The Effect of 3D Printing Temperature on the Mechanical Properties of Polypropylene

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Abstract

3D printing is a revolutionary approach to how products are designed, manufactured and brought to the market since it allows the manufacturers to fabricate without limitations and cut operating costs. Polypropylene is a thermoplastic polymer that is commonly used in a wide range of products. Despite its various applications, polypropylene is challenging for use in 3D printing since it is hard to control the results of polypropylene prints due to the fact that it has the tendency to warp. The mechanical characteristics of polymers are highly sensitive to the rate of deformation, temperature, and chemical nature of the environment. Therefore, this paper seeks to observe how the nozzle temperature affects the mechanical properties of polypropylene prints. Confirming the diffusion coefficient of polypropylene and building a temperature profile would help to establish optimal conditions for 3D printing and to obtain enhanced polypropylene prints. 3D Printer Ultimaker Extended 2+ is the main instrument used to print test samples. Samples were printed in two different orientations, with filaments being perpendicular to the printing direction (vertical orientation) and filaments being parallel to printing direction (horizontal orientation), at three distinct temperatures 215 °C, 230 °C, and 245 °C. These samples were then characterized using Raman spectroscopy, Dynamic Mechanical Analysis (DMA), Instron Tensile Test, Optical Microscopy, Optical Coherence Tomography (OCT), Scanning Electron Microscopy (SEM), and Thermal Imaging. From the data analysis, it was determined that between the tested temperatures, higher nozzle temperatures enhanced the mechanical properties for side-by-side filaments of the samples. The conditions that yielded the best mechanical properties were at 245 °C. These findings provide an important insight in the additive manufacturing field and expand the understanding on the behavior of polypropylene in 3D printing.

Keywords: 3D printing, temperature, diffusion, polypropylene, mechanical properties

1. Introduction

Additive manufacturing (AM)/3D printing is a process for making three-dimensional solid objects of virtually any shape from a digital model when and where these objects are required. The market size of 3D printing materials, equipment and parts is estimated to total $12 billion in 2025 [1]. 3D Printing is transforming how products are designed and produced. There are many variables that can affect a 3D printed product. Some of these variables can include filament choice, temperature, and print design.

Polypropylene is currently a popular filament used by engineers and manufactures worldwide. As a tough and rigid crystalline thermoplastic, polypropylene is used in many applications such as the automotive industry, consumer goods, food packaging, and furniture markets. Nonetheless, it has only recently emerged as a potential candidate for 3D printing [2].

Furthermore, polypropylene has some difficulties printing due to heavily warping upon cooling which manufactures have improved on by creating polypropylene blends. Diffusion is a vital factor in 3D printing because it explains how the bonds form between layers as they are being printed. Past studies have been carried out only on the effect of hydrostatic pressure and molecular weight on diffusion [3, 4]. In a recent study, polypropylene blends were investigated as 3D printing materials, without resulting in significant improvements in the mechanical properties of pure polypropylene [5]. This paper will investigate the impact of temperature on the diffusion and the mechanical properties of polypropylene during 3D printing.

Integrating 3D printing into existing production and expanding knowledge on optimal printing variables could lead to improved products. Since polypropylene is challenging to print with, understanding its properties would establish printing parameters to yield polypropylene-containing products with enhanced performance. Therefore, studying the diffusion and polymer properties for polypropylene is essential.

It is known that the mobility and self-diffusion of polymer molecules is largely controlled by entanglements between the molecules. These entanglements are a result of the chain-like nature of the molecules. Reptation is a polymer property which describes the thermal motion of linear entangled macromolecules in polymers, and it suggests the movement of these polymer chains as being analogous to serpentines sliding through one another. This theory ex-

plains the dependence of the mobility of a macromolecule on its length, and it relates the effect of polymer chain entanglements with molecular mass. Entanglements with other polymer chains restrict polymer chain motion to a tube, and without breaking polymer chains, the chain in motion must flow through other chains. For this motion to occur it is necessary that all segments of the primitive chain slide cooperatively and simultaneously in one curvilinear direction [6]. The logistics of random walks can show the average end-to-end distance of a section of a polymer chain, and how the average length a polymer molecule must diffuse to escape from its particular tube. Hence, the characteristic time and diffusion coefficient for this to happen can be calculated using diffusive equations. The reptation chain theory of de Gennes predicts that the self-diffusion coefficient, D_s, of a linear flexible polymer in entangled systems is inversely proportional to M2, where M is the molecular weight of the polymer [6]. However, it is hypothesized in this study, that self-diffusion in polymers is also affected by temperature since polymers are highly susceptible to temperature changes.

Based on a previous study, by Bartels et al [7], the molecular weight relates to diffusion coefficient, D. and the impact molecular weight has on the diffusion coefficient. Moreover, from the observed diffusion coefficients at certain temperature in this study [7], temperature diffusion relationship can be extrapolated. The equation for the relationship is denoted as Equation 1, where D(T) is diffusion coefficient in relation to temperature and T is temperature.

$$D(T) = 7.4909 * 10^{-6} * T^{2.44} \quad (1)$$

Mechanical properties and diffusion of polypropylene in 3D printing are important in order to improve polypropylene in its uses in multiple applications as mentioned above. In this study, samples are created via 3D Printer Ultimaker 2+ with varying conditions such as using horizontal and vertical orientation and using nozzle temperatures selected at 215, 230, and 245. Samples were printed in two different orientations, with filaments being deposited perpendicular to the printing direction (vertical orientation) and filaments being parallel to printing direction (horizontal orientation). In this study, Raman spectroscopy, DMA, Optical Microscopy (OM), Optical Coherence Tomography (OCT), Scanning Electron Microscopy (SEM), Thermal Imaging, Rheology, and Instron Tensile Testing are conducted on the 3D printed polypropylene samples. The purpose of these tests is to explore how, in the case dealing with 3D printing of polypropylene, increasing the nozzle temperature will lead to an increase in diffusion and an improvement in mechanical properties.

2. Materials and Methodology

2.1. Sample Preparation

2.1.1. Sample Specifications

The polypropylene used was Ultimaker PP polypropylene Natural (1785), 2.85 mm diameter. All samples were 3D printed with an Ultimaker 2+ with a bed temperature of 60 °C for rectangular samples, 90 °C for circular samples, and 100 °C for dogbone samples. These bed temperatures were set for different type of samples in order to fully print the samples stationary in their respective positions. Nozzle temperature was varied between 215 °C, 230 °C and 245 °C. Refraction speed was 30 mm/s and refraction length was 0.20 nm. All rectangular samples were printed to have dimensions of 42.5 mm by 10 mm by 3 mm (Length by Width by Thickness) in the form of rectangular prisms. These samples were used for Dynamic Mechanical Analysis, Raman Spectroscopy, Thermal Imaging, SEM, OCT, and Optical Microscopy. Additionally, circular samples had dimensions of 25 mm diameter with 2 mm thickness. These samples were used for rheology tests. Lastly, dogbone samples must conform to the dimensions for Type IV specimens for testing non-rigid plastics. Hence, the dogbone samples had dimensions of 6 mm width of narrow section, 33 mm length of narrow section, 19 mm width overall, 115 mm length overall, and 65 mm distance between grids. These samples were used for ASTM D630 Tensile Testing.

2.1.2. 3D Printing

Before using the 3D Printer Ultimaker 2+, G-code was created in order to meet the specifications for all the samples via MATLAB. Repetier Host is the program used to observe the shape of the desired sample as well as the orientation of the filament without printing. Two separate G-codes were developed in order to print samples with horizontal orientation and vertical orientation. After checking the G-code in Repetier Host, the G-code file was placed in an SD card used for the 3D Printer Ultimaker 2+. Before printing the samples, the 3D Printer Ultimaker 2+ was turned on and the filament was changed to the polypropylene filament. After printing each sample, the material was changed and any part of the filament thinning out at the feed end was cut. Nozzle temperature was selected to be either 215 °C, 230 °C, or 245 °C for all three types of samples (rectangular, circular, and dogbone). The nozzle was cleaned with a brush prior to printing each sample.

2.2. Analytical Methods and Characterization Methods

2.2.1. Raman Spectroscopy

Raman spectroscopy probes the vibrational spectrum of a substance via inelastic scattering of light occurring upon the irradiation of a molecule with monochromatic light such as a laser [8]. Raman spectroscopy uses vibrational properties to study polymeric systems and it is important for studying how temperature and orientation changes the structure of polypropylene as well. An

Almega Dispersive Raman Microspectrometer using a 785 nm laser was used in this study. The rectangular samples were analyzed at 64 scans with varying laser power varying temperature size, and varying duration (1-6 seconds) per exposure.

2.2.2. Dynamic Mechanical Analysis

The DMA, 3-point bending test, was performed using the DMA Q800, TA Instruments. The test was performed on vertical samples. The storage and loss moduli as functions of amplitude (displacement) were recorded. The frequency was set to 1 Hz and temperature was held constant at 30 °C.

2.2.3. Optical Clearance Tomography

Vertical samples for 215 °C, 230 °C, and 245 °C were placed on a plate and observed through the 1300 nm OCT Scanner, Series TEL320. The scanner lens was adjusted to allow the camera to focus on vertical samples. The scanner uses a beam of light to create tomographic images, or cross-section pictures, of the samples. The samples were partially transparent which is a major requirement of the OCT tests.

2.2.4. Optical Microscopy

The samples were observed under the Plugable USB 2.0 Digital Microscope for Windows (2MP , 250x Magnification). One sample of each condition was sliced in half and then placed below the lens, resolution was set at 1280 x 720 to be able to clearly see the filaments and examine the filament diffusion throughout the cross section of the rectangular prism.

2.2.5. Scanning Electron Microscopy

Three horizontally printed samples for each temperature were cut in liquid nitrogen and then shattered. The exposed filaments were then sprayed with gold and were then observed in a Zeiss LEO1550 SFEG-Scanning Electron Microscope. An SE2 detector was used and the high tension was set to 5.0 keV. Horizontal samples were used for SEM because the filaments for this orientation were perpendicular to the shatter angle, which allow the quality of diffusion between layers to be observed. The exposed homogenous parts of the surfaces resulting from shattering the samples were looked at to observe the extent of diffusion for each temperature.

2.2.6. Thermal Imaging

Thermal measurements were carried out using a FLIR A325sc IR camera which was set up to record the printing of a vertical sample at 215 °C, 230 °C, and 245 °C. IR data was analyzed using the program Research IR. In this program, the movies are loaded into the screen where the motion is depicted by pixels and frames. The temperature scale was set between 60 °C and 250 °C. Four filaments were chosen which two of them were side by side and the other two were from top to bottom with lines drawn across each filament. Temperature data was obtained across these lines at different frames over a certain period of time. The obtained values are used to build temperature profiles.

2.2.7. Rheology

Rheology measurements were carried out using a Discovery HR-2 Rheometer. The rheometer was first calibrated and set to 60 °C. Circular polypropylene samples were then placed into the testing chamber. The chamber was sealed and then radial shear stress was applied to the samples. The displacement from starting position was gradually increased while recording both storage and loss moduli. Three samples for 215 °C, 230 °C, and 245 °C were tested.

2.2.8. Instron Testing

The tensile strength, maximum strain, and Young's Modulus were measured by the Instron 5542 (Instron Co., Grove City, PA). Dogbone samples were tested with an extension rate set to 10 mm/min according to ASTM D-638 type IV. The results represented the average of five samples.

3. Results and Discussion

3.1. Sample Printing

Three different types of samples were printed: rectangular, circular, and dogbone. After using the 3D Printer Ultimaker 2+, fifty four (54) rectangular samples were successfully printed with varying conditions such as horizontal and vertical orientations and printing temperatures of 215 °C, 230 °C, and 245 °C as shown in Table 1.

Table 1: Six combinations designed for polypropylene rectangular samples

Amount and Shape of Samples	Orientation	Temperature
9 Rectangular Samples	Horizontal	215 °C
9 Rectangular Samples	Horizontal	230 °C
9 Rectangular Samples	Horizontal	245 °C
9 Rectangular Samples	Vertical	215 °C
9 Rectangular Samples	Vertical	230 °C
9 Rectangular Samples	Vertical	245 °C

Figure 1 illustrates all the printed samples and their design, along with their dimensions and respective views from Repetier Host. Figure 1 (A) displays an example of both, vertical and horizontal, printed samples based on the six combinations the research was intended to focus on when the samples were printed with polypropylene filament. Part (B) and (C) of Figure 1 illustrate the top view of the samples on Repetier Host respectively while part (D) and (E) of Figure 1 independently portray the isometric view of the samples in Repetier Host. Furthermore, fifteen

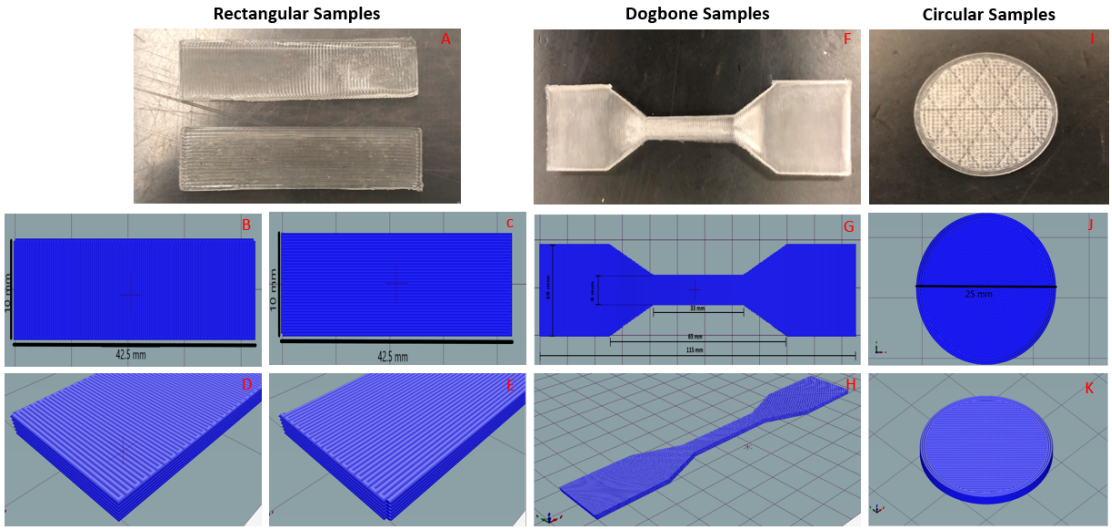

Figure 1: Set of all designed samples Rectangular samples: (A) Vertical and Horizontal polypropylene-printed samples; (B) Vertical orientation-top view; (C) Horizontal orientation top view; (D) Vertical orientation-isometric view; (E) Horizontal orientation-isometric view. Dogbone samples: (F) Displays polypropylene-printed samples. (G) Repetier Host top view of dogbone with ASTM dimensions. (H) Isometric view of dogbone in Repetier Host. Circular samples: (I) Polypropylene-printed sample. (J) Repetier Host top view of sample including diameter dimensions. (K) Isometric view of sample in Repetier Host.

dogbone samples were printed, five for each set of temperatures: 215 °C, 230 °C, and 245 °C. Figure 1 (F) shows the dogbone polypropylene-printed sample, (G) shows the required dimensions of the dogbone, and (H) displays an isometric view of the designed dogbone shape in Repetier Host. This image aids to visualize not only the shape of the sample but also the orientation of the filaments along the dogbone. Likewise, nine circular samples were printed, three for each set of temperatures: 215 °C, 230 °C, and 245 °C. Figure 1 (I) shows the circular polypropylene-printed samples whereas (J) and (K) exhibit the top and isometric view of the sample in Repetier Host severally.

Furthermore, nine circular samples were printed, three for each set of temperatures: 215 °C, 230 °C, and 245 °C. Figure 2 shows the circular polypropylene-printed samples as well as the top and isometric view of the sample in Repetier Host.

3.2. Raman Spectroscopy

Raman spectroscopy enables the analysis of the vibrational spectra with respect to the molecular configurations, conformations, and orientations, as well as deformation and degradation mechanisms. When examining orientated isotactic polypropylene in the solid state, several additional bands appear, especially in the 800 cm^{-1} to 1200 cm^{-1} range [8]. Raman spectroscopy is beneficial for having the ability to provide quantitative information on the macromolecules in different configurational, conformational, and phase states, including description of various crystalline modifications and amorphous regions with different state of order [9, 10].

In a study by Andreassen, the Raman spectroscopy numbers and their respective main active group vibrations associated with semi-crystalline isotactic polypropylene were listed [9]. This study has been used as a reference in order to show the associated peaks for each Raman spectra taken for the printed samples. Figure 2 shows polypropylene Raman spectra at different temperatures and orientations.

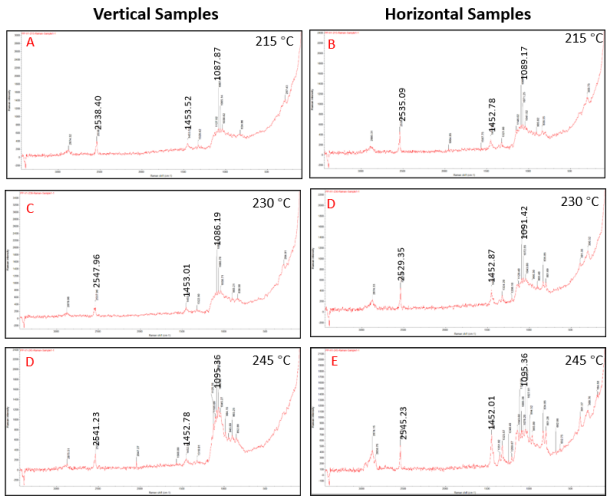

Figure 2: Raman Spectroscopy for vertical (left) and horizontal (right) samples. (A)Spectra of vertical sample at 215 °C. (B) Spectra of vertical sample at 230 °C. (C) Spectra of vertical sample at. 245 °C. (D)Spectra of horizontal sample at 215 °C. (E) Spectra of horizontal sample at 230 °C. (E) Spectra of horizontal sample at 245 °C.

In regards to the samples with vertical orientation of polypropylene, they all shared the main vibrational assignments with the most represented ones being: vCH_2 sym. or vCH_3 sym. (2871/2883), bending CH_3 asym. and bending CH_3 (1457), stretching C-CH_3, stretching CC_b, and bending CH (1034). The same vibrational assignments have been identified in the study used as reference [8]. The same major vibrational assignments were also obtained for the horizontal samples. The results obtained from Raman spectroscopy demonstrate that the structure of the samples did not change with temperature since the relative intensities of the main vibrational assignments are similar as seen in Figure 2. This also leads to the conclusion that the printing orientation does not change the molecular structure of the 3D printed polypropylene.

3.3. Thermal Imaging

Thermal imaging was performed on only vertical samples at temperatures of 215 °C, 230 °C, and 245 °C. Thermal imaging was used to study the properties of the samples as the temperature changes. A differential thermal analysis was done to observe the temperature difference over time and the analysis was useful to build a temperature profile at each distinct temperature. Figure 3 depicts the temperature profiles obtained from each temperature for the vertical samples along with the diffusion length calculated from the thermal analysis. Figure 3 (A) illustrates the temperature profile for side-by-side filaments while (B) illustrates the temperature profile for top-to-bottom filaments. From the depicted figures, it is observed that temperature gradually decreases as time increases. Also, it is seen that the profile is not continuous and that there are some small peaks along the curve, which are attributed as a result of the printing motion. As the nozzle travels away from the chosen point of analysis, the temperature of the studied filament decreases, and as the nozzle moves forward again, the temperature increases due to the close proximity between filaments.

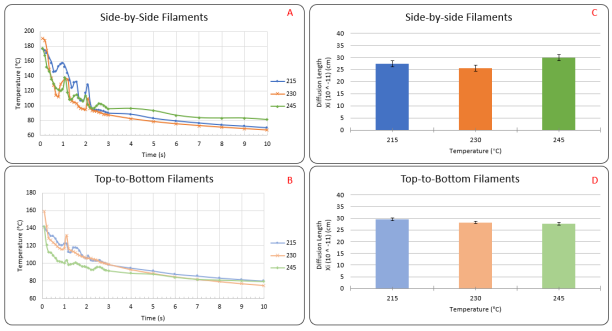

Figure 3: Temperature profiles and diffusion of vertical samples (A)Profile for side-by-side filaments at 215 °C, 230 °C, and 245 °C. (B) Profile for top-to-bottom filaments at 215 °C, 230 °C, and 245 °C. (C) Diffusion length comparison for side-by-side filaments. (D) Diffusion length comparison for top-to-bottom filaments.

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These profiles were used to determine the diffusion coefficient of the polypropylene at each of the studied temperatures. From a previous study, values of diffusion at certain temperatures were obtained and used to make a thermal plot. As a result, Equation 1 was computed in terms of temperature which was further used to determine the diffusion throughout the built temperature profile. Then, the diffusion length was calculated using Equation 2, which provides a measure of how far material diffuses in a period of time.

$$X_i = \sqrt{4Dt} \tag{2}$$

The results from this analysis were evaluated, and an averaged diffusion length was determined for each temperature. Figure 3 (C) shows the comparison of the calculated diffusion lengths for the side-by-side filaments at the three studied temperatures, and similarly (D) shows the diffusion length for top-to-bottom filaments. From this comparison, it is determined that the diffusion length increases as the temperature increases, which enforces the assumption that diffusion of polypropylene is enhanced with temperature increments.

3.4. Optical Microscopy

The samples were observed under the optical microscope to examine the filament diffusion throughout the cross section of the rectangular prism. Figure 4 illustrates the cross section of both vertical and horizontal samples at temperatures of 215 °C, 230 °C, and 245 °C.

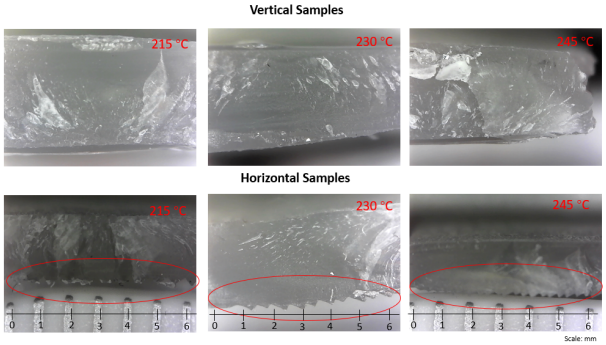

Figure 4: Optical Microscopy for vertical (top) and horizontal (bottom) samples at 215 °C, 230 °C, and 245 °C (left to right).

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As previously stated in the thermal analysis, diffusion is enhanced as temperature increases; therefore, it is expected to see that the filaments of 245 °C samples are less visible. According to Figure 4 (top), it is observed that at the vertical samples, the filaments are still distinguishable at 215 °C and 230 °C, whereas at the 245 °C samples, the filaments are seen to be more diffused to each other and minimize the difference in visibility. Furthermore, Figure 4 (bottom) likewise depicts the cross section of the horizontal samples where it is observed that more filaments

are filling the same area as temperature increases. On the x-direction, a scale of 6 mm eases to observe the difference in density of the filaments. It is clear that the filaments are more uniformly fused since at the 245 °C samples, the filaments are thinner and thus they increase in quantity. The increase amount of filaments indicate the improved diffusion hence reaffirming the statement that diffusion is enhanced at higher temperatures.

3.5. Scanning Electron Microscopy (SEM)

The horizontal samples that were printed at 215 °C and 245 °C were prepared as described in the Methodology and viewed using Scanning Electron Microscopy. The samples were viewed at different locations as shown in Figure 5 showing the samples were isotropic. Horizontal samples at 215 °C and 245 °C are depicted in Figure 5 (A and B) which show the clean break perpendicular to the fiber layers. The horizontal sample at 215 °C shows regular voids (holes) in a pattern indicating the location of the filaments. Holes are created from insufficient diffusion, whereas the horizontal sample at 245 °C shows no regular deformities.

3.6. Optical Coherence Tomography (OCT)

The 2D images of layers in each of the vertical samples at temperatures 215 °C, 230 °C, and 245 °C can be seen in Figure 5 (C, D, and E). Figure 5 illustrates how layer visibility decreases as temperature increases due to better diffusion between layers. This correlation implies the printed samples at 245 have better diffusion than the printed samples at 215 °C and 230 °C since the layer visibility was lowest in the printed samples at 245 °C.

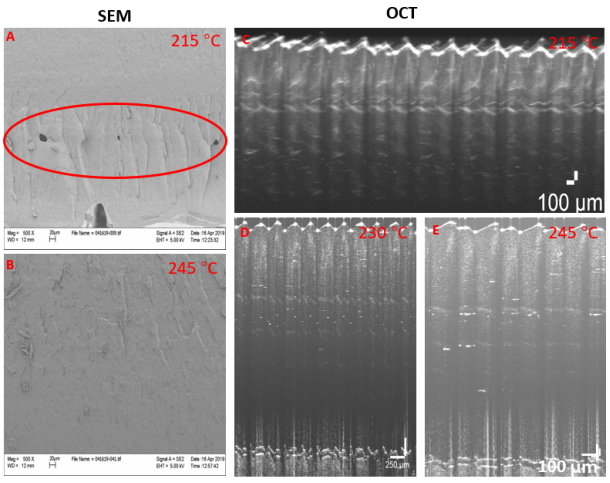

Figure 5: Scanning Electron Microscopy for horizontal samples between: (A) 215 °C and (B) 245 °C at 500x magnification. Voids in 215 °C sample circled. Optical Coherence Tomography for vertical samples: (C) 2D Image at 215 °C; (D) 2D Image at 230 °C; (E) 2D Image at 245 °C.

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3.7. Dynamic Mechanical Analysis (DMA)

The mechanical testing performed on this study focuses in the storage and loss modulus. Storage modulus corresponds to the mechanical energy stored by the material during a loading cycle. Consequently, the storage modulus is related to the stiffness and shape recovery of the polymer in study during loading while being tested. The loss modulus represents the damping behavior, which indicates the polymers ability to disperse mechanical energy through internal molecular motions. DMA test was utilized in order to show how storage modulus and loss modulus changes based on amplitude for samples with differing temperatures and differing orientations as shown in Figure 6. By gradually increasing the amplitude of oscillations, a dynamic stressstrain measurement can be done. The results of the variation of storage and loss modulus with increasing stress can be used for materials characterization, and to determine the upper bound of the materials linear stressstrain regime. DMA tests were done in both, vertical and horizontal samples. Given the orientation of the samples, the DMA test measures the strength of the material for the horizontal samples whereas for the vertical samples, it measures the strength of the bonding between side-by-side filaments. Since the material strength is not influenced by diffusion, the horizontal samples were assumed to show no significant difference in mechanical properties as temperature increased. Subsequently, only the results of the vertical samples are considered significant for the purpose of this study.

From the DMA analysis of the vertical samples, it is observed that the 245 °C print exhibited the highest storage modulus and loss modulus for tested prints, as a result of the diffusion length being larger for higher temperatures, and as seen in Equation 2. Storage and loss modulus are essential for material characterization since one is related to the storage of energy which lets us see how elastic the polymer is, and the other is related to the loss of energy which tell us the materials viscous behavior. A material exhibits more elastic-like behavior as the testing frequency increases and the storage modulus tends to slope upward toward higher frequency. The storage modulus change with frequency depends on the transitions involved.

Figure 6 (A) shows that there is a little to no change in the storage modulus from 215 °C to 230 °C, but an increase is clearly observed when the temperature increases to 245 °C. Similarly, Figure 6 (B) displays the changes in loss modulus with temperature increases; there is a very small change in the modulus from 215 °C to 230 °C, but a more significant increment is observed when the temperature increases to 245 °C. Hence, the 245 °C sample have higher storage and loss modulus. The higher storage and loss modulus indicate that polypropylene-printed samples are capable of storing more energy when bent, meaning the 245 °C samples were the most robust and have stronger mechanical properties. Ultimately, the horizontal prints showed no significant distinction between 215 °C, 230 °C or 245 °C, as predicted.

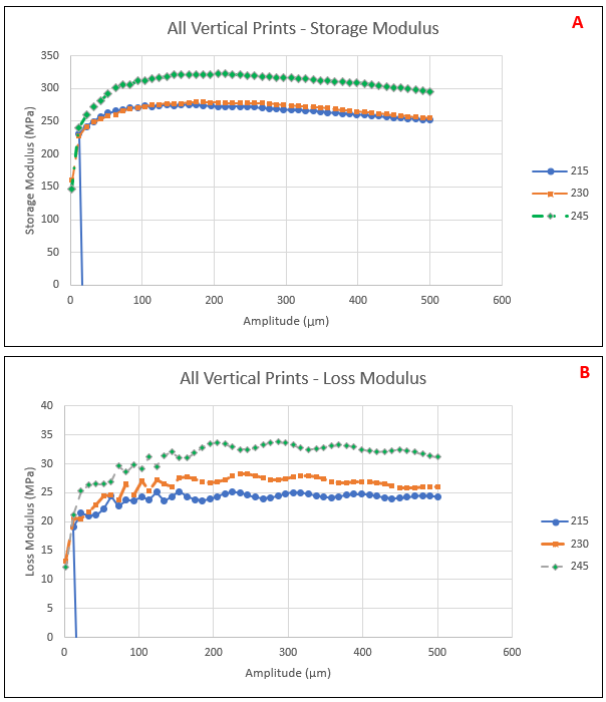

Figure 6: Dynamic Mechanical Analysis for printed samples: (A) Storage Modulus vs. Amplitude showing differing temperatures for vertical samples; (B) Loss Modulus vs. Amplitude showing differing temperatures for vertical samples.

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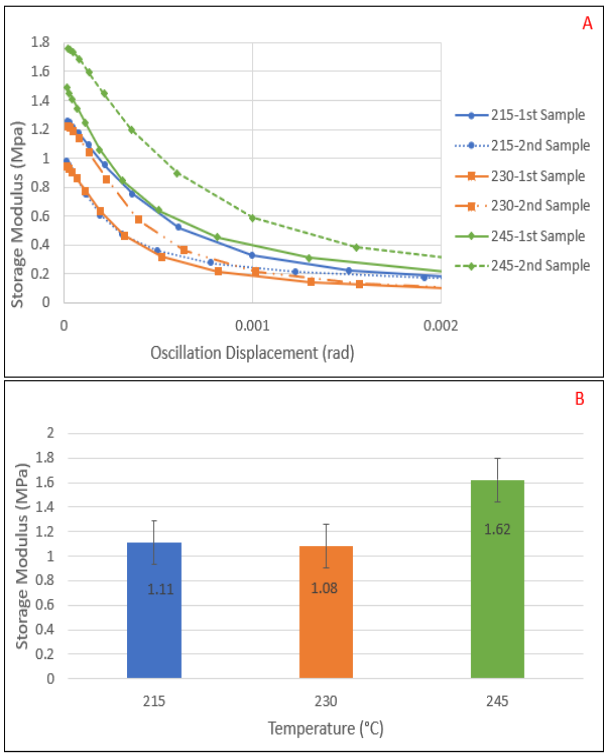

Figure 7: (A) Storage modulus (MPa) vs Oscillation Displacement (rad) from rheology conducted on two circular samples at each temperature (215 °C, 230 °C, and 245 °C). Lines with one dot between are the 215 °C samples, the dotted lines are the 230 °C samples, and lines with two dots between are the 245 °C samples. (B) Bar graph compares storage modulus at initial oscillation displacement (zero strain).

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3.8. Rheology

The rheometer measured storage modulus for two circular samples at each temperature (215 °C, 230 °C, and 245 °C). Figure 7 (A) illustrates how the storage modulus decreases as oscillation displacement increases for samples with increasing temperature. Samples printed at 245 °C have a notably higher storage modulus compared to the samples printed at lower temperatures. Figure 7 (B) compares the initial storage modulus values with the lowest recorded oscillation displacement for two circular samples at each temperature (215 °C, 230 °C, and 245 °C). Initial storage modulus at 245 °C is 30% greater than storage modulus at 215 °C and 230 °C.

3.9. Instron Testing

To further understand the influence of 3D printing temperature on the mechanical properties of polypropylene, the Instron tensile test was performed on all the dogbone samples. Values of the Young's Modulus, ultimate tensile strength, and strain were obtained through this test. Young's Modulus or modulus of elasticity is a mechanical property that measures the stiffness of a material which is the resistance to elastic deformation, and defines a relationship between the stress and stress in the elastic regime. This modulus measures of the ability of the polymer dogbone sample to return to its original length after it has been stretched. The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress. Figure 8A displays the average Young's Modulus values of the samples at each temperature.

The Young's Modulus values were not significantly different at 215 °C and 230 °C, while only a small increase is observed at 245 °C. In all temperatures the values were within the same error range, and it can be concluded that the nozzle temperatures do not have a direct effect on the Young's Modulus of polypropylene. The capacity of the dogbone samples to withstand elongation is the ultimate tensile strength. The average values for the ultimate tensile strength of the samples at each temperature are shown in Figure 8B. The average tensile strength of the 245 °C dogbone samples was nearly 30% higher than the average tensile strength of the 215 °C dogbone samples. The weaker tensile strength of the 215 °C dogbone samples can be attributed to the temperature having the lowest diffusion length.

Figure 8C illustrates the average peak strain values of the dogbone samples for each temperature. The strain value of the dogbone samples at 245 °C had over two times the strain value of the dogbone samples at 215 °C. This

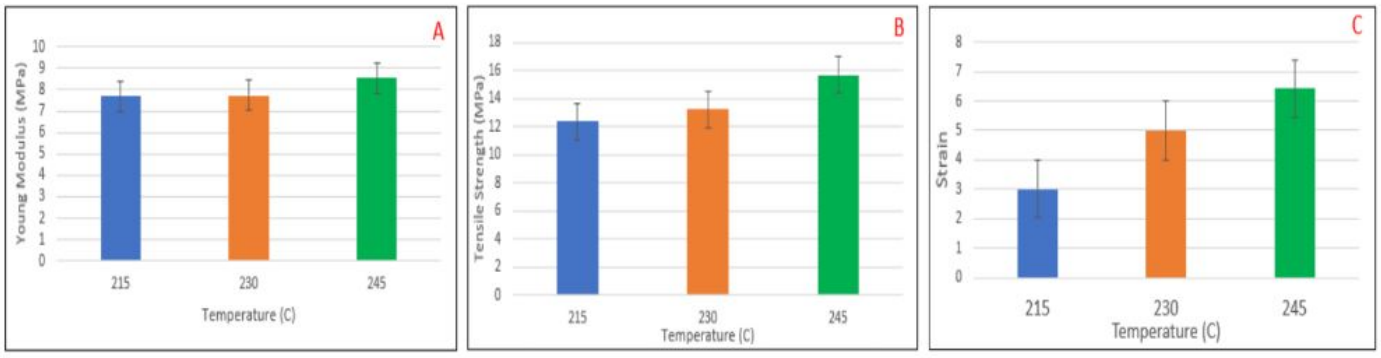

Figure 8: (A) Young's Modulus (MPa) vs temperature (°C); (B) Tensile strength (MPa) vs temperature (°C); (C) Strain vs temperature (°C). All graphs are for samples printed at 215 °C, 230 °C, and 245 °C.

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is due to a higher diffusion rate in the larger temperature improving the length at which the dogbone samples could be stretched.

4. Conclusion

In this study, 3D Printer Ultimaker 2+ was used to study the effect of printing orientation and nozzle temperature on the mechanical properties and diffusion for 3D printed polypropylene. Fifty-four rectangular samples were printed with two different orientations (vertical and horizontal) and with three different nozzle temperatures (215 °C, 230 °C, and 245 °C). Diffusion in polypropylene is related to nozzle temperature by Equation 1, where higher temperature should produce a higher diffusion rate; thus, improving mechanical properties. The analytical and characterization methods used in this study illustrate that increasing temperature of the polypropylene samples leads to improvement in the mechanical properties. This is due to greater diffusion length, supported from the temperature profiles, OCT, SEM, and optical microscope. The vertical samples at 245 °C displayed higher storage and loss moduli than any of the vertical samples at 215 °C and 230 °C. No significant difference in storage and loss moduli was seen between the horizontal samples at 215 °C and the horizontal samples at 245 °C. Enhanced diffusion was seen on both vertical and horizontal printed samples at 245 °C when compared to other vertical and horizontal printed samples at 215 °C and 230 °C. This study suggests that polypropylene has improved mechanical performance, quantified as higher storage modulus, when printed at higher nozzle temperatures.

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