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Khanh Q. Nguyen, Pascal Y. Vuillaume, Lei Hu, Andro Vachon, Audrey Diouf-Lewis, Pier-Luc Marcoux, Lambert Gagné, Mathieu Robert and Saïd Elkoun

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Khanh Q. Nguyen[1,a *], Pascal Y. Vuillaume[2,b], Lei Hu[3,c], Andro Vachon[4,d], Audrey Diouf-Lewis[5,e], Pier-Luc Marcoux[6,f], Lambert Gagné[7,g], Mathieu Robert[8,h] and Saïd Elkoun[9,i]

[1,2,3,5,6,7]COALIA, Thetford Mines, QC, Canada G6G 1N1

[4]Cégep de Thetford, Thetford Mines, QC, Canada G6G 1N1

[8,9]University of Sherbrooke, Sherbrooke, QC, Canada J1K 2R1

[a]qknguyen@coalia.ca (*corresponding author), [b]pvuillaume@coalia.ca, [c]lhu@coalia.ca
[d]avachon@cegepthetford.ca, [e]adiouflewis@coalia.ca, [f]plmarcoux@coalia.ca,
[g]lambertgagne@outlook.com, [h]mathieu.robert2@usherbrooke.ca, [i]said.elkoun@usherbrooke.ca

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Abstract. Additive manufacturing (AM) has been widely used for rapid prototyping (RP) techniques due to its low cost and customizability. This technique allows for rapid and competitive price production compared to conventional manufacturing. However, pieces fabricated with the AM technique usually possess poor mechanical and surface properties compared to the injection molding technique. Based on COALIA's recent patent, a thermal treatment approach was used to improve the performance of printed parts. In this study, acrylonitrile-butadiene-styrene (ABS) was printed using fused deposition modeling (FDM) with and without heat treatment at 35 mm/s of printing speed. The physical and mechanical properties of printed ABS parts were then investigated. Tensile tests were performed to investigate the tensile strength, elastic modulus, and elongation at break. After tensile tests, X-ray microtomography was conducted to evaluate the surface morphologies. An optical profilometer analysis was also used to measure the surface roughness.

Introduction

In recent years, 3D printing also known as additive manufacturing (AM) has gained interest in various manufacturing industries due to its low cost, rapid production, and customizability [1-3]. AM technology has been developing dramatically in industrial applications such as automotive and aircraft interiors [4]. This technology allows for the creation of products by building layers of materials directly from 3D computer-aided design (CAD) software without needing a die or mold compared to conventional manufacturing [5]. In addition, AM technology can produce parts with a lattice structure leading to lower the weight of an aircraft and increasing its fuel efficiency [6,7]. There are numerous 3D printing technologies available to print a wide range of materials including polymers, metals, liquid resin, ceramics, and combinations of these [3,8]. However, fused deposition modeling (FDM) is the most widely used technique to extrude thermoplastic polymer filament for both functional and non-functional industrial applications [9,10]. Recently, the FDM technique has popular in 3D printing technology as rapid prototyping, ease of use, and low-cost technique when compared to other techniques. Moreover, this technique can produce complex geometries. In general, the principle of the FDM technique consists of heating and extruding filaments through a nozzle. Specifically, the continuous thermoplastic filaments are pushed toward the extrusion head to precisely regulate the feeding and retracting of filaments. A heating element and a nozzle are then used to heat and extrude the filament layer by layer. Finally, each printed layer is fused to produce 3D parts in a platform as shown in Fig. 1a.

Thermoplastic polymers are the main materials for the FDM technique, including polylactic acid (PLA), polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), and nylon. ABS is, however, the most widely used due to its low cost, high-impact strength, high durability, and interesting applications [11]. In contrast, shrinkage and warping are the main problems of ABS during the printing process. These drawbacks of ABS can be attributed to its high printing temperature and high coefficient of thermal expansion (CTE) [3,12,13]. Furthermore, some limitations of materials printed with the FDM technique are poor interlayer strength, inferior mechanical properties, high porosity, and voids [14]. Many previous studies revealed that changing printing parameters such as raster angle, nozzle size and temperature, printing speed, bed temperature, and layer height could enhance the mechanical properties of printed ABS parts [15]. In particular, a good interlayer is key to obtaining superior mechanical properties. Recently, several studies have concluded that heat treatment during and after the printing process can improve the quality of the final printed parts. Singh and al. (2019) [10] indicated that heat treatment during the printing process could enhance the mechanical and surface properties of printed ABS parts. A heat treatment approach was conducted in an air-convection electric oven by controlling different temperatures of 105, 115, and 125°C. It can be concluded that heat treatment of ABS parts above its glass transition temperature (T_g) enhanced material reflow. The results showed that surface roughness was decreased by increasing the heat temperature treatment. In addition, better tensile and flexural strength was observed at an annealing temperature of 125°C. Hart et al. (2018) [16] reported that the post-process heat treatment improved fracture roughness between printed layers. As a result, the interlayer fracture toughness of printed ABS parts with heat treatment increased to 2700% compared to printed parts without heat treatment. In addition, polymer reptation and mobility at the interface were also investigated using X-ray tomography to more explain the toughening mechanisms of treated ABS parts. Sharing the same point of view, Rane et al. (2020) [17] also revealed that post-thermal treatment increased 89% the tensile strength of printed ABS parts. However, the dimensional inaccuracy of parts with post-thermal treatment is the main limitation due to undesirable residual stresses from the print process.

In this study, a radiant heating system was developed based on our previous studies to evaluate the effect of thermal treatment during printing on interlayer strength, mechanical, and microstructure properties of printed ABS parts [18-20]. The preliminary investigations were conducted with different thermal treatments (220, 240, 260, 270, and 280°C). Tensile tests were then performed to investigate the tensile strength, modulus, and elongation at break of printed ABS parts with and without thermal treatment. Various analyses such as optical microscopy and optical profilometer were also conducted to evaluate the surface morphologies and roughness.

Experimental methods

Materials

Amorphous thermoplastic acrylonitrile-butadiene-styrene (ABS M30 Ivory) filaments (Stratasys Inc., MN, USA) with a nominal diameter of 1.75 mm, a density of 1.05 g/cm^3, and a glass transition temperature of 105°C were used to print 3D parts of specimens.

Printing parameters

Before printing, ABS filaments were dried at 80ºC for 8 hours in an oven and they were then kept in a conditioned room at 75ºC to remove moisture. The FDM Prusa Mk3s+ printer was used to print ABS specimens. Type IV specimens were printed along Z-X axes with dimensions according to ASTM D638 [21] as shown in Fig.1b.

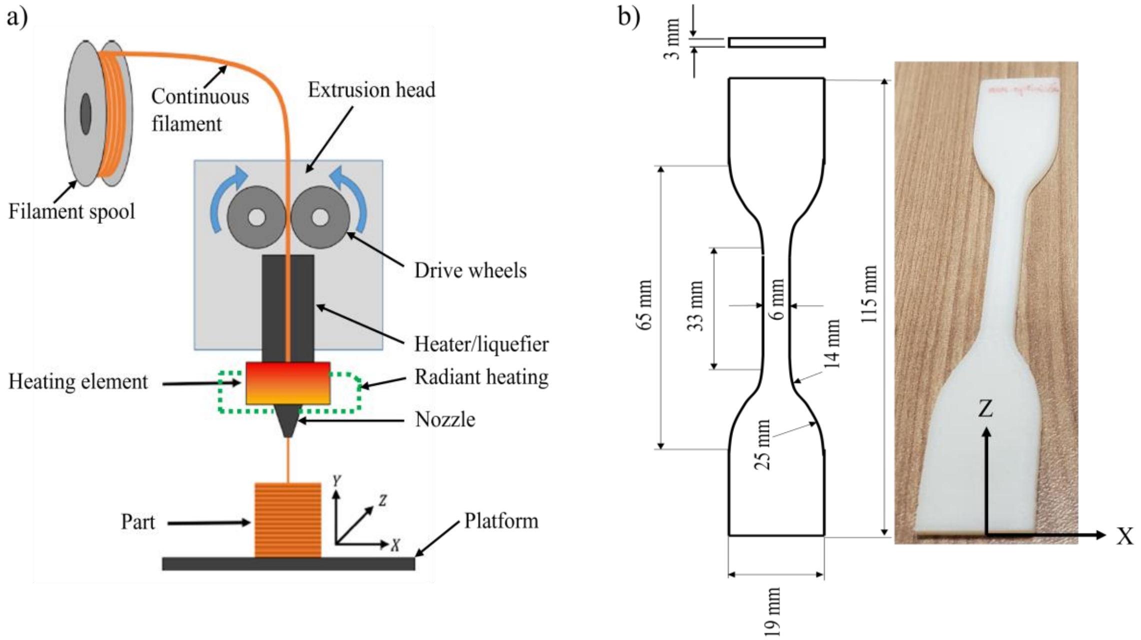

Fig. 1. a) Principle of the fused deposition modeling (FDM) technique with a radiant heating (adapted from [3]) and b) Printed ABS specimens

In this study, a radiant heating system coupled with the Prusa Mk3s+ printer (Fig. 1a) was used to evaluate the effect of thermal treatment on mechanical and microstructure properties of printed ABS parts. The printing process consists of five main stages (i) 1st heating materials, (ii) 1st extruding a portion of heated materials, (iii) creating a layer of deposition, (iv) 2nd heating a portion of the deposition layer by the radiant system, and (v) 2nd extruding a portion of heated materials to create a new layer of deposition. The nozzle and radiant heating temperatures were 295ºC and 240ºC, respectively, with a printing speed of 35 mm/s. The printing parameters were selected based on our previous studies [18,19] as shown in Table 1. The terms "treated" and "untreated" specimens in this study refer to ABS specimens printed with and without a radiant heating system, respectively.

Characterization methods

Tensile tests

The tensile test, using dog-bone specimens (Fig. 1b), was performed on a universal testing machine (Zwick/Roell Z030) at 23ºC and 50% relative humidity. A load cell of 30 kN and a rate of 5 mm/min were applied to evaluate the tensile strength of ABS printed with and without a radiant system. After five replicates, the stress-strain curves of treated and untreated ABS were then recorded. The average of tensile strength, modulus, elongation at break, and standard deviation were reported.

Table 1. Printing parameters used to untreated and treated ABS parts.

Parameters	**Values**
Nozzle diameter	0.6 [mm]
Nozzle temperature	295 [^{o}C]
Bed temperature	100 [^{o}C]
Radiant heating temperature	240 [^{o}C] (*only for treated sample*)
Extrusion factor	0.98
Layer thickness	0.2 [mm]
Infill line direction	Z-direction (0^{o}C)
Infill density	100 [%]
Printing speed	35 [mm.s^{-1}]

X-ray microtomography (µ-CT)

X-ray microtomography (µ-CT), a non-destructive imaging, is used to investigate the porosity and distribution of voids in materials. In the current study, the µ-CT analysis was conducted using a ZEISS Xradia 520 Versa 3D X-ray microscope at a voltage of 60 kV. The fractured samples after tensile tests were scanned to provide 2D radiographs. The image reconstruction Dragonfly software with tomographic data was applied for 3D visualization and analysis. Three replicates were performed to calculate the porosity of ABS printed with and without a radiant system.

Optical profilometry (OP) analysis

The effect of thermal treatment during printing on the surface roughness of printed ABS parts was investigated using an optical profilometer (Polytec micro view®+). In this study, fractured samples after tensile tests received 5 nm of a palladium-gold coating before analysis to enhance the reflectivity of samples. A non-contact optical method, white light interferometry, was used to measure surface height and profile on 3D structures. Three replicates were performed to investigate the surface roughness of untreated and treated samples.

Results and discussions

Mechanical properties

Figure 2 shows the typical stress-strain curves of untreated and treated printed ABS samples after five replicates. The results indicate a brittle fracture behavior for both untreated and treated samples. In addition, Figs. 1A, 2A, and 3A present the average tensile strength, elastic modulus, and elongation at break along with standard deviations of untreated and treated samples, respectively. It should be noted that preliminary tests with different thermal treatments of 220, 240, 260, 270, and 280^{o}C were performed to determine the optimal thermal treatment of 240^{o}C. These results were similar to our previous study [18] and can be found in supplementary data (Appendix A). As a result, the average tensile strength, elastic modulus, and elongation at break of the untreated sample were 19.0 MPa, 1921 MPa, and 1.0%, respectively. Contrariwise, the average tensile strength, elastic modulus, and elongation at break of the treated sample increased up to 30.7 MPa, 2028 MPa, and 2.1%, respectively, due to the thermal treatment. In other words, the radiant heating system can improve 62% in tensile strength, 6% in elastic modulus, and 110% in elongation at break. This observation manifested that radiant heating increased the mobility and thermal energy of polymer chains. Layers fused once achieved enough thermal energy, resulting in enhancing mechanical properties. It should be noted that the optimal heat treatment was 240^{o}C.

Contrariwise, higher heat treatments (260, 270, and 280^{o}C) could degrade the interlayer surface, leading to reduced mechanical properties (Appendix A).

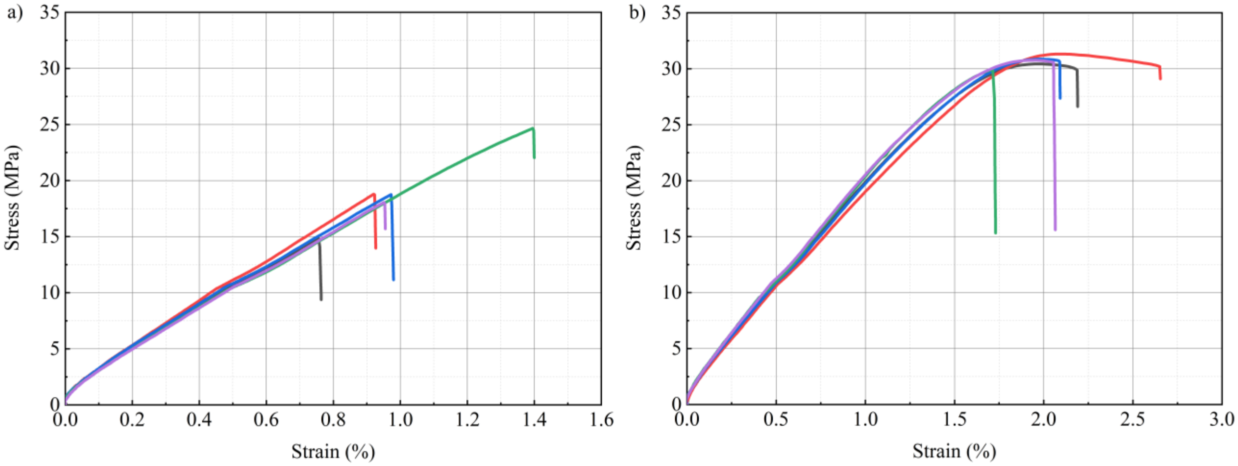

Fig. 2. Stress-strain curves of a) untreated and b) treated ABS samples.

Microstructural properties

µ-CT analysis was conducted on fractured untreated and treated ABS samples after tensile tests to investigate the degree of porosity. As illustrated, Fig. 3 presents a typical µ-CT image for both untreated and treated samples. The reconstructed volume data was generated using Dragonfly software coupled with tomographic data. The results indicate that porosity was found to be 3% and 1.6% in untreated and treated samples, respectively. According to the findings, the heat treatment could reduce porosity contents leading to enhanced mechanical strength of the treated sample.

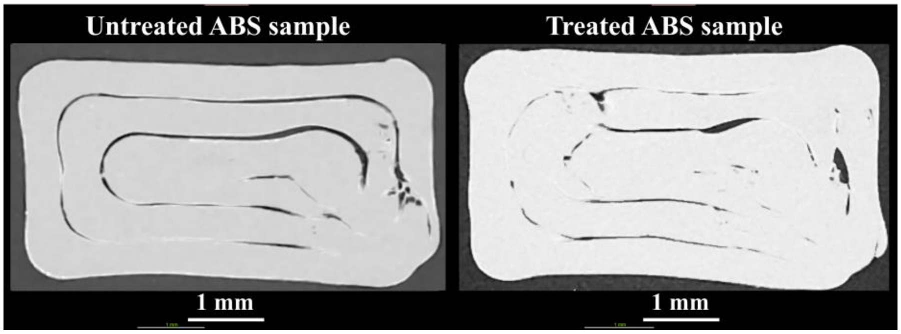

Fig. 3. µ-CT images of a) untreated and b) treated ABS samples.

Surface roughness properties

The surface roughness plays a key role in assessing the material's performance. Surface irregularities may result in fractures or material deterioration. In general, area and profile roughness are the two main parameters evaluating the surface roughness of materials. The roughness average (S_a) and the root mean square (S_q) are used to define area roughness. On the other hand, the roughness average (R_a) and the root mean square (R_q) determine the profile roughness. Figure 4 shows the area roughness of untreated and treated ABS samples. Moreover, the profile roughness of the untreated and treated ABS samples was calculated by drawing two-dimensional lines I-I and II-II, respectively. In the current study, the surface data was generated using a Gaussian filter which area and profile roughness were determined according to ISO 25178

[22] and ISO 21920 [23] as shown in Table 2. The results revealed that both the area and profile roughness of treated samples were lower than those of untreated ones. The heat treatment, therefore, helps the surface of samples less rough than untreated ones.

Table 2. Surface roughness values of untreated and treated ABS samples.

Surface roughness	Untreated sample	Treated sample
Roughness average (S_a) - Area	6.01 [µm]	4.98 [µm]
Root mean square (S_q) - Area	9.14 [µm]	7.42 [µm]
Roughness average (R_a) - Profile	2.21 [µm]	1.78 [µm]
Root mean square (R_q) - Profile	2.87 [µm]	2.39 [µm]

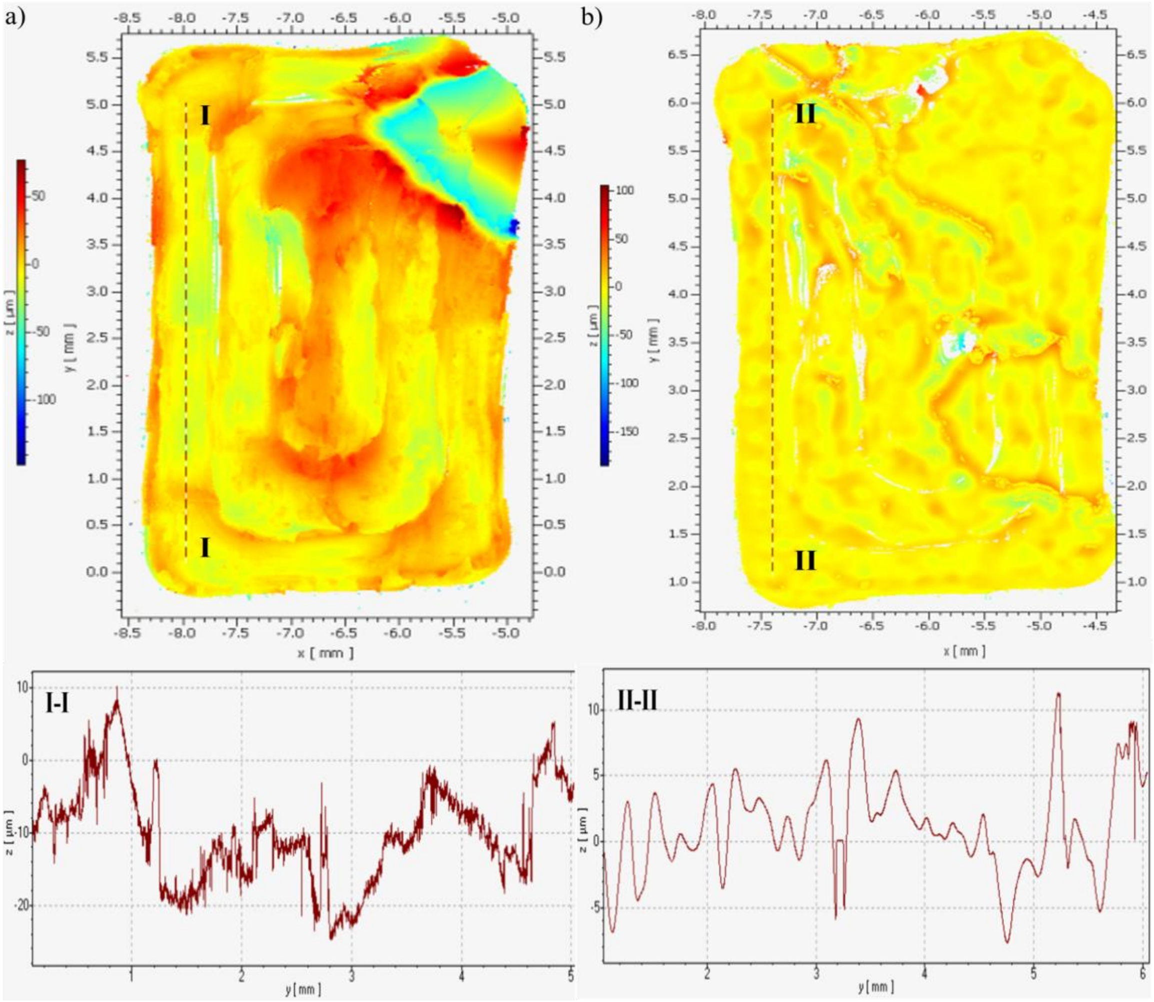

Fig. 4. Surface roughness of a) untreated and b) treated ABS samples.

Conclusions

Acrylonitrile butadiene styrene (ABS) is the most widely used in the fused deposition modeling (FDM) technique due to its low cost, high-impact strength, high durability, and interesting applications. Contrariwise, shrinkage and warping are the main problems of ABS during the printing process. In this study, thermal treatment using a radiant heating system was investigated to evaluate the microstructural, mechanical properties, and surface roughness of printed ABS parts. The thermal treatment at 240^{o}C and printing speed at 35 mm/s were chosen as optimal printing parameters. The following conclusions may be drawn:

1. The mechanical properties of printed ABS parts were enhanced by thermal treatment at 240^{o}C using a radiant heating system. Compared to untreated ones, treated samples showed increases in tensile strength of 62%, elastic modulus of 6%, and elongation at break of 110%.
2. The heat treatment could reduce porosity contents leading to enhanced mechanical strength of the treated sample. The µ-CT analysis revealed that porosity was found to be 3% and 1.6% in untreated and treated samples, respectively.
3. The heat treatment could enhance the surface roughness of printed ABS samples. Optical profilometry (OP) analysis showed that untreated samples were rougher than treated ones.
4. The finding of this study showed that thermal treatment could enhance the mechanical and microstructural properties of printed ABS parts. Further research on the FDM technique and other advanced analyses should be conducted to better understand the performance of printed parts.

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Appendix A (supplementary data)

Fig. 1A

Tensile strength of printed ABS samples at different treated temperatures

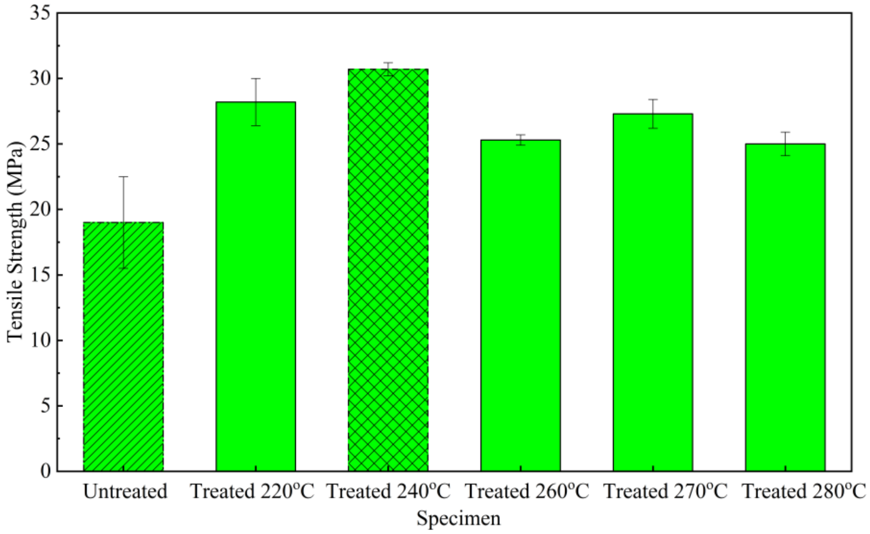


Fig. 2A

Elastic modulus of printed ABS samples at different treated temperatures

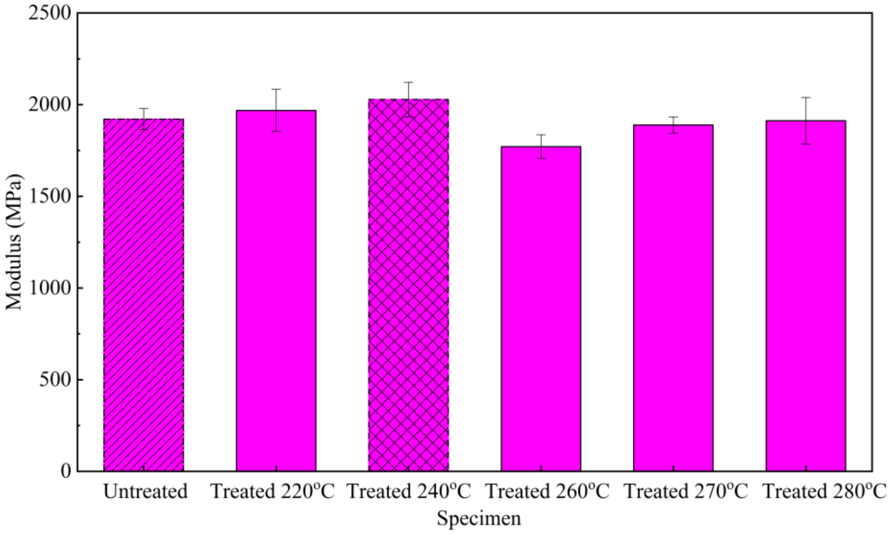
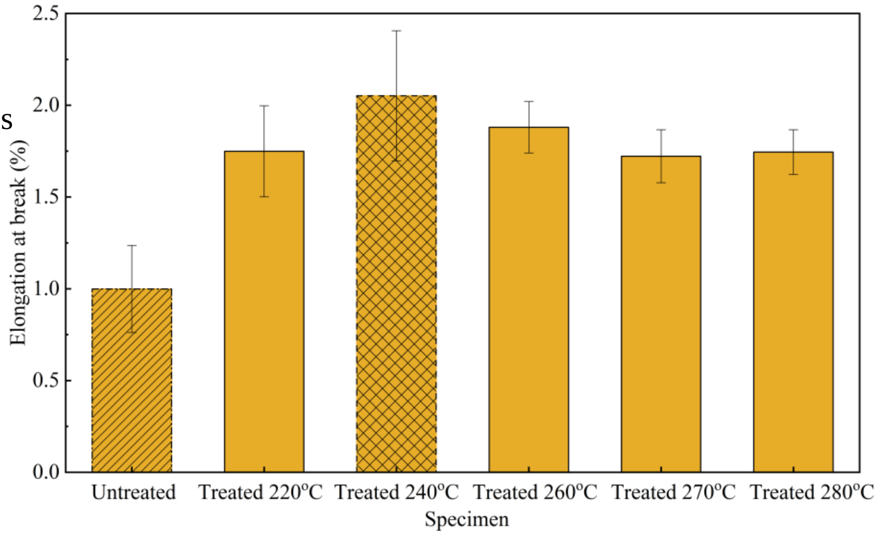


Fig. 3A

Elongation at break of printed ABS samples at different treated temperatures



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