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Printing angles of polylactic acid and carbon particles/polylactic acid composite and their effect on impact strength of 3D printers

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ABSTRACT

This work is focusing on fused deposition modelling (FDM) 3D printing; this process principle is making the sample by adding melted materials for each layer. Therefore, this process has several advantages that can solve many manufacturing problems by the control of remodelling the output sample by setting the printing parameters such as printing temperature, speed, infill percentage and layer height. Finding the suitable setting parameters for the output sample can be a great challenge for the user, which can affect the mechanical characteristics of the produced printed sample. This paper examines the impacts of the printing angles and orientation on the mechanical characteristics of the acid of polylactic (PLA) and the particles of carbon in the output sample. To calculate this influence, a 3D printed sample for tensile strength and charpy was made at 0°, -45°, /+45º, 60° and 90º. The orientation was different but, the other of the factors hold constant such as infill density and layer height. Four different results were analysed for the impact resistance of these tests. The maximum impact resistance, 23.3 kJ, was obtained with 100% infill density and 0.1 mm layer height at 45º orientation. Results showed that printing angles (0°,-45/+45º, 60°) with 100% infill density is recommended. Furthermore, by making the comparison between the analysis finding with the finding of other studies, the printer parameters and materials were found to impact the mechanical characteristics of PLA sections significantly.

KEYWORDS

3-D printing, polylactic acid (PLA), CP/PLA composite, printing angles, impact strength.

INTRODUCTION

Three-dimensional (3D) printing seems to be a technique of produce rigid 3D objects from digitally data stored, often recognized as the technique of additive manufacture (AM). Every object in this process is produced by laying down sequential material layers till the entire item is made. A 3D printer's working theory begins with the rendering of an item to be printed using pc-aided design (CAD), including a 3D modeling program to create a new item, or a 3D scanner to create digital copy of a created 3D item [1]. 3D objects can be printed in various ways. The deposition of fused, also known as fused filament manufacture, is one of the most widely used 3D approaches in the industry. The main advantages of fused deposition modelling (FDM) are low cost of maintaining, easy-to-change materials, diversity, quickly thin parts manufacture, overall tolerance = ±0.01 cm, the size of compact, low process temperature, unrequired supervision and absence of toxic materials. This manufacturing process based on adding multiple layers by extruding and a placing of melting material, usually ABS or polylactic acid (PLA) plastics. A filament is structured by the printing material which was produced a high heated nozzle. Finally, a platform will receive the melted and laid out filament. All at once, a rectilinear movement on the platform was produced by the nozzle to form the final shape of a sample layer by layer [9].

All of these methods, nevertheless, were added, and that the only variant is how the layers are intended to generate the final item. The advancement of AM for quickly prototyping includes a percentage of basic technologies [2–6]. In recent years, There was widespread application of an open source (OS) platform, RepRap. The RepRap could be designed for less than $1000 (Prusa versions could now be produced for approximately $500), increasing the possible user base of rapid prototypers considerably. The RepRap is invented by Adrian Bowyer and has been largely supported and inspired by various contributors thru the online wiki, that offers extensive assembly instructions for multiple 3D printer variants [7,11]. The model of OS is enabled quickly technological advancement with quick improvement of the printers [12]. The models of OS, even so, have restrictions as comparison with commercial methods [13–15]. They are capable of producing extremely accurate productions with a 0.1 mm reliability in positioning [7]. The FDM process enables controlling of mechanical characteristics by calibrating the printing parameters, such as shell number, distance between nozzle and platform, layer thickness and direction.

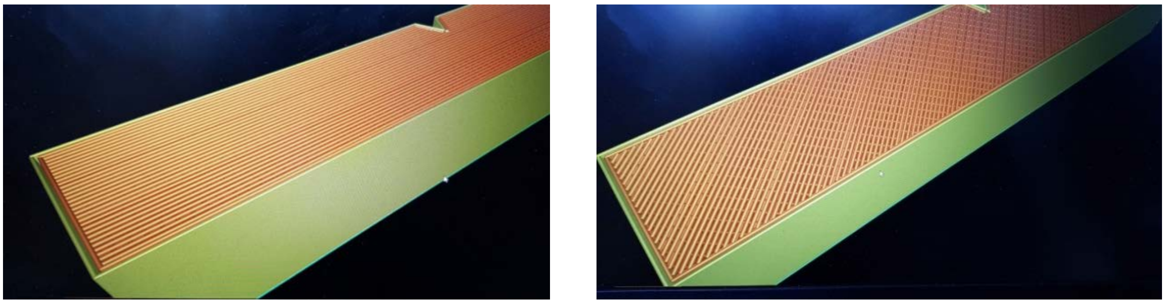
Many previous papers examined the printing parameters such as superficial roughness, where this process contains the material's melting solidification that produces the stresses of the residual. This was caused by the temperature difference and contraction created throughout the Kantaros and Karalekas (2013) process [16] after analyzing the impact of layer's thickness and orientation on the remaining strain, he determined that this was minimal if the longitudinal orientation was (0º) and the thickness of layer was 0.025 cm [17]. Additionally, it was noticed that FDM method produced samples had emptiness percentage, i.e. micro voids of the sample structure was not filled with extruded material. That can be due to the changes in the process that happened suddenly that majorly found in the areas near the surface. Additionally, (Rodríguez 2003) [18] focused on adhesion resistance process of the filament when it is smaller the nominal ABS resistance; hence, the produced sample's mechanical characteristics are estimated to be various from the nominal PLA material. To resolve this issue recent work (Nikzad 2011) [19] had successfully point out the development of new printing materials by the mixture of PLA with Fe and Cu small particles, which can modify the mechanical characteristics of the produced parts.

In addition to that, there been some developments in carbon fibre-reinforced plastic to improve its mechanical characteristics (Ning 2015) [20]. 3D printing materials have a great using history, going back to the early years of the revolution of technological [16]. PLA seems to be a consumable material which is utilized lightly [17]. Natural polylactic acid blended with particles of carbon is called composite PLA. This research focuses on the mechanical characteristics and 3D-printing materials porosity, utilizing composite PLA and PLA. The filament orientation was investigated throughout the process of printing (Ziemian and Sharma, 2012) [21]. To evaluate the strengths impact and the tensile four different orientations (0, 45, 60 and 90)º were tested. One of the main disadvantages of this method is that the stiffness and strength for the components of FDM is smaller comparison with those shown by a continuous sample produced of the same material produced by traditional manufacturing, including injection molding (Lee et al. 2007) [22]. The influence of processing parameters on mechanical characteristics must be evaluated. Therefore, tensile tests are performed on printed parts.

METHODOLOGY

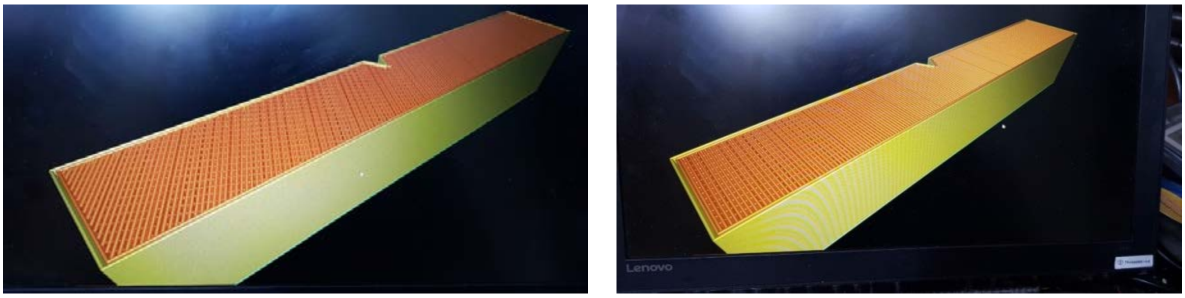
To identify the mechanical characteristics of 3D-printing materials, PLA Carbon/PLA composite consisting of natural PLA blended with carbon particles with a 35:65 ratio was used. Given the variability of these characteristics if using various parameters for slicing and printing, this study searching at the association between fill ratio and height of layer to strength of impact. The TEVO-type 3D printer was used to print the impact specimen analysed in this study, as shown in Figure 1. The specimens were modelled with SolidWorks CAD Software (Solidworks 2016, Dassault Systemes, Waltham, MA USA). The geometry of the specimens was defined by ASTM E2298 (ASTM E2298 - Standard Test Method for Instrumented Impact. Testing of Metallic Materials [2015]) [23] for determining the Izod Pendulum Impact testing of the subject material through a quick blow by a swinging pendulum.

This impact testing measures the energy absorption of the material, which is an indicator of material toughness [25]. Specimens conforming to ASTM E2298 contain a V-shaped notch, which provides a stress concentrator on the material. The notch tests the resistance of the material through crack propagation. The model of CAD was distributed as a standard tessellation language file (STL) and uploaded into G-code language, which is proprietary slicer software. A different software, such as Slic3r or Cura, has been utilized for STL files slicing into machine-readable G-code, as shown in Figure 1. Although all specimens were printed from the same STL file, they were sliced and printed with different settings, such as extruder temperature, where all specimens of the natural PLA and carbon particle (CP)/PLA composite were printed at 200 ºC. Figure 2 shows the samples after printing at different angles.



Sample before printing at 0° angle

Sample before printing at 45° angle



Sample before printing at 60° angle

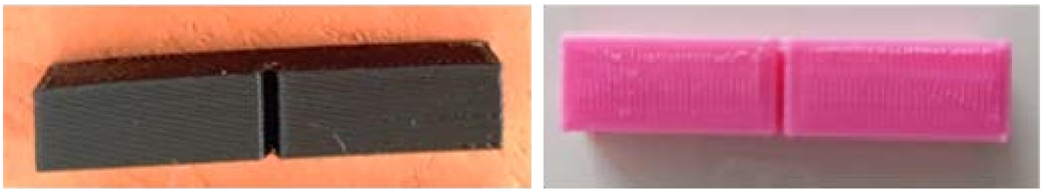
Sample before printing at 90° angle

Figure 1. Samples before printing at different angles

CPs were chosen because parts with CP can take advantage of the characteristics of CP composites. However, these parts sometimes experience impact loading, thus making this information extremely valuable. Nevertheless, CPs were reported as the weakest of the fibre reinforcements for impact resistance [26].

PLA at 0°

CP /PLA composite at 45°



CP/PLA composite at 60°

CP/PLA composite at 90°

Figure 2. Samples after printing at different angles

A study conducted by Roberson et al. [27] examined the effects of 3D-printed impact specimens, which had V-notches either printed with the part or added by a machine after printing. The study also determined the effects of printing the specimens in different parameters on the build plate. In the case of PLA, different print angles made a significant difference in the impact resistance, while printed versus milled V-notch specimens showed statistically insignificant differences in impact resistance. Further studies were performed to analyse the impact resistance of various materials that were 3D printed using FDM printing methods [25]. These studies all concluded that the orientation of a specimen during printing was an important factor due to the inherent anisotropic nature of FDM-printed specimens.

The anisotropy of FDM parts may be due to polymer molecules aligning themselves with the direction of flow while being extruded in the FDM process [28]. Another source of anisotropy may be due to the formation of pores within the print and the weak interlayer bonding of the material [29]. Composite materials suffer a serious limitation due to the negative effects of localised impact loadings [30]. Failure modes due to impact loading include splitting delamination, intralaminar matrix cracking, longitudinal matrix splitting, fibre/matrix debonding, fibre pull-out and fibre fracture [31]. Interlaminar shear deformations and flexure are the major absorbing energy mechanisms in composite materials that are subject to impact loading [32]. CPs are commonly used as a mechanical reinforcement of materials in composite industrial because of their low density, great specific modulus, stiffness, and strength [33]. The strength characteristics of carbon fibre composites largely rely on mechanical characteristics. The effect of material characteristics is their ability to absorb and distribute energies utilized to calculate a material's strength under shock or impact loading. Expressing impact strength (J / m2) is determined with the absorbed energy by the test of impact separating thru the fracture cross-sectional area [24]:

$$\text{Impact strength (Gc)} = \frac{\text{Uc}}{\text{Ac}} \tag{1}$$

where Gc is the impact strength of the material (J/m^2), Uc is the energy of impact (J), and Ac is the cross-sectional area of the sample (m^2). PLA filaments and CP/PLA composite were used to build the samples. The degree of extrusion temperatures, extrusion speed and height of layer are fixed, as shown in Table 1. Throughout the experiment, these parameters were constant samples with print angles (0º, 45º, 60º and 90º) built by 3D printing the PLA and CP/PLA composite, which were tested for impact strengths. The samples were loaded until they broke. A total of 24 samples of each PLA neat and CP/PLA composite were printed in the same printing parameters: 100% infill density, 0.1 mm height of layer and 50 mm/s printing speed).

Table 1. Constant parameters

Fixed Parameters	TEVO Printer
Print Density	100%
Shell Option	Bottom and Top three Layers
Perimeter/Outer Wall	3
Support Material	Yes
Layer height	0.1 mm
Print Pattern	Rectilinear

The other parameters that were changed during printing were the different printing angles and materials, as shown in Table 2. The effects of these parameters on impact testing were examined. The layer thickness is known as the height of the deposited slide from the nozzle. The parameter of layer thickness was used to study the effect of building thicker or thinner layers on the quality of the results, [4] showing that a 0.1-mm height of layer was the ideal height of layer that could affect strength. Moreover, 12 samples for each material, PLA neat and CP/PLA composite were printed under the same conditions as 100% infill density and 50 mm/s printing speed. All samples were printed at different printing angles as 0/90º, -45/+45º and 60º part orientation. According to ISO 180 standard, the impact test was performed.

Table 2. Variable parameters

Parameters	TEVO Printer
Printing angle	0º, 45º, 60º and 90º
Filament material	PLA and CP/PLA composite

RESULTS AND DISCUSSION

All the 12 samples of natural PLA and 12 samples of CP/PLA composite were fabricated utilizing a 3D machine. Then, an impact test was carried out. The average values of impact strength were obtained using Equation (1) at different values of printing angles and at constant height of layer and infill density. Depending on the tabulated findings in Table 3, the natural PLA sample with the greatest impact strength had the parameters of 23.3 kJ/m^2 at 45º orientation with 0.1 mm height of layer and 100% infill density. The sample of the lowest impact strength had the parameters of 10 kJ/m^2 at 90º orientation. The values of impact strength at 0º and 60º orientation were close to the value of the impact strength at 45º orientation, which were 18.7 kJ/m^2 and 19 kJ/m^2, respectively. Table 3 shows the impact of strength at different printing angles. The calculated values at 0º, 45º and 60º could lead to high impact strength. At 0º, 45º and 60º degree angles, the rectangular filaments were directed to the loading direction, as shown in Figure 1.

The specimens were exposed to pressure throughout impact tests to align with the axial direction due to the current building additive, that could cause single layers to slide along till specimen finally breaks. The direction of the force from the hammer of the impact test device on the filaments was perpendicular to the filament direction of the samples that were printed at 0º, 45º and 60º orientation. The force from the hammer was parallel to the filament direction of the samples that were printed at 90º orientation. The lowest impact strength was 10 kJ/m^2, as recorded in Table 3. This value was due to the direction of the printing filaments along with the direction of the notch of the impact samples, as shown in Figure 2. The samples printed at 90º orientations could not absorb the energy and the force applied. Therefore, the samples were easy to break, as seen in the samples that were printed at 90º orientations (Figure 3). The results of the average values of impact strength are clearly shown in Chart 1.

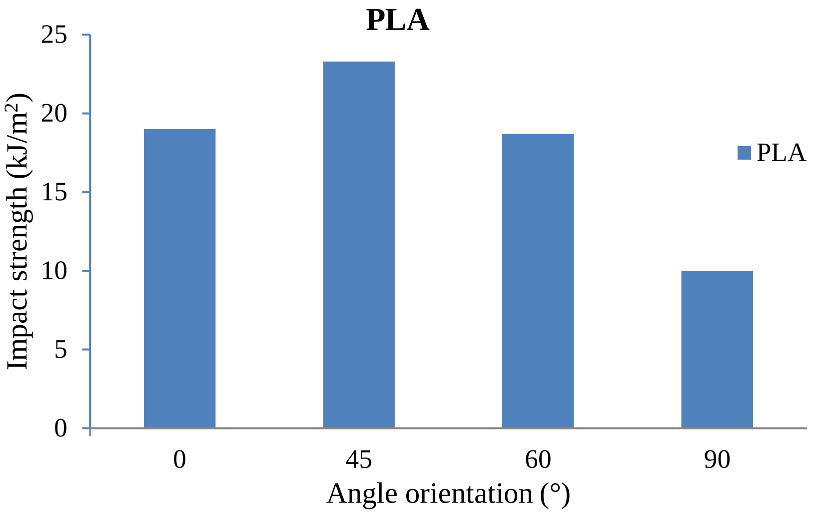
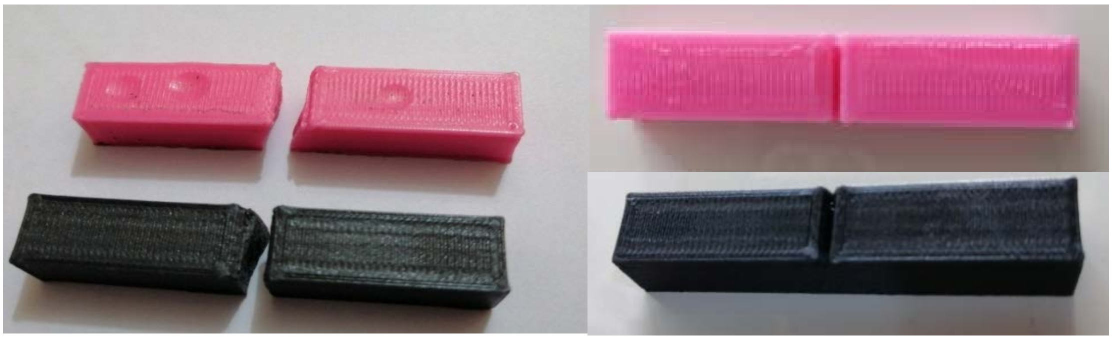


Chart 1. Show the relationship between the angles orientation and impact strength of PLA


Samples after breakage of PLA and CP/PLA composite at 90°

Samples before breakage of PLA and CP/PLA composite at 90°

Figure 3. Samples before and after breakage of PLA and CP/PLA composite at 90º

Table 3. Average impact strength of natural PLA material and average impact strength of CP/PLA composite

No. of samples	Printing angles (º)	Average impact strength of PLA (kJ/m^2)	Average impact strength of CP/PLA composite (kJ/m^2)
3 samples	0º	19	14.5
3 samples	45º	23.3	14.16
3 samples	60º	18.7	14
3 samples	90º	10	9.3

At 0º, the oriented parts also recorded the highest impact strength given that the test force was applied along the filament direction. In contrast, the specimen that showed the smallest resistance was the 90º filament orientation. Tymrak (2014) [34] characterised the mechanical characteristics of test specimens that were printed with PLA, taking into account the filament orientation values. The rest of the parameters had constant values and filling. The results showed that the 0º, 45º and 60º orientation at 100% infill density and 0.1 mm layer thickness values yielded the best results from the impact strength test. Other researchers recorded greater tensile strength at 0º, 45º and 90º orientation [35]. Furthermore, the CP/PLA printed samples with 0.01 cm thickness of layer and 0º, 45º, 60º and 90º orientations were 14.5 kJ, 14.16 kJ, 14 kJ and 9.3 kJ, respectively. Table 3 shows that the highest impact strength during the tests were at 0º, 45º and 60º orientation. The impact strength values of PLA decreased when CPs were added given the fragile characteristics of CPs [26]. The results of the average values of the impact strength of PLA composites are clearly shown in Chart 2.

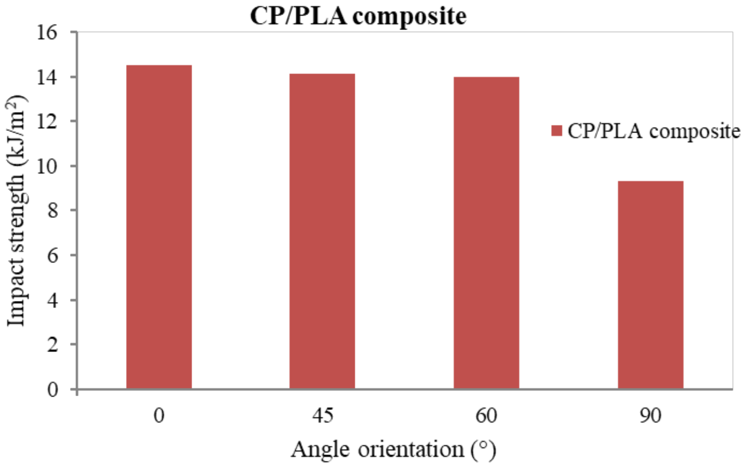


Chart 2. Show the relationship between the angle's orientation and impact strength of PLA/CP composite

Depending on the angle of the filaments relative to the direction of the force applied, the distribution of stress in the filaments varies according to the raster angle. The raster angle at 0º, 45º and 60º orientation could provide a stiff structure, which might explain that the best results for impact were observed for the 0º, 45º and 60º raster angles. The stiffness refers to geometric stiffness and not material stiffness. Given that the raster angle is a geometric parameter, the facts presented may still be valid. The lower layer thickness at 0.1 mm had better adhesion between layers, thus showing that the best results of the impact were observed in the lower layer thickness at 0.1 mm.

CONCLUSION

This work focuses on the parameters that affect the FDM process on the characteristics of the printed sections, particularly the impact strength. The raster angle or orientation is one of the parameters that directly affect the characteristics of the printed parts. The standard sample experiments of PLA and the CP/PLA composite have been conducted on 3D printing machines under standard environment and specification. Depending on the raster angle of the filaments relative to the direction of the force applied, the distribution of stress in the filaments varies. Therefore, the best results for the impact were observed at 0º, 45º and 60º raster angles. The stiffness refers to geometric stiffness and not material stiffness. Given that the factors were analysed individually, their behaviour when combined with one another could be observed. Some combinations analysed were Infill Density*Extrusion Temperature and Infill Density*Raster Angle. In the ANOVA, the second factor was analysed as a function of the first. In other words, we saw how the response changed when the first factor was constant and the second factor was altered. The investigation showed that the smallest thickness of layer had the highest impact strength. Meanwhile, high infill density produced great impact strength. These parameters were fixed, and the printing angles were changed to identify the effect of new factors on the characteristics of the printed sections.

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