Tensile properties of the FFF-processed thermoplastic polyurethane (TPU) elastomer

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Abstract
Fused filament fabrication (FFF) has become one of the most popular, practical, and low-cost additive manufacturing techniques for fabricating geometrically complex thermoplastic polyurethane (TPU) elastomer. However, there are still some uncertainties concerning the relationship between several operating parameters applied in this technique and the mechanical properties of the processed material. In this research, the influences of extruder temperature and raster orientation on the mechanical properties of the FFF-processed TPU elastomer were studied. A series of uniaxial tensile tests was carried out to determine tensile strength, strain, and elastic modulus of TPU elastomer that had been printed with various extruder temperatures, i.e., 190–230 °C, and raster angles, i.e., 0–90°. Thermal and chemical characterizations were also conducted to support the analysis in this research. The results showed the ductile and elastic characteristics of the FFF-processed TPU, with specific tensile strength and strain that could reach up to 39 MPa and 600%, respectively. The failure mechanisms operating on the FFF-processed TPU and the result of stress analysis by using the developed Mohr’s circle are also discussed in this paper. In conclusion, the extrusion temperature of 200 °C and raster angle of 0° could be preferred to be applied in the FFF process to achieve high strength and ductile TPU elastomer.

Keywords Fused filament fabrication · Extruder temperature · Raster angle · Mechanical properties · Thermoplastic polyurethane

1 Introduction
Recently, fused filament fabrication (FFF), or interchangeably called fused deposition modeling (FDM) after being patented by Scott Crump in 1989 [1], has become one of the most popular, practical, and yet inexpensive additive manufacturing techniques for the fabrication of a geometrically complex and custom-designed polymer-based part [2, 3]. The principle of the FFF relies on the extrusion and deposition of a semi-molten polymeric filament to form a stack of slices that builds up the designed 3-dimensional part [4]. The applications of this technique have so far been growing, starting as a tool for rapid prototyping process up to the fabrication of various consumer goods and patient-specific biomedical implants [5–8]. Up to now, the number of polymeric materials that could have been successfully processed by using the FFF has also been increasing [9], including the attractive and biocompatible thermoplastic polyurethane (TPU) elastomer [10–12]. As reported in the previous works, the additively manufactured TPU-based tracheal and cartilage porous scaffolds have been successfully tested for their biocompatibility to support tissue regeneration [11, 12]. The FFF has also been used to fabricate drug-loaded TPU forms, enabling personalized dosage for patient treatment [10]. Considering such potential applications, the performances of the additively manufactured TPU elastomer should therefore be ensured, including those related to its load-bearing capabilities [1].

Mechanical properties of the FFF-processed material are basically determined by the thermal history experienced by the printed material during the extrusion and deposition to form and build up multiple layers of a solid 3D part [13,
In their works, Bühr and Westkämper [13] and Tan et al. [8] noticed four phases experienced by the filament material during its processing with FFF, i.e., (1) sinter phase, (2) crystallization phase, (3) glass transition phase, and (4) shrinkage phase. At first, the filament material should be heated up to its sinter temperature before the extrusion and deposition onto the printer platform. After being deposited, the semi-molten material cools down and enters its crystallization phase to form crystallites and then the glass transition phase where the material property shifts from elastic to brittle. As further cooling down to its surrounding temperature, the 3D-printed part shrinks to some extent and finally obtains its final form.

The thermal history experienced by the filament material itself depends on its processing parameters applied during the FFF, such as the nozzle or extruder temperature [15–19]. Notably, tensile strength and elastic modulus on FFF-processed polylactic acid (PLA) could be enhanced with the nozzle temperature [15] as a consequence of the improved sintering process of this material at high nozzle temperature [18, 19]. However, other studies revealed a minor role, even no contribution, of the nozzle temperature on the strength of acrylonitrile butadiene styrene (ABS) material [17, 20, 21]. Therefore, considering the critical but uncertain role of this processing parameter, the studies concerning the influence of the nozzle or extruder temperature on the mechanical properties of any particular FFF-processed polymeric material are yet still open.

Besides the nozzle or extruder temperature, the orientation of rasters printed has been recognized as the other influencing parameters determining the anisotropy and mechanical properties of the FFF-processed material [22–25]. For example, the work of Rajpurohit and Dave [23] reported that the highest tensile strength could be achieved by the PLA that was printed with rasters oriented parallel to the loading axis or with a raster angle of $0^\circ$. However, the tensile strength of the FFF-processed polymer then decreased as the raster angle increased to $90^\circ$ [23–25].

Up to recently, the studies concerning the mechanical properties of a solid FFF-printed TPU are also growing but still having been published in limited numbers. The earlier study conducted by Xiao and Gao [26] demonstrated superior strength and toughness of the FFF-processed TPU, as printed with a temperature of 215 °C and raster angle of 45°. Meanwhile, Hohimer et al. [27] noticed in their work the importance of air gap rather than raster angle and printing temperature on the tensile strength of FFF-processed TPU. Furthermore, elasticity and resilience are among the challenges encountered during the printing of TPU with FFF, as noted by Tan et al. [8]. With such properties, this material could be easily deformed when entering the heating section of the 3D printer prior to the deposition process [8] and consequently may compromise the integrity of the printed TPU material. Nevertheless, more extensive works are still needed to ensure appropriate printing parameters that can be used to realize a part from TPU elastomer with desired mechanical properties by using the FFF.

In this research, tensile behaviors of a solid FFF-processed TPU elastomer extruded with temperatures of 190–230 °C were studied. Prior to this experiment, the thermal characteristics of the TPU filament and the chemistry of its printed form were first characterized to indicate the critical temperatures of this material as being heated and cooled down during the printing process. Besides, the influence of raster orientation on tensile properties, i.e., maximum tensile strength, strain at break, and elastic modulus, of such the FFF-processed TPU was discussed and analyzed by using the developed Mohr’s circle.

2 Materials and methods

A series of tensile tests was performed in this research by using a dog-bone-shaped specimen printed from a yellow TPU filament according to ASTM D638–14 standard. As shown in Fig. 1, the raster angle ($\theta$) of the tensile specimen is defined as the angle formed by the raster orientation and the tensile loading axis of the specimen. At first, five groups of specimens having $\theta=0^\circ$ and $90^\circ$ were prepared with the extruder temperatures ($T_e$) of 190, 200, 210, 220, and 230 °C, to determine the influence of such thermal parameters on mechanical properties of the printed TPU elastomer. Meanwhile, the effect of raster orientation on mechanical properties of TPU elastomer was studied by using specimens printed with $\theta=30^\circ$, $45^\circ$, $60^\circ$, $0^\circ$/90°, and 45°/$-45^\circ$. All these specimens were printed by using an open-source FDM 3D-printer with a deposition speed of 35 mm s$^{-1}$, 100% infill, and layer thickness of 0.2 mm.

The tensile test of each specimen group was conducted for five specimens by using Zwick Z020 universal testing machine (Zwick/Roell, Germany) at room temperature and with a cross-head speed of 5 mm min$^{-1}$, also according to ASTM D638 standard. A pre-load of 0.1 MPa was first applied prior to the data acquisition to align the specimen at the correct position over the holder of the universal testing machine. After the tensile test, fracture surface morphologies of all the specimens were then examined by using Zeiss EVO10 electron microscope (Carl Zeiss, Germany). In the end, all the data obtained from the mechanical test were processed by using one-way ANOVA ($\alpha=0.05$) and Tukey’s test in Microsoft Excel 2016.

To aid in determining the influence of extrusion temperature applied, the TPU filament was first characterized by using differential scanning calorimetry (DSC) under N$_2$ gas flush and with the heating and cooling rates of 10 °C min$^{-1}$. Meanwhile, the chemistry of all the printed TPU specimens was characterized by using Shimadzu IRPrestige-21 Fourier
transform infra-red (FTIR) spectroscopy (Shimadzu Corp., Japan). With this technique, the changes in functional groups over the PLA material that possibly occurred to respond to the increasing extruder temperature would be able to be determined.

3 Results and discussion

Up to recently, various types of polymeric materials have been successfully processed by using FFF, including the ductile and biocompatible TPU elastomer [26, 27]. As mentioned earlier, this technique is promising for the fabrication of biomedical implants based on such elastomeric materials, e.g., the tracheal and cartilage scaffolds [11, 12]. However, there are remaining issues that need to be addressed dealing with the properties and performances of such the additively manufactured TPU elastomer. For instance, it is not clear how the mechanical properties of this material would be compromised and the failure mechanisms would be operating as the extruder temperatures was varied during the printing process. Owing to the flexibilities in choosing the printing direction, further explorations are still open for generating a TPU part with appropriate mechanical properties by controlling its raster orientations. In this research, a solid TPU elastomer has been successfully fabricated by using FFF process. A series of investigations were then carried out to determine the effects of extruder temperatures and raster orientations on mechanical properties and failure mechanisms of the FFF-processed TPU elastomer material.

As noted earlier, the thermal history experienced by an FFF-processed polymer would determine its chemistry and mechanical properties. In this research, a DSC test was first carried out to examine the phase changes that possibly occurred once the TPU filament was heated and cooled during the printing process. As shown in Fig. 2, a shallow, convex bump together with a small peak could be recognized at \( T = 75 \) to 150 °C and 170 °C over the heating curve obtained, respectively, while a visible peak at \( T = \sim 72 \) °C was present over the cooling curve. This finding confirmed the result obtained in the previous work [28], in which the wide peak at \( T \) between 75 and 150 °C found in this research might correspond to the glass transition point (\( T_g \)) of the TPU at \( \sim 100 \) °C. Meanwhile, a notable peak at \( T = 170 \) °C over the heating curve and a small peak at a temperature of \( \sim 72 \) °C over the cooling curve in the same figure indicated the melting point (\( T_m \)) and the recrystallization temperature (\( T_c \)) of the TPU elastomer, respectively [28].

With the presence of such \( T_v \) point, it is also confirmed that the TPU filament consisted the soft and hard segments following the formation of amorphous and crystalline structures upon the cooling of this material. As such, the printed TPU possessed excellent flexibility and glassy at room temperature [28].

Figure 3 shows the FTIR spectra obtained from TPU in both the filament and the printed form. All the spectra depicted in this figure were seen as identical by showing several bands that indicated urethane as the main compounds of the elastomer. In this case, the presence of carbonyl group (C=O) and amide (-NH) could be recognized from two bands at the wavenumbers of 1670–1570 cm\(^{-1}\) and 3500–3000 cm\(^{-1}\), respectively. Meanwhile, a band at around 2337 cm\(^{-1}\) was also visible, indicating the presence of the isocyanate region of the TPU. The identical FTIR spectra of all the specimens in this research might correspond to the \( T_g \) values applied, i.e., 190, 200, 210, 220, and 230°, that were all higher than the \( T_g \) and \( T_m \) of the TPU filament.

In this research, the influence of extruder temperature applied during the printing on mechanical properties of the FFF-processed TPU was studied with two specimen configurations, i.e., with the \( \theta = 0 \) and 90°, which corresponded to the axially and the transversally loaded specimens, respectively. As seen in Fig. 4a, both the \( \sigma-\varepsilon \) diagrams demonstrated the presence of the elastic and quasi-plastic regions without visible yield points in between. Interestingly, the stress-strain diagrams of both these specimen groups were similar to those
obtained in the previous work, indicating the presence of elastic and quasi-plastic regions [28].

On the basis of the stress-strain diagrams in Fig. 4a, the $\sigma_{\text{max}}$, $\varepsilon_{\text{break}}$, and $E$ values of all the FFF-processed TPU could then be plotted separately as a function of the $T_e$ values applied, such as shown in Fig. 4b–d. As seen in Fig. 4b, the $\sigma_{\text{max}}$ values of the axially loaded TPU were obviously higher than those of the transversally loaded ones, except those printed with $T_e = 200 ^\circ$C. The ANOVA test of the $\sigma_{\text{max}}$ values of the axially loaded specimen, however, revealed a lower calculated $F$ value ($F_{\text{calc}} = 2.461$) than its critical value ($F_{\text{crit}} = 3.478$); implying that the change of $T_e$ from 190 to 230 $^\circ$C did not significantly influence $\sigma_{\text{max}}$ of these specimens. This finding might confirm the identical FTIR spectra presented in Fig. 3 and the work of Hohimer et al. [27]. On the other hand, a significant influence of $T_e$ on $\sigma_{\text{max}}$ could be seen for the transversally loaded specimens, as indicated by the higher

Fig. 3 The FTIR spectra of the TPU filament and its forms after FFF

Fig. 4 The effect of extruder temperature on mechanical properties of FFF-processed TPU elastomer: (a) the stress-strain diagram, (b) maximum tensile strength, (c) tensile strain at break and (d) elastic modulus
$F_{\text{calc}}$ (14.545) than its $F_{\text{crit}}$ value (3.478). Further analysis by using Tukey’s test (with $T_{\text{crit}} = 10.381$) revealed that the $\sigma_{\text{max}}$ values of TPU printed with $T_e = 200$ and 230 °C were significantly higher than the others. In this case, the use of $T_e = 200$
and 230 °C could achieve TPU with higher $\sigma_{\text{max}}$ values than the other $T_e$ values, which might imply that inter-raster bond strength over the printed TPU was more sensitive to the changes in the extruder temperature rather than the material itself. Similar to the case in this research, Yang et al. [29] reported an increase in tensile strength and elastic modulus of the FFF-processed poly-ether-ether-ketone (PEEK) with the increasing nozzle head temperature applied from 360 to 420 °C. However, the use of higher nozzle temperatures than 420 °C led to a decrease in those properties, possibly due to the deterioration of polymeric material structure as a result of the excessive melting temperature [29]. On the other hand, it is also important to note that the increasing nozzle or extruder temperature would increase the fluidity of the molten polymer, which could in the end not only improved the diffusion and adhesion of the deposited material with its preceding layer, but also reduced the number of pores formed at the interstices of the adjacent layers [15, 29]. Considering these phenomena, a stronger interlayer adhesion over the FFF-processed polymer and a higher tensile strength could be achieved, such as shown in the case of TPU elastomer printed with $T_e = 230 \, ^\circ\text{C}$ in this research.

Confirming the previous study [26, 27], Fig. 4c demonstrated the excellent ductility of the FFF-processed TPU elastomer, as indicated from their strain-at-break values that could reach 400 and 600%. The $\varepsilon_{\text{break}}$ values obtained in this research are also higher than polylactic-acid (PLA) and acrylonitrile butadiene styrene (ABS) produced with the same technique [23, 24] and the laser-sintered TPU elastomer [28]. Interestingly, the ANOVA test revealed a significant influence of $T_c$ on $\varepsilon_{\text{break}}$ of both the axially and transversally loaded specimens, each with $F_{\text{calc}}$ of 5.470 and 7.644, respectively, that were all higher than their $F_{\text{crit}}$ (3.478). Tukey’s test after ANOVA demonstrated the highest $\varepsilon_{\text{break}}$ of the transversally loaded TPU printed with $T_e = 200 \, ^\circ\text{C}$. Meanwhile, the ANOVA revealed that the changes in $T_c$ could only determine the elasticity of the transversally loaded TPU. The result of Tukey’s test ($T_{\text{crit}} = 5.782$) after ANOVA also demonstrated that the highest $E$ value of the TPU material printed with $T_c = 200$ and 230 °C, i.e., around 37 MPa, such as shown in Fig. 4d.

The influence of raster orientation on the mechanical properties of the FFF-processed TPU is shown in Fig. 5. In this experiment, all the TPU specimens were printed 220 °C. Similar to the stress-strain characteristics presented in Fig. 4a, all these diagrams generally show the presence of the elastic and plastic region with an invisible yield point in between. By using the typical stress-strain diagrams in Fig. 5a, the relationships between raster angle $\theta$ and the $\sigma_{\text{max}}$, $\varepsilon_{\text{break}}$, and $E$ values of the FFF-processed TPU could be determined and shown in Fig. 5b–d. The result of ANOVA of this experiment shows higher $F$ values, i.e., 56.091, 37.188, and 4.533, than their critical value, i.e., 2.848, which implied a significant difference among all the average $\sigma_{\text{max}}$, $\varepsilon_{\text{break}}$, and $E$ values of

Fig. 7 The effect of extruder temperature on fracture surface morphologies of the FFF-processed TPU specimens after tensile test, for specimens printed with raster angles of (a)-(c) 0° and (d)-(f) 90°

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each specimen group tested in this study, respectively. As seen in Fig. 5b–d, the highest and lowest $\sigma_{\text{max}}$, $\varepsilon_{\text{break}}$, and $E$ values could be achieved by printing the TPU in unidirectional raster orientation with $\theta$ values of $0^\circ$ and $90^\circ$, respectively. Obviously, the use of bidirectional raster orientation seemed not to improve the mechanical properties of the

Fig. 8 The effect of raster orientation on fracture surface morphologies of the FFF-processed TPU specimens after tensile test, for specimens printed with raster angles of (a) $30^\circ$, (b) $45^\circ$, (c) $60^\circ$, (d) $0^\circ/90^\circ$, (e) $45^\circ/-45^\circ$.
As the raster orientation was skewed to the loading axis of the specimen, in the case of specimen with \( \theta = 0^\circ/90^\circ \), its fractured site was stretched to some extent, leaving the pulled-out layers that did not appear with regular pattern over the ruptured surface. Similarly, the specimen with \( \theta = 90^\circ \) also displayed irregular arrangements of the deposited TPU material, as shown in Fig. 7d–f. As indicated in Fig. 7, this phenomenon occurred in both the TPU specimens printed with \( \theta = 0^\circ \) and \( \theta = 90^\circ \). In the latter specimen, however, raster separation that occurred following the inter-raster path of the material could hardly be recognized. This finding might imply that inter-raster bond strength over the printed TPU was stronger than the material. Unfortunately, the influence of the extruder temperature on the fracture surface morphologies could not be clearly seen in this research.

The fracture surface morphologies of the TPU elastomer printed with various raster angles are shown in Fig. 8. As can be seen in Fig. 8a–c, the fracture surface morphologies among the TPU specimens printed with \( \theta = 30^\circ, 45^\circ, \) and \( 60^\circ \) could not be easily distinguished. All these specimens also displayed irregularly arranged stacks of deposited TPU layers. In addition, several TPU layers were seen being pulled out to respond to the tensile load applied. In the case of specimens printed with \( \theta = 0^\circ/90^\circ \) and \( \theta = 45^\circ/−45^\circ \) (Fig. 8d–f), the fracture
surfaces of these materials could be seen as having a stack of fibrous layers crossing each other, such as shown at the circled area in Fig. 8e. However, all these surfaces were also generally irregular and covered with the presence of pulled-out layers.

To give further insight into the relationship between the raster orientation and the tensile strength of the FFF-processed TPU, a wedge-shaped element from the printed specimen was analyzed together with all the working stresses over this element, such as illustrated in Fig. 9a. In this work, however, $\sigma_y$ and $\tau_{xy}$ were nullified as there was no tensile load acting at $y$-direction and external shear load working on the wedge element, respectively. The working stress $\sigma_x$ could then be transformed into the stresses that operate along the $x'$- and $y'$-axes, which in the end led to the generation of a so-called Mohr’s circle, such as indicated in Fig. 10. With this circle, the stress variations over the specimen could be visualized as a function of the raster angle $\theta$.

According to the Mohr’s circle in Fig. 10, $P$ and $S$ represent the in-plane principal stresses working on material, i.e., $\sigma_{x,1}$ and $\sigma_{x,2}$, respectively, and their magnitudes can be determined by using Eq. (1) [30]:

$$\sigma_{x,1,2} = \frac{\sigma_x}{2} \pm \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + \tau_{xy}^2}$$  \hspace{1cm} (1)

In this equation, $\frac{\sigma_x}{2}$ and $\sqrt{\left(\frac{\sigma_x}{2}\right)^2 + \tau_{xy}^2}$ are known as the average stress ($\sigma_{avg}$) and the maximum in-plane shear stress ($\tau_{max}$), which can be determined from the centre and the diameter of the Mohr’s circle, respectively. By considering that the raster angle $\theta = \pi/2 - \alpha$ (Fig. 9), the normal ($\sigma'$) and shear stresses ($\tau'$) experienced by the inter-raster bond region of the printed TPU could be derived as a function of this angle by using Eqs. (2) and (3):

$$\sigma' = \sigma_x - \tau_{max}\cos2\alpha = \frac{\sigma_x}{2} - \tau_{max}\cos2\theta$$  \hspace{1cm} (2)

$$\tau' = \tau_{max}\sin2\alpha = \tau_{max}\sin2\theta$$  \hspace{1cm} (3)

To validate the Mohr’s circle developed in this research, the $\sigma_{avg}$ and $\tau_{max}$ values of the printed TPU should first be determined, i.e., by using the tensile strength data obtained from the specimen having a raster angle of $\theta = 45^\circ$. By substituting this angle value to Eqs. (2) and (3), both the $\sigma_{avg}$ and $\tau_{max}$ values were found to be $\sigma_x = 15.1$ MPa. As noted earlier in this work, the maximum inter-raster bond strength was achieved when the TPU was printed with $\theta = 90^\circ$. The substitution of this angle value to Eq. (2) yielded $\sigma' = 30.2$ MPa, which was indeed slightly higher than, but still close to, the experimental tensile stress of the specimen with the corresponding raster angle, i.e., $\sim 25$ MPa. In the case of specimen printed with $\theta = 0^\circ$, the calculation by using Eq. (2) yielded $\sigma' = 0$, which was considered appropriate for indicating that the uniaxial load applied during the test was all held by the printed TPU material, instead of the inter-raster region between two adjacent rasters printed over the specimen.

With the Mohr’s circle in Fig. 10, it is also interesting to indicate the normal and shear stresses that act together during the tensile test of material with $\theta = 30^\circ$, 45°, and 60°. This phenomenon was confirmed by the findings presented in Figs. 6a–c and 8a–c, which demonstrated a skewed fracture surface and showed the presence of ruptured, twisted rasters over the fracture surfaces over the TPU specimens printed with such raster angle configurations.
In the case of the FFF-printed TPU with $\theta = 0^\circ/90^\circ$ and $45^\circ/-45^\circ$, it can be noted that there were pairs of layers deposited perpendicularly one another. As a result, there was less contact area over the printed material with such configuration than with unidirectional raster orientation, such as illustrated by the top-view of the rasters deposited over the specimens in Fig. 11. In this figure, the gray area represents the contact area that is formed between the illustrated rasters and the adjacent layers on top of them. As indicated in Fig. 11b, the contact area between the two crossing rasters in the specimen was square but smaller than that of the rasters printed with aligned orientation in Fig. 11a. This phenomenon is confirmed from the fracture surface morphology of the TPU specimen in Fig. 8e, where the low bonding quality could be seen between two adjacent rasters, as being printed perpendicularly one another.

As demonstrated in Fig. 5, the TPU specimen having $\theta = 45^\circ/-45^\circ$ was slightly stronger than that printed with $\theta = 0^\circ/90^\circ$. The Mohr’s circle in Fig. 10 reveals that the working stresses over the paired layer of TPU printed with $\theta = 45^\circ/-45^\circ$ could be represented by points $Q$ and $T$, at which the maximum $\tau$ value was achieved and experienced by all pairs of deposited layers but oriented oppositely due to their crossing orientation at $\theta = 45^\circ$ and $-45^\circ$. Meanwhile, the $\sigma'$ experienced by the printed material equals to the $\sigma_{avg}$ value obtained from the Mohr’s circle, i.e., $-15.1$ MPa. With all layers having such magnitudes of normal and shear stresses, the TPU specimen printed with $\theta = 45^\circ/-45^\circ$ therefore possesses higher load-bearing capability than that printed with $\theta = 0^\circ/90^\circ$, whose two adjacent layers must hold different magnitudes of stresses due to their crossing orientation. Figures 6g and 8f confirmed the presence of the oppositely directed shear stresses in the TPU printed with $\theta = 45^\circ/-45^\circ$, by indicating a saw-teeth-shaped fracture site and twisted, pulled-out fibers over the fracture surface area of the TPU printed with this configuration.

4 Conclusions

In this research, the influences of extruder temperatures and raster orientations on mechanical properties of FFF-processed TPU elastomer were investigated. In general, the FFF-processed TPU demonstrated excellent ductility and can be considered an alternative elastic material for engineering and biomedical applications. In addition, the Mohr’s circle developed from this experimental work was found helpful for aiding the way to determine the influence of raster orientation and mechanical properties of the FFF-processed TPU. On the basis of all the results obtained in this research, it can then be concluded that:

1. The extrusion temperature of $T_e = 200$ °C is preferable to be applied in the FFF to achieve TPU elastomer with the highest tensile strength and ductility among the others that had been prepared with the range of $T_e$ used in this study.
2. The TPU elastomer with the highest tensile strength and ductility could be produced by the FFF with raster angle of $\theta = 0^\circ$, with which the tensile load was held by the printed material itself instead of the inter-raster bond region between the two adjacent rasters. In addition, the use of a bidirectional configuration did not improve the mechanical properties of the FFF-processed TPU elastomer.

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