Compressive test Fractured Surface analysis on PLA-Cu composite filament printed at different FDM conditions

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Abstract. Additive manufacturing technology has found its development in the various emerging engineering fields. Fused Deposition Modeling (FDM) had proven to be a suitable built-up technique for any complicated and instant shapes. Owing to the advantage of additive manufacturing and emerging industrial needs, the 3D composite filament has been used as a competitive material over the available materials. Commercially available Poly Lactic Acid (PLA), ABS filaments have been widely used in FDM. In the present work, copper particles of mesh size mesh 20-30 micrometers are taken as the reinforcement in the PLA matrix. After primary investigation, 12% of copper particles are found to be a suitable weight percentage in the PLA matrix. The suitable proportional mixture is ball milled for 2 hours, melted to 120°C, and then hot extruded to get a filament diameter of 1 mm. The newly fabricated 3D composite filament is printed at different FDM conditions for the compression test to the ASTM D695-15 standard. The printed samples are subjected to a compression test until failure. Failure mechanism happened on different condition printed samples are examined through scanning electron microscope (SEM) examination. The compression effect causes the squeezing and slippery action of copper particles inside the structure leads to having a displacement of particles.

Keywords: Fused deposition model; Composite Filament; Printing Parameters; Compressive Strength.

1. Introduction

FDM has been evolved to create prototypes along with functional parts with a complex shape in a short time. According to Dipen et al [1], FDM provides excellent controllability on device geometry with the specific power density and describes the performance of polymer composite part prepared by FDM and applications in engineering fields such as Peng et al [2], chemical storage systems. Jiang et al [3] prepared 3D printable graphene composite for thermal applications. Rafael et al [4] identified that the carbon fiber reinforced in PLA composite filament on FDM produced a uniform high oriented material deposition that had enhance the mechanical property to a greater extent. Valentina et al [5] stated that the demand for engineering materials in 3D printing technology gives raise to PLA composite filament with natural as reinforcement.
Saude et al [6] confirmed that the addition of reinforcement in acrylonitrile butadiene styrene found to have an improved hardness with reduction of ductility on copper as reinforcement. Miguel et al [7] confirmed that the orthotropic characteristics will be observed in additive manufacturing based FDM techniques was due to fused filament fabrication and this results in a change of mechanical behavior on the sample. Hence proper studies on the 3D printed samples are to be done before defining the applications.

Yung et al [8] prepared polyethylene samples for the compressive test according to ASTM695-15 and supported the use of these materials in biomedical applications. Sugiyama et al [9] used a 3D printer to produce sandwich structures in different geometrical shapes and conducted the flexural analysis and declared rhombus shape is stronger than other structures. Hyuk et al [10] suggested from compression test on PLA scaffolds fabricated from the melt-tube drawing method to better mechanical performance for biodegradable polymer applications. Venkatapavan et al [11] investigated the effect of infill density on mechanical properties 3D printed components and stated highest tensile strength is observed at single infill density and impact strength is proportional to infill density.

Zhaobing et al [12] reported that samples build with the orientation of +45°/−45° or raster angles had found to have the highest mechanical strength and young's modulus. According to Chacon et al [13], the ductility of the materials will decrease with the increase of layer height and feed rate. Lebedev et al [14] through the experimental study on 3D printed samples observed that deposition scheme alone will not determine the properties besides secondary operations like compression will also signify on the mechanical property. Shilpesh et al [15] experimental study on PLA samples fabricated through FDM by varying Printing conditions like raster width, layer height, and raster angle and stated these printing parameters have a significant influence on the mechanical properties.

2. Materials and method

Commercially available PLA pellets and copper powder are procured from Coimbatore metal and polymers supplier, Coimbatore, India. PLA pellets are grounded to a fine powder and 12% weight percentage of copper was blended for 24 hours. The powders are allowed into the Hopper where they are heated to 190 degrees Celsius and moved through screw conveyor. The filament of 1 mm is rejected through a special design die. The film is water cold and rolled on a circular disc and now the filament is ready for printing. Initial investigations like density, porosity, and melting of filament are conducted on the sample to evaluate is a property all the available filament.

A Manifester made 3D SLS printer that has the Printer Volume: 230 x 270 x 200mm, Minimum Tolerance: 1mm Typical Layer thickness: 0.25mm was used to print the sample at different parametric condition. The fabricated filament is printed to the ASTM D695-15 at different printing conditions. Three significant printing parameters such as nozzle temperature, bed temperature, and layer height are taken as the independent parameter. Each parameter has three levels of printing conditions. Considered printing parameters and it’s three levels as shown in Table 1.

| Exp. No. | Nozzle temperature (Deg) | Bed temperature (Deg) | Layer height (mm) |
|----------|--------------------------|-----------------------|-------------------|
| L1       | 190                      | 50                    | 0.10              |
| L2       | 190                      | 60                    | 0.14              |
| L3       | 190                      | 70                    | 0.18              |
| L4       | 210                      | 50                    | 0.14              |
| L5       | 210                      | 60                    | 0.18              |
| L6       | 210                      | 70                    | 0.10              |
The fabricated filament is printed according to the table shown and the compressive property of the fabricated filament is examined through universal tensile tester that has the maximum load of 5 tons and the load is applied at the gear rotational speed of 1.25mm/min. The universal tensile machine is manufactured by associated scientific engineers work, New Delhi that uses FIE software. The experimental setup, 3D printed component before and after testing as shown in Figure 1. The samples are built with a uniform shell thickness of 0.8mm with flat orientation and filled at the raster angle of 45°.

|    | L7  | L8  | L9  |
|----|-----|-----|-----|
|    | 230 | 230 | 230 |
|    | 50  | 60  | 70  |
|    | 0.18| 0.10| 0.14|

The observation on the compressive strength of different FDM printed samples are shown in Figure 2. The significance of the different printing parameter conditions shows considerable change in the compression strength property of the material. The temperature difference exhibits in the mixture predominantly determine the compressor strength of these samples. Changes in printing temperature cause a reduction of ductility. The cooling tendency of the reinforced copper particle significantly affects hello the bonding property with the PLA matrix. The presence of void regions and the bonding that exists between the PLA and copper particles determine the compressive strength.

Figure 1. Experimental arrangements and test samples

3. Results and discussion

3.1. Evaluation of Compressive Behavior

The observation on the compressive strength of different FDM printed samples are shown in Figure 2. The significance of the different printing parameter conditions shows considerable change in the compression strength property of the material. The temperature difference exhibits in the mixture predominantly determine the compressor strength of these samples. Changes in printing temperature cause a reduction of ductility. The cooling tendency of the reinforced copper particle significantly affects hello the bonding property with the PLA matrix. The presence of void regions and the bonding that exists between the PLA and copper particles determine the compressive strength.
4. Surface topography

4.1. Fracture analysis

Surface topography analysis is performed on high compressive load withstanding capacity samples and high-density sample. Figure 3(a-c) shows the different magnification images on the fracture surface of the L9 sample. At high compressive load condition, copper particles reinforced into the matrix tend to change its position, as it slides over the plane and creates wear marks. The wear track created by the movement of the copper particle as shown in Figure 3(a). The reinforcement of the copper acts as an assistant material and it helps in improving the load withstanding capacity. From Figure 3(a) a cleavage is observed where the complete shift of particles has taken place due to the applications of the load. On closer magnification on the surface, it is clear to state that the copper particles are submerged or covered by the PLA elements. As load increases, the sliding of PLA progresses and the load is slowly transformed to the copper particles and it is shown in Figure 3(b). Solid-body, copper particle resist the load, as the load increases the threshold value, the slippery of copper particle takes place along with the PLA particles. The slippery of the plane takes place along the whole boundary of the sample. In all the experimental conditions irrespective of printed condition, the sleep reaction takes place with an angle of 30 to 45 degrees. The failure observed under compressive test looks similar to shear failure, as one plane slides over the other plane over into the application of load.

Closer examination on the fractured surface clearly shows the void region formed at the time of printing the sample at L9 condition. The squeezing of copper particles is clearly visible in Figure 3(c). As the copper particle slides over the PLA elements and it has been pullout and this action creates a small peak at the ejection point of the copper particle. Small copper particles are been easily pulled away whereas the large particles resist the load and it creates an impression before being pulled out from the surface.
Figure 3. Typical SEM images on the fractured surface

Figure 3(d-f) shows the fracture surface of the high-density composite that was printed at the L6 condition. The bulk deformation of materials removed in an irregular way that can be witnessed in Figure 3(d). With the increase of load condition the week bonded (void) surfaces tend to slip over the other plane and it causes the bulk removal of material. The copper particles are stick over the peeled off region resembles a ductile type of failure mode. On closer examination of the peak, the region shows the wear mark of copper particles also crushing and squeezing of PLA elements that raised to have a sharp peak like arrangements after deformation. Further higher magnification studies on high-density samples show the bulk removal of material that creates a cleavage type of structure on the
fractured surface. Squeezed and crushed copper particles are presented in Figure 3(f). The presence of excess number small size copper particles in the surface shows the effect of the void region as compared to Figure 3(c). An increase in the void allows the slipping of the planes as small copper particles cannot able to stand the applied load contents to move or slip along with the plane. Whereas the presence of small size copper particles fails to withstand high load capacity however the compressive load of L9 is quite higher because of an increase in the brittle property which was greatly influenced by the nozzle and bed temperature on PLA on elements.

4.2. 3D optical study

To understand the fracture mechanics that happened at different printing conditions on PLA-Cu composite filament are studied using 3D optical microscopy analysis. Typical cases such as L1, L5 and L9 taken into consideration, the fracture surface is being captured and it is shown in Figure 4. Based on the density of the sample the following 3 experimental cases are taken into study. Figure 4(a) represents an L5, low-density sample. The presence of excess void regions progress to have low density. When the load applied to the samples, PLA-Cu elements are squeezed to occupy the void region leaving behind some high peaks. The rate of deformation is quite high and progress to material failure with the propagation of large cracks with the less compressive load. Red and blue color over the surface represents the peak and the valley regions, respectively.
Figure 4. Typical 3D optical images on the fractured surface

Figure 4(b) represents the L1 printing condition. Density obtained of this sample is recorded to be high than the other experimental conditions. The applied load is uniformly distributed the materials present in the sample were squeezed and it reduces the height of the sample and leads to buckling or bending effect. This can be insured with the least displacement record observed on the load-displacement curve. As load exceeds the threshold limit, the irregular deformation happens with course surface failure and can be validated from Figure 4(b).

Figure 4(c), represents the L9 experimental condition. Excellent bonding has occurred at this operating condition which can be validated from the image. As the application of load, the samples have undergone severe defects with the displacement of particles. As the week bonding region that is PLA rich zone squeezes and transform the load to the nearby particle. With the increase in load, the copper particle reinforced tends to slide within the boundary and cause the reduction of length of the sample. The uniform distribution of load has been witnessed from the peaks. The peaks formed has its own direction denotes that the material has withstood the excess amount of load. The particles present in the sample slides uniformly and form a peak and then undergoes the failure. Most of the regions are appear to be smooth hence the material that undergoes this kind of failure is many suitable materials for medical applications.

In 3D optical microscopic image, some of the surface profile parameters such as Sa, Sp, Sv, Sz, SSk, Sku are being analyzed. Sa represents the surface profile roughness. In all three cases, Sa observation is found to be in the range of 16 to 17 µm. Here, the peaks and the valley regions are to be analyzed because the constitution of both peak and the valley region provides the surface roughness of the measured surface. Considering the above, Figure 4(c) shows huge variations between the peak and the valley observations. This is because of the squeezing effect caused due to the application of the compressive load. This can be validated from Ssk Skewness observation as in Figure 4(a&b), the Ssk observation is almost equal to zero represents the even height of peaks and pits, whereas in Figures 4(c).Ssk observation is quite high here the height distribution is skewed below the mean plane. From the Sku observations, it can be concluded that all three conditions fall less than three means that the fractured surface is free from sharp peaks.

5. Conclusion

The 3D composite filament with 12 percentage of copper reinforcement in the PLA matrix is successfully prepared through a hot extrusion process with a diameter of 1 mm. Composite is printed with the varied FDM conditions and tested for compression strength. Based on the fractured surface examination conducted through SEM and 3D optical microscope examinations are as follows:

- Squeezing of copper particles owing to the application of load creates bulk removal of material for high-density samples and cleavage surface on the low-density samples.
• High-density samples resist the load in all directions and progress to peak formation with the least significant effect on surface profile roughness.

6. References

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