CHARACTERIZATION OF MATERIALS FOR CUSTOMIZED AFO USING ADDITIVE MANUFACTURING

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Abstract

Neurodegenerative conditions and compressed nerves often cause an abnormal foot drop that affects an individual gait and make it difficult to walk normally. Ankle Foot Orthosis (AFO) is the medical device which is recommended for the patients to improve the walking ability and decrease the risk of falls. Custom AFOs provide better fit, comfort and performance than pre-manufactured ones. The technique of 3D-printing is suitable for making custom AFOs. Fused deposition modelling (FDM) is a 3D-printing method for custom AFO applications with the desired resistance and material deposition rate. Generally, FDM is a thermal process; therefore materials thermal behaviour plays an important role in optimizing the performance of the printed parts. The objective of this study is to evaluate the thermal behaviour of PLA, ABS, nylon and WF-PLA filaments before manufacturing the AFO components using the FDM method. In the study, the sequence of testing materials provides a basic measuring method to investigate AFO device parts thermal stability. Thermal analysis (TG/DTG and DSC) was carried out before 3D printing is to characterize the thermal stability of each material.

Keywords: Additive Manufacturing, Ankle Foot Orthosis (AFO), Fused Deposition Modelling, Thermal Analysis

I. Introduction

Neurodegenerative conditions and compressed nerves are a few undesirable effects in patients. This condition often causes the foot drop which affects an individual gait abnormality and causes difficulty in normal walking and increases the risk of falls incidence [I] [II]. Ankle Foot Orthosis (AFO) is the medical device which is recommended for the patients to improve the walking ability and decrease the risk of falls. The device also strengthens the lower limb with weight-bearing capacity and stabilizes the redundant abnormal motion of the foot during all phases of walking [III]. Current techniques in the manufacture of custom AFO involves several steps: i)
ankle and foot measurement, ii) development of a successful design based on negative perception of plaster, iii) adjustment of the successful plaster design to accommodate the patient's physiology, and iv) AFO vacuum thermoforming and patient fitting [IV]. Four major challenges pose this common way of producing AFO using conventional manufacturing methods: i) labour intense and lengthy processing time, ii) material selection is minimal iii) limited flexibility in design, and iv) constraint on the capacity of the technician to accomplish quality consistency [V]. Additive manufacturing (AM) offers several advantages compared to conventional manufacturing technologies, particularly where customization on a large scale is required [VII]. This is especially common in certain medical applications, such as orthopaedics, where the effectiveness of a procedure is strongly linked to the anatomical structure of each patient [VIII]. Parts with intricate geometries that are complicated and sometimes impossible to generated using traditional subtractive methods can be very easily produced with AM. By forming consecutive cross-sectional layers of an element, AM processes produce components. The procedure starts with a solid 3D model, originally designed as a virtual CAD document and subsequently separated by a dedicated slicing program across thousands of layers. Every surface is created to form a printed primitive by the successive deposition of material [IX]. AM process has many potential benefits along with desired strength, stiffness, weight optimisation to improve biomechanical function, comfort and material deposition rate other than pre-fabricated ones [V]. Fig. 1 gives some examples of various types of AFOs using AM process. This research is focused on the processing PLA, ABS, nylon and wood floor based PLA composite polymers and then assessment of their thermal stability with an FDM procedure while 3D printing. FDM is among the AM procedures more successful and effective because of its capacity to construct models of intricate and complex designs with just a reasonable amount of time [X]. The schematic process of the FDM is as shown in Fig. 2. Because of its ability to build the AFO between less expense, time and material waste in the AM process it is emerging as one of the major technology. FDM is naturally a thermal process, so that investigation of thermal behaviour and thermal evolution of the materials using in the FDM process is necessary. This may reduce the defects in the parts related to thermal properties of the accumulated layers and thereby enhance the mechanical properties as well as to surface quality of the manufactured parts [XI].

Fig. 1: Various types of AM produced AFOs [VI].

Fig. 2: Schematic process of the FDM.
A summary of various AFOs design and manufactured with the FDM method as follows. For more details, a systematic review of designing and manufacturing of 3D printed AFOs is available in Wojciechowski et al 2019. In 2012, Patar et al developed safe and low-cost dynamic ankle-foot orthosis for therapeutic treatments by contributing maximum performance using the FDM process.

In 2016, M. Walbran et al., using the FDM process, developed a 3D printed AFO consisting of calf and foot parts with an interchangeable central carbon fibre spring. The results of the study illustrated that the device could be stronger, more comfortable and flexible in various activities with adaptively restrains ankle movement. In another study 2017, N. Wierzbicka and colleagues have designed and produced a lower weight and solid ankle joint orthosis. Study results demonstrated that the device could fit the patient and wear with regular shoes.

In 2019, Alberto et al designing a fully customized 3D-printed AFO have been defined. The study outcomes revealed that the system has a strong geometric relationship between the AFO and the patient's foot with considerable comfort and enhances clinical usability.

The intention to carry out this research is to assess the thermal properties of pre-layer deposition of (3D printed) Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), nylon and wood floor based PLA composite (WF-PLA) polymer materials that are using in FDM-based AM processes. Further, the materials have been characterized by thermal analysis (TG/DTG and DSC). The study begins with the evaluation for every polymeric material as well as its major thermal properties measurements.

II. Materials and Experimental Methods

Four filament materials such as PLA, ABS, Nylon, and wood have a 1.75 mm diameter were selected for the testing. All were purchased from the CubePro®, 3D systems, USA.
Tensile tests were performed on filaments of the four raw materials to evaluate the main mechanical properties such as tensile strength, elongation at yield and modulus of elasticity. In this study, we choose to quantify the properties directly on filaments by conducting tensile tests as they will be the starting material for the FDM process. The filaments are supplied in coils as solid wires with a diameter of 1.75 mm and the studies were conducted directly while applying tensile forces to the filament lengths as per the ASTM standard dimensions using adaptable bench tensometer (KPIL-PC 2000) as shown in Fig.3. Each filament sample was uniaxially loaded up to the breakpoint by steadily increasing the tensile load. The load was gradually applied from 0 N to 50 N. The head travel velocity was set to 5 mm/min for certain materials.

Use of a thermogravimetric analyzer was to disclose any information about the thermal decomposition of the appropriate samples. TGA tests are conducted in a Simultaneous Thermal Analyzer (STA 7200), Hitachi HTG, Japanese equipment. The crucible alumina is taken as a test vessel based on the property of this experiment sample. First, a heating rate of 10°C/min between room temperature to 100°C was developed then kept isothermal about 5 minutes to balance the sample until the run started. The research was conducted whereas the specimens were heated at 20°C/min, in both flowing nitrogen (50ml/min) and static air atmosphere from 25°C to 700°C. TA Instruments Universal Analysis 2000 software was used to evaluate the resulting TGA curves.

DSC experiments are conducted with a differential scanning calorimeter; DSC-7020 model (Hitachi HTG, Japan). Run the test with a 25°C to 300°C heating rate. The heating process allowed the collection of material properties information due to extrusion of filaments. By subtracting specimen signals and an empty crucible, the baseline was calculated. All measurements were performed with a heating speed of 10°C/min in non-isothermal mode uses nitrogen (50ml/min) for the purge gas. The material testing weight in a sealed aluminium container was around 5 mg. The DSC study results are used to measure the significant thermal characteristics like glass transition, crystallization and melting temperatures.
III. Results and Discussion

Tensile Properties of Filaments

Table 1 shows the mechanical properties such as tensile strength, elongation and modulus of elasticity for the samples. As can be seen the results PLA is more rigid and has a high tensile strength whereas ABS and Nylon have more ductile in nature.

Table 1: Mechanical tensile properties of the filaments

| Material | Colour | Tensile strength (MPa) | Elongation at yield (%) | Modulus of Elasticity (GPa) |
|----------|--------|------------------------|-------------------------|-----------------------------|
| PLA      | White  | 49                     | 5                       | 3.4                         |
| ABS      | Blue   | 43.4                   | 18                      | 2.2                         |
| Nylon    | White  | 38.2                   | 42                      | 2.9                         |
| Wood     | -      | -                      | -                       | -                           |

TG/DTG analysis

The thermal behaviours of PLA, ABS, nylon, and WF-PLA filaments collected using a thermo-balance under static air atmosphere, reported in Fig. 4.

Fig. 4: TG curves of weight loss percentages corresponding samples for (a) PLA (b) ABS (c) Nylon (d) WF-PLA at 20°C/min, under the static air atmosphere.

The degradation rate of the filaments tested generally involved changes in the polymer's molecular weight, and usual changes in properties include decreased ductility and embrittlement, crystallinity, a general decrease in certain other appropriate physical and chemical properties [XVI]. The analysis of TG curves in Fig. 4 revealed a single-stage degradation process for all four samples. While the PLA and nylon were degraded at around 500°C, the ABS and WF-based PLA
samples showed a higher residual thermal decomposition rate of up to 700°C, which is consistent with research evidence that shows the full degradation of the pure PLA and nylon [XVII] [XVIII]. According to data indicated in Fig. 4 also reveal that the WF had little influence on PLA thermal stability. The PLA’s extrapolated initial thermal degradation temperature significantly decreased with the addition of WF, and the percentage of the WF based composite PLA material's final residual thermal decomposition increased.

This behaviour was quantitatively verified by measuring the temperatures at a mass loss of 10% ($T_{10\%}$), which is a measure of their thermal stability. $T_{10\%}$ values with the maximum decomposition rate and residual thermal decomposition percentages at 700°C were recorded in Table 2. The major reason for such a problem is whether the temperature for WF in thermal decomposition is much low and the residual thermal decomposition percentage is significantly greater than PLA sample [XIX]. Likewise, results indicate that ABS has a 3% residual thermal decomposition rate at 700°C, indicating lower thermal decomposition compared with PLA and nylon filaments.

Table 2: Temperature measurements at maximum decomposition, 10% weight loss and residue percentages at 700°C in static air atmosphere.

| Sample | Extrapolated initial point $T_d$(°C) | Maximum decomposition level point $T_{max}$(°C) | Extrapolated endpoint $T_f$(°C) | $T_{10\%}$(°C) | Residue (%) |
|--------|-------------------------------------|-----------------------------------------------|---------------------------------|----------------|-------------|
| PLA    | 320.6                               | 365.9                                         | 415.3                           | 350.2          | 0           |
| ABS    | 220.9                               | 443.7                                         | 488.7                           | 406.8          | 3.0         |
| Nylon  | 348.8                               | 471.6                                         | 494.9                           | 414.9          | 0           |
| Wood   | 237.9                               | 355.5                                         | 486.7                           | 329.7          | 8.9         |

Fig. 5: DTG curves of maximum decomposition rate corresponding samples for (a) PLA (b) ABS (c) Nylon (d) WF-PLA at 20°C/min, under the static air atmosphere.
DTG curves in Fig. 5 displays the peak decomposition rates of the examined samples, which have been occurred due to the thermal deprivation of their molecular chain. There is no further weight loss after 500°C; this stage mainly signifies the process of carbonization in the molecular chain [XX]. According to the data double peak was obtained during heating for the ABS material with $T_{\text{max}}$ at 443.79°C. The observed double peak is the result of the melting/recrystallization/re-melting caused by polymer filament extrusion and deposition, resulting in lamella thickening and/or the development of two unique crystal phases [XXI]. DTG peaks in the Fig.5 emphasize that thermal stability of both ABS and nylon is higher compared to PLA and WF-PLA materials. The changes in thermal stability can be observed due to their molecular characteristics, structure and composition.

**DSC analysis**

DSC measurements of filaments are performed and the glass transition temperature, crystallization temperature and also melting temperature values are presented in Table 3. According to data indicates in Fig. 6 displays DSC (µW) vs. temperature (°C) for filament materials of PLA, ABS, nylon, and WF-PLA. The results illustrate that $T_g$ of PLA filament and WF additive PLA filament was recorded with a small difference of 0.58°C and $T_c$ of PLA increased from 92.12°C to 96.09°C with the addition of WF.

**Table 3: Glass transition temperature ($T_g$), crystallization temperature ($T_c$) and melting temperature ($T_m$) of filaments from DSC analysis.**

| Sample | $T_g$ (°C) | $T_c$ (°C) | $T_m$ (°C) |
|--------|------------|------------|------------|
| PLA    | 62.39      | 92.12      | 167.49     |
| ABS    | 98.62      | -          | -          |
| Nylon  | -          | -          | 198.96     |
| Wood   | 62.97      | 96.09      | 149.9      |
The $T_g$ value relies on the molecular characteristics, structure and stability of the elements in the WF-PLA [XXII]. Moreover, due to better compatibility, the $T_g$ could be recognized to good interfacial adhesion among WF and PLA. The influence of WF in the PLA matrix interfered with the crystallization approach of the pure PLA and increased the temperature of $T_c$ from 92.12°C to 96.09°C. Lee et al. noticed that with the adding up of WF, the crystallization enthalpy, as well as the crystallinity of PLA, could be varied. This could be primarily caused due to inhibition impact of WF on the formation of PLA crystals [XIX]. The data in Fig. 6 reveals that the $T_m$ of PLA with WF was lower than that of pure PLA from 167.49°C to 149.9°C. The lowering $T_m$ is recognized to the significant decrease of PLA material in WF based composite PLA. On the other hand, the $T_g$ of the ABS sample was 98.62°C and due to amorphous, it has no true melting point. The nylon material has high $T_m$ among all tested at 198.96°C was observed due to its high thermal stability.

IV. Conclusion

The study tested the mechanical properties and thermal stability of PLA, ABS, and nylon and WF-PLA filaments to create customized AFO before printing with AM technology. Further, it is proved that the deep understanding of the thermal properties of the material has made it possible to enhance the printing capabilities and product quality. The extrapolated initial thermal degradation temperatures of the ABS and WF-PLA filaments were low, and the final residual thermal decomposition percentages of those filaments high compared to PLA and nylon, as indicated by the TG/DTG analysis. The DSC analysis showed that the process parameters such as built bed temperature and nozzle extrusion temperatures were important because the thermal stability of material filaments was very sensitive. Besides, the DSC of the WF-PLA sample displayed an entirely altered calorimetric behaviour. There is a significant reduction in melting temperature and also an increase $T_c$, a contrast to the pure PLA sample which might be due to the influence of wood flour in the polymer composition. Further work to determine additional material characteristics such as...
viscosity, conductivity and also microstructure while mechanical testing of a main 3D printing component should be discussed.

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