improve the processability of composites, because PLA itself is a brittle polymer, and it is difficult to process PLA from wood fibers without suitable additives.

Combination of wood fibers and PLA with bio-additives could provide better mechanical properties to parts that can be used in the automotive industry. It is worth noting that the mechanical performance of composites

depends on the internal orientation of the fibers in composites. That is why it is very important to analyze the mechanical properties of PLA parts reinforced with wood fibers and bio-additive (Awal *et al*., 2014; Awal *et al*., 2010; Awal *et al*., 2011; Awal *et al*., 2012).

## 3. Improving mechanical properties for PLA reinforced with cellulosic fibers by using bio-additives

The tensile strength, bending resistance and impact resistance of biocomposites was determined using a universal test machine (Instron) and an impact resistance tester.

Wood fibres (WP) with a density of about 1.5 g/cm$^3$ and BioamideTM 500, Rheinchemie, Germany were used. The basic properties of PLA are shown in Table 2. Before processing, the PLA and the wood fibre were dried at 80°C for 24 hours to remove moisture from the samples.

**Table 2**

*Physical and mechanical properties of PLA (Awal et al., 2015)*

| Physical properties | | |
|---|---|---|
| Specific gravity g/cm$^3$ | 1.24 | ASTM D792 |
| Melt index, g/10 min (190°C, 2,16 kg) | 35 | ASTM D1238 |
| Crystal melting temperature (ºC) | 155-170 | ASTM D3418 |
| Glass transition temperature (ºC) | 55-60 | ASTM D3418 |
| Mechanical properties | | |
| Tensile strength (MPa) | 62 | ASTM D638 |
| Elongation at break , % | 3.5 | ASTM D638 |
| Bending resistance (MPa) | 108 | ASTM D790 |
| Notched isode impact, ft-lb/in | 0.3 | ASTM D256 |
| Heat distortion temperature (ºC) | 55 | ASTME2092 |

The mixture used is presented in Table 3 and, in the research, we went on the last variant of the mixture in Table 3, i.e. PLA 78.7%, wood pulp 20% and 1.3% bioadimide.

**Table 3**

*Mixture used (Awal et al., 2015)*

| PLA (wt%) | | Wood pulp (wt%) | Bioadimide (wt%) |
|---|---|---|---|
| 100 | | 0 | 0 |
| 80 | | 20 | 0 |
| 78.7 | | 20 | 1.3 |

The values obtained for tensile strength for the mixture variants given in Table 3 are given in Table 4. As wood fibers were incorporated into bio-

composites, PLA/WP's tensile strength increased due to fiber reinforcement. The addition of 1.3% by weight of bioadimide to the PLA / WP bio-composite leads to a slight increase in tensile strength, attributed to the strong interactions between wood fibers and bioadimide which facilitated better interfacial adhesion inside the wood fiber PLA.

**Table 4**

*Tensile strength and elasticity module (Awal et al., 2015)*

| Sample type | Tensile strength (MPa) | Elasticity module (GPa) |
|---|---|---|
| Polylactic acid | 65.70 ± 1.70 | 2.95 ± 0.13 |
| PLA/ pulp (80/20), wt.% | 65.80 ± 1.39 | 3.82 ± 0.07 |
| PLA/Wood pulp/Bioadimide (78.7/20/1.3), wt.% 109.78 ± 1.35 | 68.00 ± 1.84 | 3.84 ± 0.08 |

The values obtained for bending strength for the mixing variants shown in Table 3 are shown in Table 5. Due to the hardening of wood fibers, the elasticity module of PLA / WP bio-composites has been substantially improved compared to simple PLA. The addition of bioadimide was found more effective in improving the elasticity module of biocomposites compared to tensile or bending resistance.

**Table 5**

*Bending resistance and elasticity module (Awal et al., 2015)*

| Sample type | Bending resistance (MPa) | Elastic module (GPa) |
|---|---|---|
| Polylactic acid | 114.11 ± 2.79 | 3.13 ± 0.09 |
| PLA/ pulp (80/20), wt.% | 93.43 ± 2.24 | 3.85 ± 0.03 |
| PLA/Wood pulp/Bioadimide (78.7/20/1.3), wt.% 109.78 ± 1.35 | 109.78 ± 1.35 | 3.94 ± 0.01 |

In general, the impact resistance (notched sample) of polymers or their composites is greater than that of the impact resistance when using notched sample, because the un notched test piece can absorb more energy or has a higher load resistance (Fig. 5a and 5b).

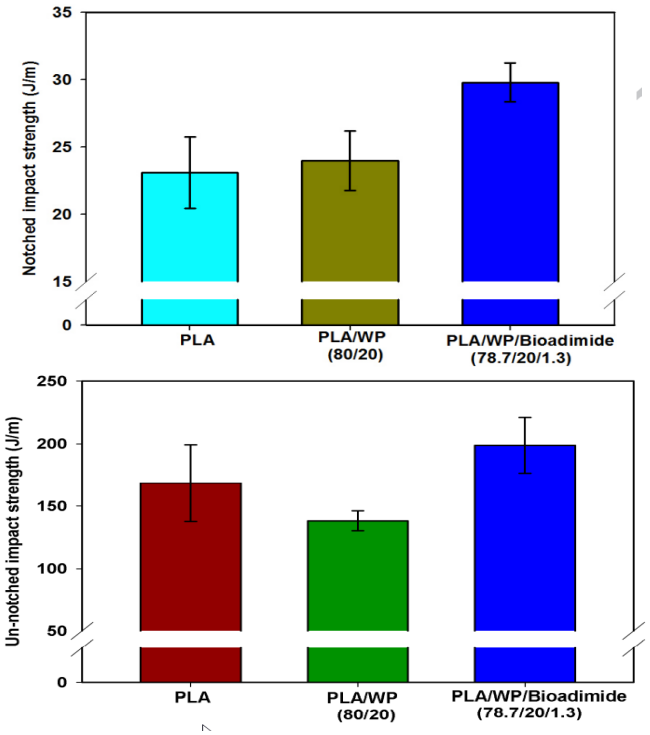



Fig. 5 – Impact resistance of PLA: a) notched sample; b) notchless sample.

According to Fig. 5a, the impact resistance, when using notched sample of PLA biocomposites reinforced with wood fibers increases by adding 20% wood fibers to PLA sample. Impact resistance has been significantly improved due to the addition of bioadimides to the PLA/WP composition, which have improved adhesion between layers. Also, the addition of bioadimide to the PLA/WP bio-composite leads to a significant increase in impact resistance and in the case of uncreated sample (Fig. 5b), (Awal *et al*., 2015; Awal *et al*., 2010; Graupner *et al*., 2008; Graupner *et al*., 2009; Graupner *et al*., 2011).

## 5. Conclusions

Invented in the late 1980s, 3D printing technology began to be widely used in various fields, such as medicine, fashion, robotics, automation, automotive, etc., due to the many advantages it has, among which, to mention, it would be possible to obtain complex sample using a wide range of plastics or biomaterials. In the case of PLA reinforcement with wood fiber, the material does not develop high cohesion with strong interstrated interactions, as shown by the transverse tensile properties of the printed samples.

In the paper, the research took into account parts obtained by 3D printing (longitudinal and transverse) from PLA reinforced with wood fibers of 100% width, 200% and 300% compared to parts obtained by pressing. Also, the reinforced pieces of PLA with wood fibers and a bio-additive were analyzed. The tensile behavior of printed and compressed samples in the longitudinal direction (to 0º) is almost similar while at transverse printing (90º) there are no significant differences in this elastic behavior. However, there is a significant decrease in tensile strength in transverse to longitudinal printing. Then, the variation of the width of the printed sample induces a major change of the mechanical behavior in the sense that in the parts printed at 0º it presents a more ductile behavior with its increase. Compared to compressed samples with the same printing direction (0° and 90°), the tensile strength is significantly reduced (30% and 50%) for 100% and 300% printed biocomposites, while Young's module decreases by 50% and 65%, due to the fact that a high porosity favors the damage of the parts.

The adhesion between fibers and matrices can be improved using a bioadimide, and the addition of only 1.3% bio-additive has led to an increase in tensile strength due to improved adhesion between wood fibers. There was an increase in Young's module, so a slight increase in the rigidity of the parts. Impact resistance, when using notched sample, is greater than that of impact resistance when using notched sample, because the un notched test piece can absorb more energy or have a higher resistance under load.

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# INFLUENȚA PARAMETRILOR DE PRINTARE 3D ASUPRA PROPRIETĂȚILOR MECANICE A PLA – A REVIEW

(Rezumat)

Datorită multiplelor avantaje pe care le prezintă printarea 3D, aceasta este utilizată în foarte multe domenii industriale, de la robotică la industria alimentară, de la industria auto la cea aerospațială.

Rezultatele din lucrare se referă la piese obținute prin printare 3D (longitudinal și transversal) din PLA ranforsate cu fibre de lemn de lățimi 100%, 200% și 300% comparativ cu piesele obținute prin presare. Au fost studiate și comportamentul pieselor ranforsate din PLA cu fibre de lemn și un bio-aditiv. Nu s-au înregistrat diferențe notabile din punct de vedere a rezistenței la tracțiune la printarea pe direcție transversală față de piesele obținute prin presare, iar în situația printării longitudinale comportamentul este asemănător. În schimb, există o scădere semnificativă a rezistenței la tracțiuni la printarea transversală față de cea longitudinală. Variația lățimii reperului printat influențează comportamentul mecanic în sensul că la piesele printate la $0^{o}$ a fost înregistrat un comportament mai ductil odată cu creșterea acesteia. Aderența dintre fibrele de lemn și matrice poate fi îmbunătățită folosind o bioadimidă, iar adăugarea a numai 1.3% de bio-aditiv a condus la o creștere a rezistenței la tracțiune datorită îmbunătățirii aderenței dintre fibrele de lemn. De asemenea, a fost înregistrată o creștere ușoară a rigidității pieselor datorită creșterii modulului lui Young. Rezistența la impact a fost mult mai mare în cazul epruvetelor fără crestătură deoarece, cum este și firesc, acestea pot absorbi mai multă energie comparativ cu epruvetele cu crestătură.