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ORIGINAL ARTICLE

Influence of warm isostatic press (WIP) process parameters on mechanical properties of additively manufactured acrylonitrile butadiene styrene (ABS) parts

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Abstract
Owing to the deposition mechanism, parts fabricated from the material extrusion (ME) process have intrinsic air gaps that negatively impact their mechanical properties. Thus, the amount of air gaps should be minimized. In this study, a warm isostatic press (WIP) process was adopted to decrease the amount of air gaps, resulting in improved mechanical properties using acrylonitrile butadiene styrene (ABS). To identify changes in the mechanical properties, tensile tests were performed with specimens heat-treated by the WIP processes with different pressure–temperature profiles. The influence of the temperature and pressure on tensile strength, elongation at break, and toughness was investigated. Water tightness evaluation was conducted to prove the decrease in the air-gap size. Based on the investigation, the WIP process was concluded to be effective for decreasing the intrinsic air gaps and improving the mechanical properties owing to the increase of the bonding force between the lines and layers, which led to the suggestion of a method that optimizes the parameters of the WIP process.

Keywords Additive manufacturing (AM) · Material extrusion (ME) · Warm isostatic press (WIP) · Mechanical properties · Tightness

1 Introduction

Additive manufacturing (AM) technology can build complex parts that cannot be fabricated by conventional manufacturing technology. Owing to this advantage, it has received significant interest as an alternative in various industrial fields [1–4]. In ASTM F2792-12a, AM technologies are divided into the following seven groups: material extrusion (ME), vat photopolymerization (VP), material jetting (MJ), binder jetting (BJ), powder bed fusion (PBF), direct energy deposition (DED), and sheet lamination (SL) [5].

Among these groups, ME technology is the most used and actively studied owing to its accessibility and usability. It also has only a few restrictions on the use of thermoplastic polymers, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyamide (PA), polysulfone (PSU), polyetherimide (PEI), and polyetheretherketone (PEEK) [5–10]. However, parts manufactured with the ME technology have mechanical properties that are inferior to those of conventional processes [11, 12], whereas parts fabricated using other AM technologies demonstrate superior or similar mechanical properties [13, 14]. The cause of deterioration for the mechanical properties in ME-fabricated parts has been investigated, and several studies have revealed that the intrinsic air gaps originating from the extrusion process are the main reason [15, 16]. In addition, these air gaps can result in the poor quality of a part, such as weight unbalance, poor surface integrity, and poor tightness [17–20].

The air gap has been attempted to be reduced by optimizing the process parameters, where all process parameters should be tailored to narrow the space between the lines or layers. A narrow nozzle tip or a large infill overlap can be considered to narrow the space between the lines [11, 21,

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22]. A small layer thickness can reduce the space between the layers [23, 24]. In certain cases, the infill pattern can affect the density of the fabricated part [25]; however, in many cases, optimization focuses on the dimensional accuracy and surface quality. Thus, the intrinsic air gap remains after optimization of the process parameters. Chemical or heat treatment has been investigated as another approach. In the former method, chemicals attack polymer chains and degrade them, resulting in the deterioration of mechanical properties [18, 19]. In addition, it was found that the chemicals did not reach the internal air gaps. Heat treatments can affect the internal air gap and have been used to improve the warpage and release the internal stress in the injection molding [26]. As a result of heat treatment, an improvement in the toughness and tensile strength of a fabricated part was reported [27–29]. Upon increasing the temperature in the chamber, the deposited polymers were re-melted and cooled. The adjacent lines or layers slowly re-bonded during the heat treatment, and the residual stress between the lines and layers was released. This process can improve the toughness [30]. Although the fact that heat treatment reduces air gaps has not been reported, the high temperature provides an environment for the internal movement of polymers [31].

In this regard, authors were interested in the effect of temperature on reducing the air gap. However, increasing the temperature as a conventional heat treatment was insufficient to reduce the air gap. The heat can improve the mobility of a polymer, but heat cannot lead to the flow state of the polymer [32]. Hot isostatic pressing (HIP) can be considered as an alternative, which has been mainly used to reduce the internal air gap of a metal part with a high pressure and temperature [33]. Several studies have been conducted with diverse materials for the hot isostatic pressing (HIP) process. In the case of aluminum alloys fabricated by PBF, the HIP process was conducted in an argon atmosphere at a temperature of 480 °C and pressure of 120 MPa for 120 min. The ultimate tensile strength and elongation at break of AA2024 specimens increased by approximately 16% and 26%, respectively, with a reduction in air gap, compared to those without HIP [34]. The HIP process was carried out for a TiB_2/316L stainless steel (STS) composite fabricated by PBF in an argon atmosphere at a temperature of 1150 °C and pressure of 2070 bar. The microhardness of the specimen subjected to HIP twice increased by approximately 1.4 times when compared to that of the specimen subjected to HIP once [35]. Furthermore, the PBFed STS 316L, NiAl-Cr-Mo alloy, EP741NP nickel alloy, Co-Cr-Mo alloy, and Inconel 625 alloy were taken through the HIP process at temperatures above 1000 °C and pressures above 1000 bar after the PBF process. The experiments demonstrated that the HIP process is positive in terms of physical properties [33, 36–40]. The results mentioned above show that temperature and pressure are effective in reducing the internal voids generated during the metallic PBF process, and the optimal condition of the temperature and pressure should be determined by the type of materials. However, the pressure and temperature in the HIP process are excessively high for the polymer part. Hence, the authors chose to use warm isostatic pressing (WIP) similar to the HIP process, which has been used for semiconductor component manufacturing, reactor of material polymerization, and lamination of sheets.

In this study, the authors found the process window of the temperature at which the warpage cannot appear and proposed a method to determine an effective net pressure into a part. Based on the experimental results, the authors determined a proper pressure–temperature profile for the WIP process. The mechanical properties of the specimens processed under the designed WIP process, such as tensile strength, elongation, and toughness, were quantitatively compared to those of the non-processed specimens. Finally, the effectiveness of the WIP process was demonstrated by verification of the reduction of the air gap and the increase of the mechanical properties. Based on the analysis of the investigation, the authors suggested a method to optimize the parameters in the WIP process.

2 Experimental

2.1 Fabrications of tensile and water tightness evaluation specimens

Tensile specimens were used to investigate the influence of the parameters of the WIP process on the warpage and the mechanical properties. A tightness specimen was fabricated to qualitatively estimate the reduction in the air gap. Tensile and tightness specimens were additively manufactured with a commercially available ME process (Fortus 250mc, STRATSYS, U.S.A.). Acrylonitrile butadiene styrene (ABS plus, STRATSYS, U.S.A.) with a glass transition temperature (T_g) of approximately 108 °C was utilized for the fabrication. The infill pattern for the tensile specimen fabrications was +45°/−45° of the raster angle with one contour, as shown in Fig. 1(a). The cylindrical tightness specimens with holes were manufactured with the same infill pattern shown in Fig. 1(b). The fabrication layer was 0.254 mm thick. The process parameters used for the ME process, such as the nozzle temperature (°C), chamber temperature (°C), nozzle diameter (mm), and nozzle moving speed (mm/s), were those set by the machine manufacturer.

2.2 Design of the WIP process

2.2.1 Equipment

Figure 2 presents the equipment used for the WIP system that was designed to independently control the temperature and pressure under the surrounding heater and inert gases,

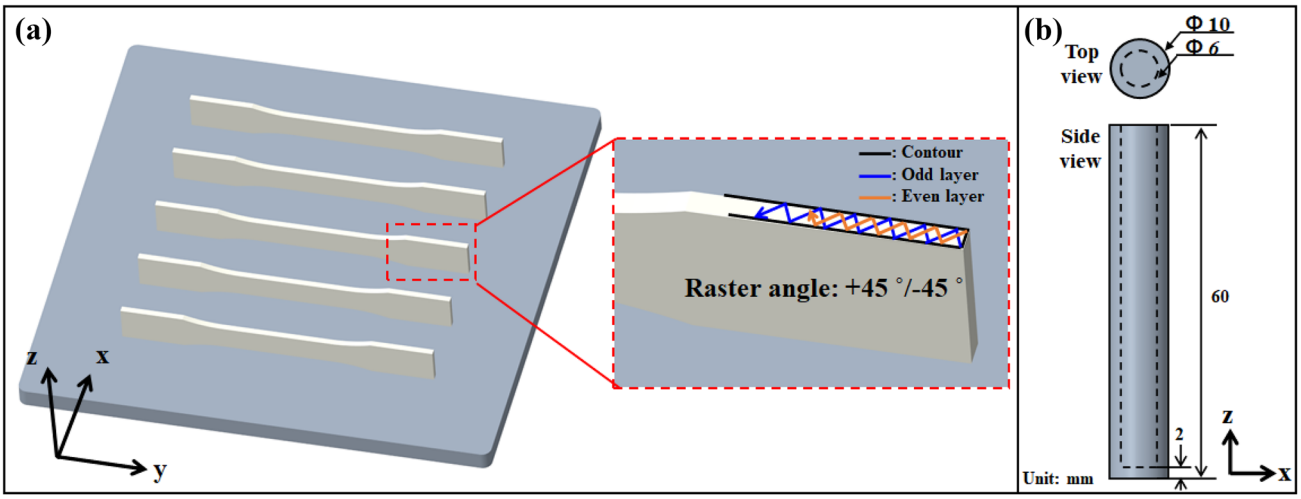

Fig. 1 **a** Built orientation of tensile specimens and **b** dimensions of water tightness evaluation specimens

such as argon or nitrogen. The temperature and pressure in the chamber can be increased up to 350 °C and 100 bar, respectively. During the WIP process, all the specimens were placed inside a chamber with a volume of 5000 cm^3.

2.2.2 Pressure–temperature profile

A profile for the pressure and temperature is required for the WIP process. In this study, the initial profile for the pressure and temperature was built by referring to the profile of the hot isostatic press (HIP) process. The following three profiles were considered to estimate the influence of the individual parameters in the WIP process: only temperature (OT), first pressure (FP), and first temperature (FT). The OT case is designed to estimate the influence of the temperature by comparing it with and without the OT process, as shown in Fig. 3(a). The temperature profile of the OT was designed by referring to the annealing process to remove residual stresses [30]. FP and FT cases were designed to estimate the influence of the application order of the pressure and temperature for the effect of the WIP process. For example, FP initially increases the pressure in the chamber, which is followed by an increase in the temperature, as shown in Fig. 3(b). The concept of FT is opposite to that of FP, as shown in Fig. 3(c). To determine the proper chamber pressure and temperature, the chamber pressures were set to 0, 10, 50, and 90 bar and the temperatures to 110, 120, 130, and 140 °C, respectively. All specimens in this study were processed with a holding time of 1 h. The heating rate was 5 °C/min, and the pressure was filled in the chamber within 1 min. After the holding time passed, the specimens were slowly cooled in the chamber. Prior to the WIP process in this study, the specimens were vacuum packed to increase the net pressure, which is the difference between the inner and the outer pressures. Accordingly, all specimens were vacuum packed with a polyamide (PA) packaging film by using a vacuum packing machine (AZC-010, Intrise Corporation, Republic of Korea) for 30 s before the WIP process. The specimens were processed with and without vacuum packing under FP conditions to understand the vacuum packing effect.

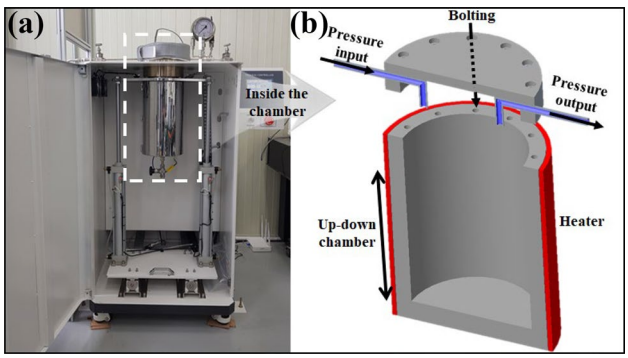

Fig. 2 **a** Photograph of the equipment and **b** schematic of the cross section for the WIP system

2.3 Measurements of properties

The tensile specimens were fabricated with a thickness of 3.2 mm according to the ASTM D638 type 1 standard. A universal testing instrument (DTU-900, Daekyung Tech, Republic of Korea) was used for the tensile test, which was conducted under the standard condition. The mechanical properties, such as the tensile strength, elongation at break, and toughness, were evaluated by averaging five measurements and displayed as the mean ± standard deviation. The toughness was calculated according to Eq. (1):

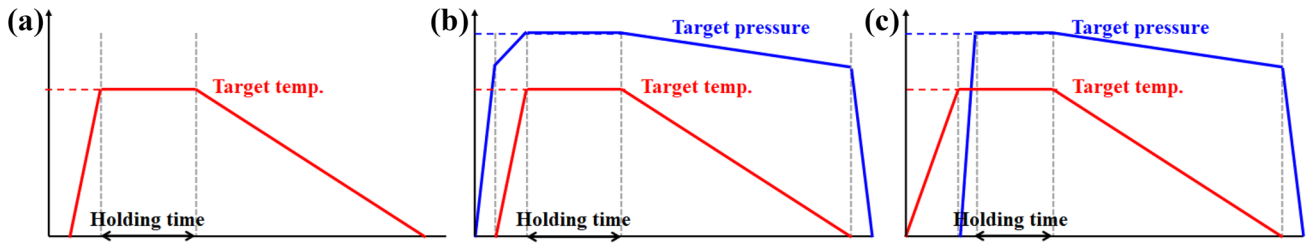

Fig. 3 Temperature–pressure profile for **a** only temperature (OT), **b** first pressure (FP), and **c** first temperature (FT)

$$W = \int_0^{\epsilon_m} \sigma d\varepsilon \tag{1}$$

where σ is the stress and ε is the strain. The energy absorption or toughness can be calculated by integrating the area under the stress–strain curve per unit volume for a specimen, up to a strain ϵ_m [41].

For the confirmation of air gaps, the cross sections of the fractured specimens were observed with an optical microscope (OM; Axio Vert A1, ZEISS, Germany). The quantitative size of an air gap was calculated with the threshold of OM. All air gap sizes were represented in the OM image.

The water tightness evaluation was performed by inserting an air hose into the sample entrance. The entrance of the specimens was wrapped with parafilm to prevent the injected air from escaping. The specimens were immersed in water, and 1 bar of air was injected to check for air leakage from the specimens with and without the WIP treatment.

3 Results

3.1 Effect of vacuum packing in the WIP process

3.1.1 Prevention of the warpage in the WIP process

The WIP process should be conducted above T_g to improve its effect. As the temperature increases, a warpage phenomenon in the specimen is found during the WIP process. Figure 4 presents the warpage of the tensile specimens according to the chamber temperature and fixation. The temperatures in the figures are maximum temperatures at which warpage appears. The specimens without fixation began to deform at 100 °C, which occurred at the center of the specimen during heating because they were obliquely placed in the chamber, as shown in Fig. 4(a). To address this problem, the specimen was drilled at the center of the grip section and hung at the top of the chamber, as shown in Fig. 4(b). In the case of hanging fixation, the specimen was deformed around the drilled hole at 130 °C, which is approximately 1.2 T_g. Finally, the authors decided to use a jig to prevent deformation caused by the high temperature. The jig was composed of polyetheretherketone (PEEK), as shown in Fig. 4(c), which can withstand high temperatures because super-engineered plastic has superior thermal properties. The specimen was deformed at 140 °C and 1.3 T_g for jig fixation, and was deformed in a direction that was not closed by the jig. In addition to using the jig, vacuum packing was used to prevent deformation toward the direction unclosed by the jig, which prevented deformation at 140 °C. The following conclusions can be drawn based on the results. The specimen weight may affect its deformation under isostatic pressures and high temperatures. Vacuum packing may be helpful for preventing the deformation of a specimen under high pressures and temperatures [42].

3.1.2 Enhanced mechanical properties

Figure 5 presents the changes in the mechanical properties and sizes of the air gaps under the following three conditions: without WIP, with vacuum packing, and without vacuum packing during the WIP process. All specimens were subjected to a chamber pressure and temperature of 90 bar and 130 °C, respectively. For all cases, the tensile strength exhibits an insignificant change, as shown in Fig. 5(a). These specimens had a contour parallel to the tensile load. Therefore, the tensile strength is more dependent on the intrinsic strength of the layer than on the interlayer bonding [5, 43].

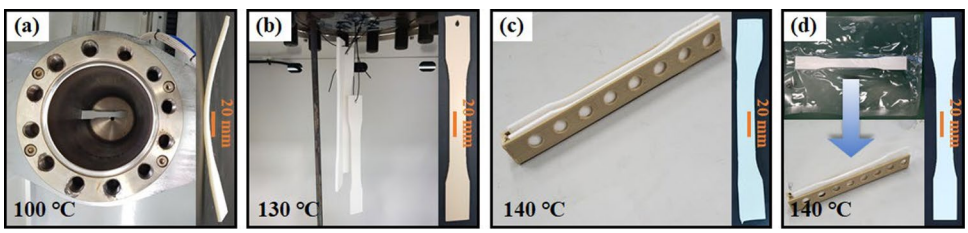

Fig. 4 Warpage of tensile specimens according to chamber temperature: **a** without fixation, **b** with hanging fixation, **c** with jig fixation, and **d** with vacuum packing and jig fixation

The elongation at the break and toughness of the specimens demonstrated significant differences, as shown in Figs. 5(b) and (c). In the case of vacuum packing during the WIP process, the mechanical properties demonstrated a higher elongation and toughness. Figure 5(d) presents the direction of the pressure inside the air gap and chamber.

Without vacuum packing, the pressure inside the air gap is equal to the pressure inside the chamber and the direction of the two pressures is opposite. The pressure condition disturbs the air-gap reduction during the WIP process. Thus, the improvement in the mechanical properties of the specimen processed without vacuum packing is due to the stress-relief effect of the chamber temperature rather than the reduction of the air gap by the chamber pressure [44].

Therefore, it is essential for the pressure to be applied to the specimen surface to reduce the air gap. In the case where vacuum packing was utilized, the chamber pressure only applies to the surface of the specimen. This phenomenon can help reduce the air gaps and improve the mechanical properties. Figure 5(e) presents the change of the air gap in the three cases. The size of the air gaps in the specimen processed without vacuum packing was slightly reduced in comparison to that processed without the WIP. However, the air gaps in the specimen with vacuum packing were barely noticeable.

Based on the aforementioned observation, vacuum packing should be implemented during the WIP process to reduce air gaps. Therefore, all the specimens for the subsequent tests were vacuum packed during the WIP process.

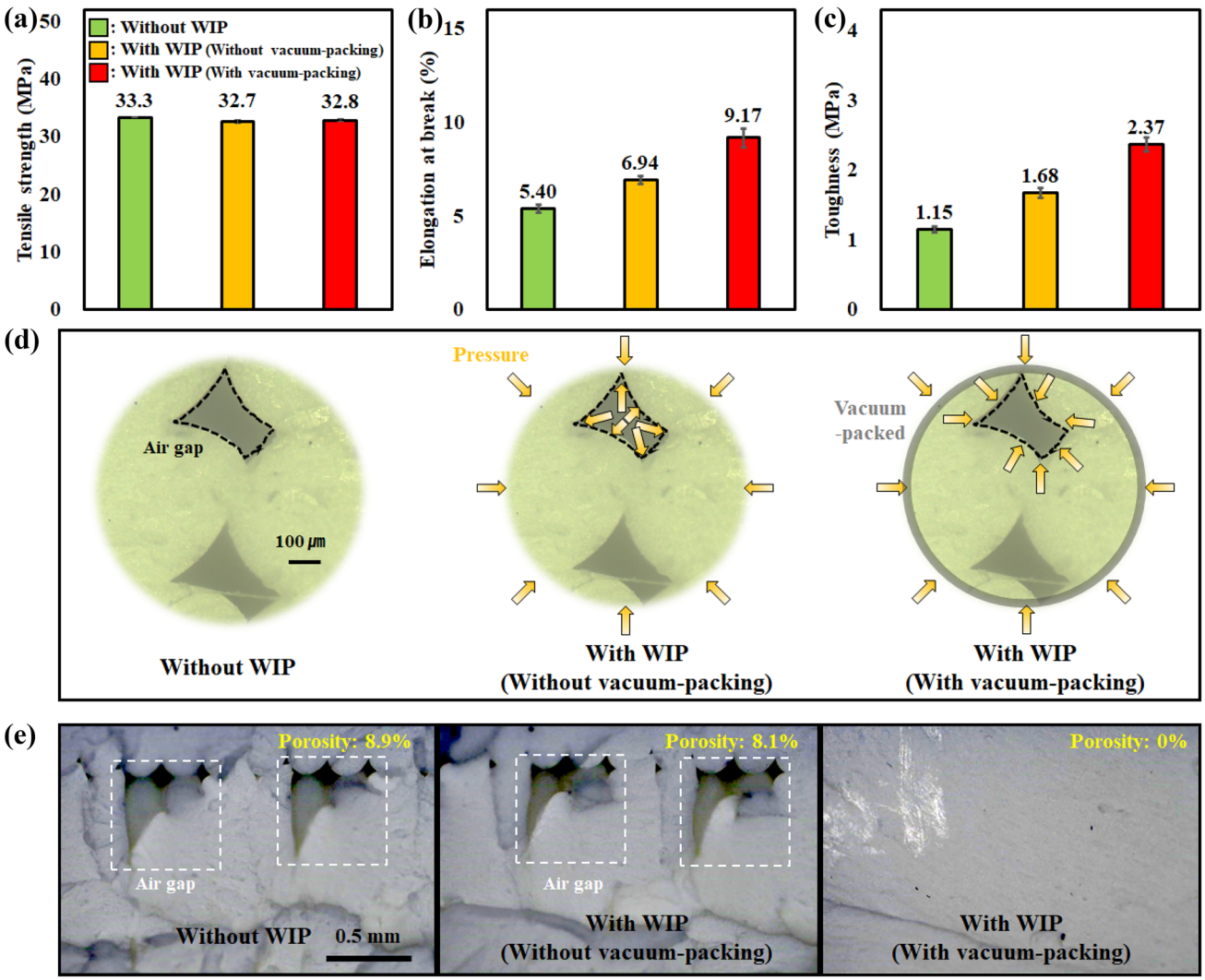

Fig. 5 Comparison of mechanical properties: **a** tensile strength, **b** elongation at break, **c** toughness, **d** air-gap reduction, and **e** air gap without WIP and with WIP (without vacuum packing and with vacuum packing)

3.2 Estimation of the WIP process parameters for mechanical properties

3.2.1 Effect of the application order of pressure and temperature

As indicated in Sect. 2.2.2, the chamber pressure and temperature can be independently controlled in the WIP process. The order of applying the parameters could be considered as a parameter that leads to changes in the mechanical properties of the specimens during the WIP process. To investigate the effect of the application order, it is necessary to observe the change in the mechanical properties with the change in the application order. Figure 6 presents the tensile results and the changes in the air gap. All the cases considering tensile strength are similar, as shown in Fig. 6(a). The elongation at the break and the toughness increased, as shown in Fig. 6(b) and (c), when compared to the specimen processed without WIP. Regarding the tensile strength, it is a reasonable value compared to the results in Fig. 5(a). Figure 6(d) presents the reduction of the air gap by the WIP process. The application order of pressure and temperature had no significant effect on the mechanical properties of the parts fabricated by the ME process.

3.2.2 Effect of pressure

In general, the conventional heat treatment of polymers is conducted by controlling the temperature profile over time [26, 27, 45]. This mainly aims to relieve the residual stress on the polymer chain formed during the process. There is no external force during the heat treatment. Hence, the air gap produced during the ME process remains after heat treatment. In contrast with the conventional heat treatment of polymers, pressure is added in the WIP process. Thus, the effect of the pressure needs to be investigated.

To investigate the effect of pressure, the specimens were processed under various pressures and a temperature of 130 °C. Figure 7 demonstrates the tensile results and sizes of the air gaps in the specimens treated from the only temperature (OT) and WIP process with different chamber pressures. There was no significant difference in the tensile strength. The elongation and toughness increased steadily with an increase in the chamber pressure, and the air gap decreased with pressure as well.

Based on the results, the effects of both stress relief and reduction of air gaps occurred by the WIP process [27, 44, 46]. The reduction in the air gaps is more closely related to the elongation at the break and toughness rather than the tensile strength. The increase in the bonding area between the lines and layers caused by the reduction of the air gaps is more effective in increasing the elongation and toughness, and the effect of the stress concentration by the air gaps is insignificant in the static test of the polymer [47].

3.2.3 Effect of temperature

Temperature is an important parameter in the WIP process because temperature or heat provides energy for the polymer chain to physically move [48]. However, if the

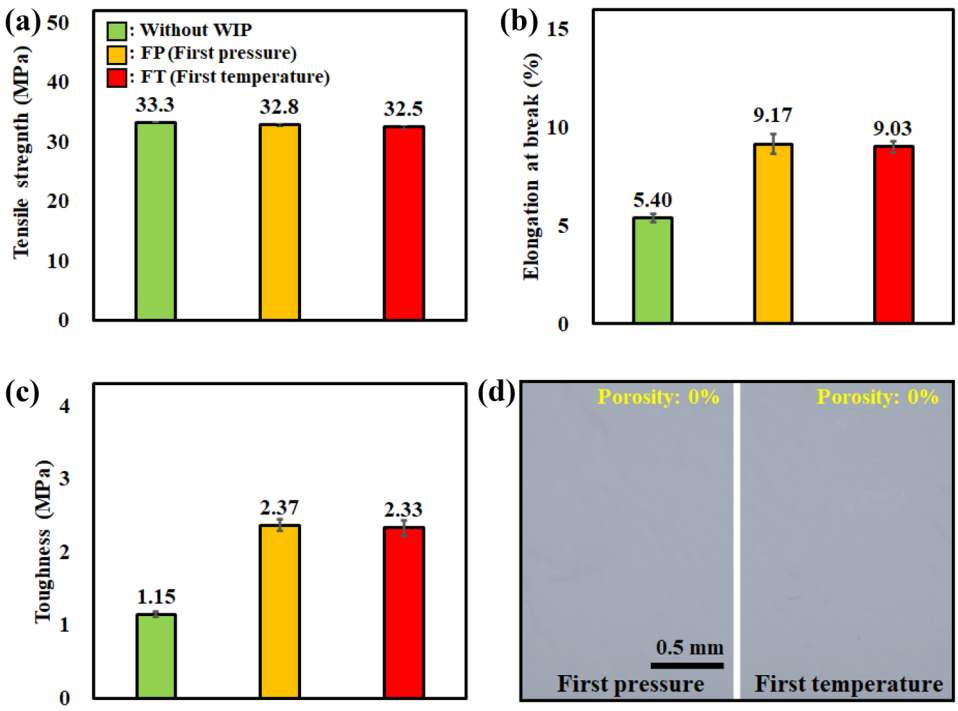

Fig. 6 Comparison of mechanical properties: **a** tensile strength, **b** elongation at break, **c** toughness, and **d** air gap of first pressure (FP) and first temperature (FT)

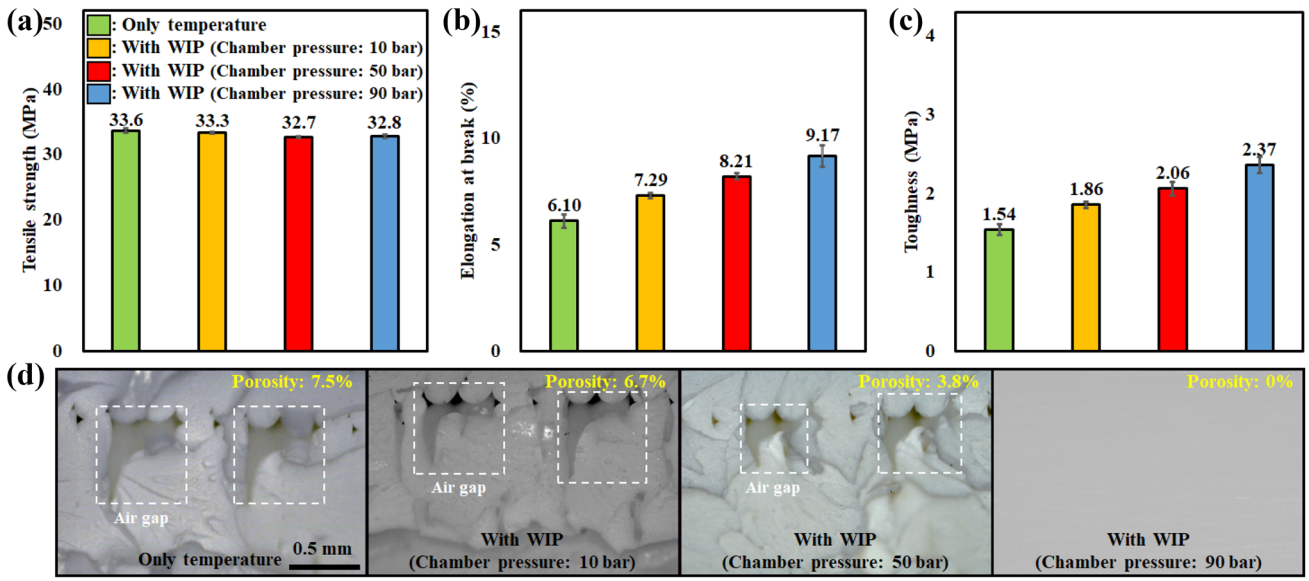

Fig. 7 Comparison of mechanical properties: **a** tensile strength, **b** elongation at break, and **c** toughness, and **d** air gaps for the only temperature (chamber pressure: 0 bar) and with WIP process with different chamber pressures

temperature is too high, there is a possibility of polymer degradation [49]. Therefore, it is necessary to determine the proper chamber temperature at which degradation does not occur.

Figure 8 presents the tensile strength results and the size of the air gaps in the specimens from the WIP process with different temperatures. All the specimens were processed under a chamber pressure of 90 bar. The tensile strength demonstrates no noticeable change, as shown in Fig. 8(a). The elongation at the break and toughness represent the best values at a chamber temperature of 120 °C, as shown in Fig. 8(b) and (c), even before the air gap was fully closed (Fig. 8(d)). Although there is a downward trend at a chamber temperature of 130 °C, the elongation and toughness remain higher than those of the specimens without WIP, as shown in Fig. 5(b); however, when the chamber temperature was 140 °C, they were lower than those of the specimen without WIP.

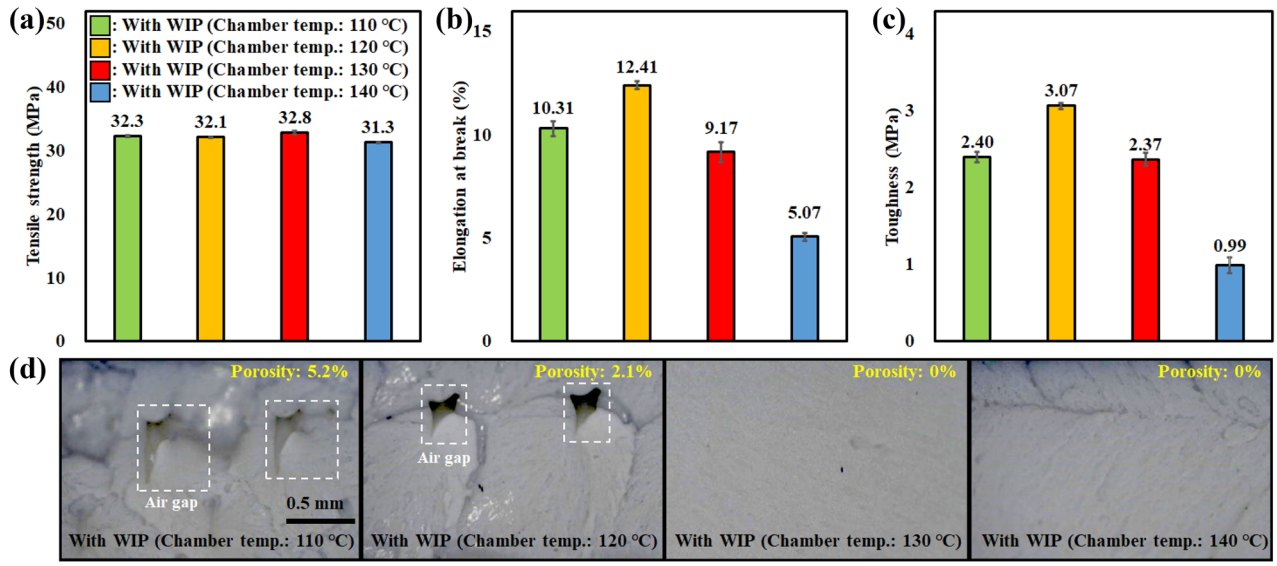

Fig. 8 Comparison of mechanical properties: **a** tensile strength, **b** elongation at break, **c** toughness, and **d** air gaps in different chamber temperatures

Based on the aforementioned results, the degradation of the specimen begins at a chamber temperature of 130 °C, and the degradation is a dominant factor for the determination of the mechanical properties, despite the specimens having no air gaps. Namely, the degradation of the polymers should be considered when determining the temperature for the WIP process.

3.3 Qualitative estimation of the reduction of the air gaps

Air gaps randomly exist in parts fabricated by the ME process [50, 51]; thus, it is impossible to estimate the number of air gaps. However, it is possible to qualitatively evaluate the reduction of the air gaps by a water tightness evaluation. The tightness samples were processed under the same conditions used to treat the tensile specimen. All specimens fabricated with or without the WIP process were connected to a yellow air-pressure hose and placed in a beaker containing water. An air pressure of 1 bar was injected before and after the WIP-processed parts, as shown in Fig. 9. Bubbles appeared in the case without the WIP process. However, bubbles did not form in the WIP-processed specimen because the air gaps were closed. Based on these observations, the water tightness evaluation can be concluded as a method that estimates the effect of the WIP process for the reduction of air gaps and waterproof characteristics.

4 Discussion

In this study, the authors focused on the influence of the WIP parameters to reduce air gaps, which is inevitable in the ME process. Two parameters of the WIP process (pressure and temperature) were considered to identify the effect of the WIP process.

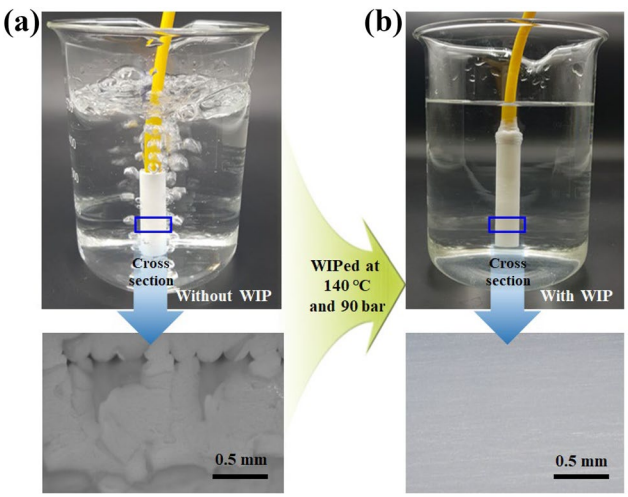

Fig. 9 Photograph of tightness results: **a** before and **b** after WIP

Figure 10(a) and (c) demonstrate that tensile strength is similar for all cases, while the elongation at the break is slightly different. This may be attributed to the fact that tensile strength is highly dependent on the intrinsic material properties but the elongation at the break depends on the appearance of the degradation of the polymer and the increase of the bonding area. The degradation of the polymer and the change of the bonding area are highly related to the values of the WIP process parameters, as indicated in Sects. 3.2.2–3.2.3. Thus, the optimal condition for the WIP process should be determined based on the elongation at the break. Based on this study, a pressure and temperature of 90 bar and 120 °C, respectively, may be near the optimal condition.

However, the optimal condition needs to be determined carefully. In this study, the authors used standard specimens that had a simple shape and uniform thickness. Thus, a higher pressure is better for the optimal pressure, and a temperature of 120 °C is the best for the WIP process. If a part has various features with different thicknesses, the optimal condition may not be valid owing to the possibility of damaging a feature in a part by the pressure. Hence, the optimal pressure and temperature should be carefully determined.

Based on the analysis of the results, the authors suggest a method to determine the optimal pressure, temperature, and holding time. First, the maximum pressure for the WIP process was determined. As indicated in Sect. 3.2.2, a higher pressure is better for the WIP process. Thus, determining the optimal pressure determines the maximum pressure. The following two cases should be considered when determining the maximum pressure: (1) the maximum pressure applied by the WIP equipment and (2) the pressure at which a feature with a minimum thickness is not broken. The two pressures may be the same or different; if two pressures are different, the smaller pressure would become a valid maximum pressure, and would be the optimal pressure.

The determination of the optimal temperature is dependent on the warpage and degradation of the polymer, as indicated in Sects. 3.1.1 and 3.2.3. The optimal temperature under the maximum pressure can be determined as a value that demonstrates the maximum elongation at a break where the warpage does not occur.

The holding time determined in this study was an hour, where the thickness of a part should be considered. Heat should reach the center of a part to cause polymer flow. Thus, the time to reach the center of a feature varies with the thickness of a feature. The maximum thickness should be considered when determining the holding time because it takes the longest time for heat transfer. Depending on the type of polymer, the holding time for the annealing treatment ranges from 30 to 60 min per 1/4 in. The holding time in the WIP process can be determined by referring to the guide of

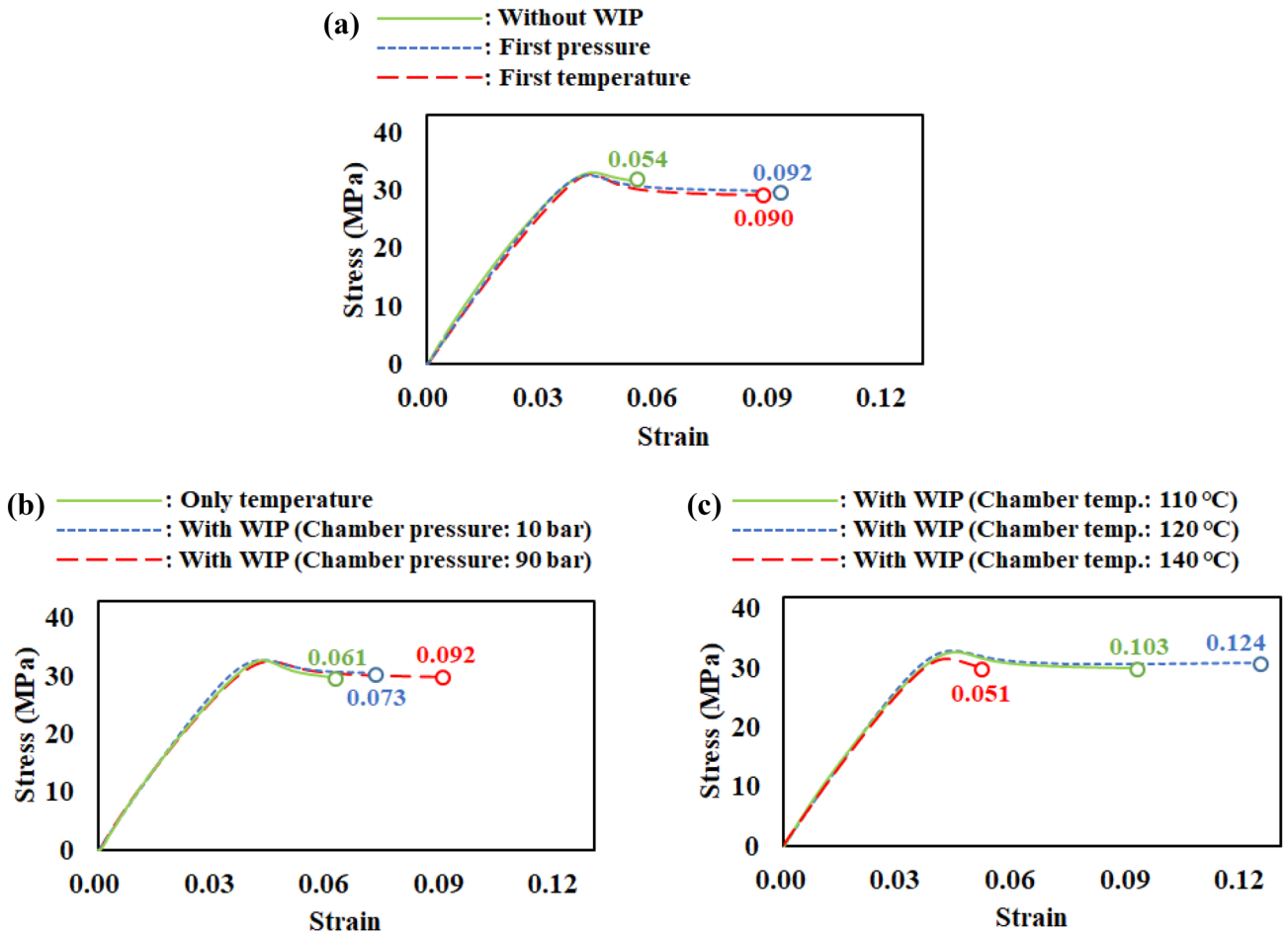

Fig. 10 Stress–strain curves representing the **a** effect of the application order of pressure and temperature, **b** effect of pressure, and **c** effect of temperature

the holding time in the annealing treatment. When determining the holding time based on the maximum thickness, degradation of the polymer at the minimum thickness is also considered. The authors determined the holding time based on the recommendation of the holding time in an annealing treatment.

In this study, the authors did not attempt to optimize the parameters for the WIP process but investigated the change of the mechanical properties with the pressure and temperature. Based on the investigation, the authors suggest a method to optimize the parameters, which may have flaws. Nevertheless, the authors believe that the suggested method contributes to the wide adoption of the WIP process as a post-process for various materials such as carbon/glass fiber composites and as the manufacturing process of the ME, polymer-PBF, and BJ process. In addition, the anisotropic properties that generally appear in the AM process were not considered because this study focused on the investigation of the WIP process parameters for the change of mechanical properties. In a subsequent study, the authors will investigate the influence of the WIP process parameters for the anisotropic properties.

5 Conclusions

Inevitably, the parts manufactured by the ME process involves air gaps of hundreds of micrometers, which can weaken the mechanical properties. In this study, the authors adopted a heat treatment method, namely WIP, that can be applied along with the temperature and pressure to reduce the air gap within a part. The influence of the parameters of the WIP process for the changes in the mechanical properties and the size of the air gap was investigated. Based on the investigations, the following conclusions can be drawn:

(1) Weight affects the warpage with an increase in temperature. To increase the temperature at which warpage does not appear, an approach that removes the effect of weight should be designed. Jig was used in this study,

due to which the warpage can be prevented at temperatures greater than 140 °C.

(2) To increase the effect of pressure to reduce air gaps, the net pressure should be increased. Vacuum packing was proposed in this study. Its effectiveness was proven by comparing the mechanical properties of the specimens processed with and without vacuum packing.
(3) In the WIP process, the application order of temperature and pressure in the chamber did not affect the change in the mechanical properties. Thus, the first pressure (FP) and first temperature (FT) conditions yielded similar results.
(4) In addition, the simultaneous application of pressure and temperature, rather than only temperature, has a significant effect on the mechanical properties by reducing the air gap.
(5) Regarding the mechanical properties, a higher pressure is advantageous when a warpage does not appear.
(6) The pressure is critical when simultaneously applied with the proper temperature. The increase in pressure is closely related to the change in elongation and toughness. In this study, the elongation and toughness linearly increase with the pressure.
(7) The degradation of the polymer affects the mechanical properties of the specimens fabricated with the WIP process. Thus, the specimens fabricated at 120 °C demonstrate the highest elongation and toughness. The effect of degradation increases at temperatures greater than 120 °C, resulting in brittleness. The inflection temperature should be considered as the optimal temperature when determining the proper temperature for the WIP process.
(8) The near zero air-gap condition achieved by the WIP process can help adopt the MEed part in various fields.

As a post-processing technique, the WIP process demonstrated the removal of air gaps in the fabricated part by the ME process. Only a built orientation was considered in this study. Thus, the effect of the WIP process for anisotropy was not investigated, which will be considered by the authors in a future study. In addition, a more detailed optimization procedure for the WIP process will be studied while considering the shape of a feature.

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Code availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

1. Lee JE, Park SJ, Yoon Y, Son Y, Park SH (2019) Fabrication of 3D freeform porous tubular constructs with mechanical flexibility mimicking that of soft vascular tissue. J Mech Behav Biomed Mater 91:193–201
2. Jung HD, Jang TS, Lee JE, Park SJ, Son Y, Park SH (2019) Enhanced bioactivity of titanium-coated polyetheretherketone implants created by a high-temperature 3D printing process. Biofabrication 11
3. Park SJ, Lee J, Choi JW, Yang JH, Lee JH, Lee J, Son Y, Ha CW, Lee NK, Kim SH, Park SH (2021) Additive manufacturing of the core template for the fabrication of an artificial blood vessel: the relationship between the extruded deposition diameter and the filament/nozzle transition ratio. Mater Sci Eng C Mater Biol Appl 118
4. Kim SH, Yeon S-M, Lee JH, Kim YW, Lee H, Park J, Lee N-K, Choi JP, Aranas C, Lee YJ, An S, Choi K, Son Y (2020) Additive manufacturing of a shift block via laser powder bed fusion: the simultaneous utilisation of optimised topology and a lattice structure. Virtual and Physical Prototyping 15:460–480
5. Park SJ, Lee JE, Lee HB, Park J, Lee NK, Son Y, Park SH (2020) 3D printing of bio-based polycarbonate and its potential applications in ecofriendly indoor manufacturing. Addit Manuf 31
6. Popescu D, Zapciu A, Amza C, Baciu F, Marinescu R (2018) FDM process parameters influence over the mechanical properties of polymer specimens: a review. Polym Testing 69:157–166
7. Wu W, Geng P, Li G, Zhao D, Zhang H, Zhao J (2015) Influence of layer thickness and raster angle on the mechanical properties of 3D-printed PEEK and a comparative mechanical study between PEEK and ABS. Materials (Basel) 8:5834–5846
8. Song Y, Li Y, Song W, Yee K, Lee KY, Tagarielli VL (2017) Measurements of the mechanical response of unidirectional 3D-printed PLA. Mater Des 123:154–164
9. Zaldivar RJ, Witkin DB, McLouth T, Patel DN, Schmitt K, Nokes JP (2017) Influence of processing and orientation print effects on the mechanical and thermal behavior of 3D-Printed ULTEM® 9085 Material. Addit Manuf 13:71–80
10. Ding S, Zou B, Wang P, Ding H (2019) Effects of nozzle temperature and building orientation on mechanical properties and

microstructure of PEEK and PEI printed by 3D-FDM. Polym Test 78
11. Ahn SH, Montero M, Odell D, Roundy S, Wright PK (2002) Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping Journal 8:248–257
12. Lay M, Thajudin NLN, Hamid ZAA, Rusli A, Abdullah MK, Shuib RK (2019) Comparison of physical and mechanical properties of PLA, ABS and nylon 6 fabricated using fused deposition modeling and injection molding. Compos Part B Eng 176
13. Yang C, Zhao YJ, Kang LM, Li DD, Zhang WW, Zhang LC (2018) High-strength silicon brass manufactured by selective laser melting. Mater Lett 210:169–172
14. Pegues JW, Roach MD, Shamsaei N (2019) Additive manufacturing of fatigue resistant austenitic stainless steels by understanding process-structure–property relationships. Materials Research Letters 8:8–15
15. Ferretti P, Leon-Cardenas C, Santi GM, Sali M, Ciotti E, Frizziero L, Donnici G, Liverani A (2021) Relationship between FDM 3D printing parameters study: parameter optimization for lower defects. Polymers (Basel) 13
16. Das A, McIlroy C, Bortner MJ (2020) Advances in modeling transport phenomena in material-extrusion additive manufacturing: coupling momentum, heat, and mass transfer. Progress in Additive Manufacturing 6:3–17
17. Gordeev EG, Galushko AS, Ananikov VP (2018) Improvement of quality of 3D printed objects by elimination of microscopic structural defects in fused deposition modeling. PLoS ONE 13
18. Jayanth N, Senthil P, Prakash C (2018) Effect of chemical treatment on tensile strength and surface roughness of 3D-printed ABS using the FDM process. Virtual and Physical Prototyping 13:155–163
19. Galantucci LM, Lavecchia F, Percoco G (2010) Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling. CIRP Ann 59:247–250
20. Wang P, Zou B, Ding S (2019) Modeling of surface roughness based on heat transfer considering diffusion among deposition filaments for FDM 3D printing heat-resistant resin. Appl Therm Eng 161
21. Solomon IJ, Sevvel P, Gunasekaran J (2021) A review on the various processing parameters in FDM. Materials Today: Proceedings 37:509–514
22. Gebisa AW, Lemu HG (2018) Investigating effects of fused-deposition modeling (FDM) processing parameters on flexural properties of ULTEM 9085 using designed experiment. Materials (Basel) 11
23. Zhang J, Yang B, Fu F, You F, Dong X, Dai M (2017) Resistivity and its anisotropy characterization of 3D-printed acrylonitrile butadiene styrene copolymer (ABS)/carbon black (CB) composites. Appl Sci 7
24. Özen A, Abali BE, Völlmecke C, Gerstel J, Auhl D (2021) Exploring the role of manufacturing parameters on microstructure and mechanical properties in fused deposition modeling (FDM) using PETG. Appl Compos Mater
25. Akhoundi B, Behravesh AH (2019) Effect of filling pattern on the tensile and flexural mechanical properties of FDM 3D printed products. Exp Mech 59:883–897
26. Jo W, Kwon OC, Moon M-W (2018) Investigation of influence of heat treatment on mechanical strength of FDM printed 3D objects. Rapid Prototyp J 24:637–644
27. Geng P, Zhao J, Wu W, Wang Y, Wang B, Wang S, Li G (2018) Effect of thermal processing and heat treatment condition on 3D printing PPS properties. Polymers (Basel) 10
28. Park SJ, Lee JE, Park J, Lee NK, Son Y, Park SH (2021) High-temperature 3D printing of polyetheretherketone products: perspective on industrial manufacturing applications of super engineering plastics. In press
29. Yang C, Tian X, Li D, Cao Y, Zhao F, Shi C (2017) Influence of thermal processing conditions in 3D printing on the crystallinity and mechanical properties of PEEK material. J Mater Process Technol 248:1–7
30. Akhoundi B, Nabipour M, Hajami F, Shakoori D (2020) An experimental study of nozzle temperature and heat treatment (annealing) effects on mechanical properties of high-temperature polylactic acid in fused deposition modeling. Polym Eng Sci 60:979–987
31. Shah D, Maiti P, Jiang DD, Batt CA, Giannelis EP (2005) Effect of nanoparticle mobility on toughness of polymer nanocomposites. Adv Mater 17:525–528
32. Basgul C, Yu T, MacDonald DW, Siskey R, Marcolongo M, Kurtz SM (2020) Does annealing improve the interlayer adhesion and structural integrity of FFF 3D printed PEEK lumbar spinal cages? J Mech Behav Biomed Mater 102
33. Lavery NP, Cherry J, Mehmood S, Davies H, Girling B, Sackett E, Brown SGR, Sienz J (2017) Effects of hot isostatic pressing on the elastic modulus and tensile properties of 316L parts made by powder bed laser fusion. Mater Sci Eng, A 693:186–213
34. Liu X, Liu Y, Zhou Z, Zhong H, Zhan Q (2022) A combination strategy for additive manufacturing of AA2024 high-strength aluminium alloys fabricated by laser powder bed fusion: role of hot isostatic pressing. Mater Sci Eng A 850
35. AlMangour B, Grzesiak D, Yang J-M (2017) Selective laser melting of TiB2/316L stainless steel composites: the roles of powder preparation and hot isostatic pressing post-treatment. Powder Technol 309:37–48
36. Khomutov M, Potapkin P, Cheverikin V, Petrovskiy P, Travyanov A, Logachev I, Sova A, Smurov I (2020) Effect of hot isostatic pressing on structure and properties of intermetallic NiAl–Cr–Mo alloy produced by selective laser melting. Intermetallics 120
37. Sentyurina ZA, Baskov FA, Loginov PA, Kaplanskii YY, Mishukov AV, Logachev IA, Bychkova MY, Levashov EA, Logacheva AI (2021) The effect of hot isostatic pressing and heat treatment on the microstructure and properties of EP741NP nickel alloy manufactured by laser powder bed fusion. Addit Manuf 37
38. AlMangour B, Luqman M, Grzesiak D, Al-Harbi H, Ijaz F (2020) Effect of processing parameters on the microstructure and mechanical properties of Co–Cr–Mo alloy fabricated by selective laser melting. Mater Sci Eng A 792
39. Liverani E, Lutey AHA, Ascari A, Fortunato A (2020) The effects of hot isostatic pressing (HIP) and solubilization heat treatment on the density, mechanical properties, and microstructure of austenitic stainless steel parts produced by selective laser melting (SLM). Int J Adv Manuf Technol 107:109–122
40. Kreitcberg A, Brailovski V, Turenne S (2017) Effect of heat treatment and hot isostatic pressing on the microstructure and mechanical properties of Inconel 625 alloy processed by laser powder bed fusion. Mater Sci Eng, A 689:1–10
41. Wang Z, Li Z, Ning J, Zhao L (2009) Effect of heat treatments on the crushing behaviour and energy absorbing performance of aluminium alloy foams. Mater Des 30:977–982
42. Wang Y, Li L, Hofmann D, Andrade JE, Daraio C (2021) Structured fabrics with tunable mechanical properties. Nature 596:238–243
43. Lee JE, Park SJ, Son Y, Park K, Park SH (2021) Mechanical reinforcement of additive-manufactured constructs using in situ auxiliary heating process. Addit Manuf 43
44. Chiu H-T, Huang S-Y, Chen Y-F, Kuo M-T, Chiang T-Y, Chang C-Y, Wang Y-H (2013) Heat treatment effects on the mechanical

properties and morphologies of poly (lactic acid)/poly (butylene adipate-co-terephthalate) blends. Int J Polym Sci 2013:1–11
45. Hart KR, Dunn RM, Sietins JM, Hofmeister Mock CM, Mackay ME, Wetzel ED (2018) Increased fracture toughness of additively manufactured amorphous thermoplastics via thermal annealing. Polymer 144:192–204
46. Kim H-C, Kim D-Y, Lee J-E, Park K (2017) Improvement of mechanical properties and surface finish of 3d-printed polylactic acid parts by constrained remelting. Adv Mater Lett 8:1199–1203
47. Sun Q, Rizvi GM, Bellehumeur CT, Gu P (2008) Effect of processing conditions on the bonding quality of FDM polymer filaments. Rapid Prototyp J 14:72–80
48. Dunstan DE (2019) The viscosity-radius relationship for concentrated polymer solutions. Sci Rep 9:543
49. Esmizadeh E, Tzoganakis C, Mekonnen TH (2020) Degradation behavior of polypropylene during reprocessing and its biocomposites: thermal and oxidative degradation kinetics. Polymers (Basel) 12
50. Garzon-Hernandez S, Garcia-Gonzalez D, Jérusalem A, Arias A (2020) Design of FDM 3D printed polymers: an experimental-modelling methodology for the prediction of mechanical properties. Mater Des 188
51. Ahn D-K, Kwon S-M, Lee S-H (2008) Expression for surface roughness distribution of FDM processed parts. International Conference on Smart Manufacturing Application 2008:490–493