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# Tensile Strength Improvement of FDMed ABS Parts by a WIP Heat Treatment

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***Abstract***

***Background/Objectives:*** Fused deposition modeling (FDM) has been widely adoptedowing to low-cost machines from the machine manufacture vendors, based on open-source. In the FDM process, a filament (a primary material used in FDM) is melted for passing a heating block. The melted filaments are fused in a layer-by-layer manner until a final part is obtained. The mechanical properties of the part fabricated by FDM process are dependent on the bonding strength of two successive layers or two neighboring lines in the fusion of the melted filaments. In the fusion of the two successive layers or two neighboring lines, voids and cracks are inevitable. However, they should be removed to improve the mechanical properties. In this study, the authors propose a method to reduce defects such as voids and cracks.

***Methods/Statistical analysis:*** Warm isostaticpress(WIP)is used to alleviate the defects for the part formed through FDM. In the WIP process, the pressure, temperatureand holding time for two process parametersare the main process parameters to be controlled. The shapes of process profileswere designed by referring to high isostatic pressure process profiles. The tensile tests were conducted with specimens fabricated with the process profiles. Measured results of tensile tests were compared to evaluate the effects of the process parameters on thevoids.

***Findings:*** During WIP, warpage does not occur below 0.8 glass transition temperature (Tg) forthe acrylonitrile butadiene styrene(ABS) used. To prevent warpage, the maximum temperature wasset to 0.8 Tg. Pressure and processing time were controlled for the fabrication of specimens. By comparingthe results from the tensile tests, wediscovered that WIPcould be an effective method to reduce mechanical defectsin a part formed through FDM without unfavorable shape deformations.

***Improvements/Applications:*** The tensile strength for the ABS part formed through FDM increased to 11% compared withthe standard specimen without WIP.

***Keywords:*** *Additive manufacturing, Fused deposition modeling(FDM), Warm isostatic press (WIP), Mechanical defects, Tensile strength*

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November-December 2019
ISSN: 0193-4120 Page No. 78 – 85

## I. Introduction

Rapid prototyping technologies have been used to produce prototypes. Owing the advancement of the technologies, they can produce the final part. Recently, the rapid prototyping technologies is called as additive manufacturing (AM) technologies, due to the capability to produce a final part. [1] As the AM technologies is based on the fabrication of layer-by-layer fashion, it is possible to build a complex part which cannot be fabricated on existing manufacturing process such as machining and casting, and to minimize material waste. [2]The AM technologies are divided into seven groups according to the ASTM F2792-12a standard. The following terms are used for categorizing current and future AM technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. [3]

As fused deposition modeling (FDM) is one of material extrusion (ME) processes, FDM process has become widely adopted, thanks to a range of materials and low-cost machines. [4] The FDM process consists of preparation and fabrication processes. In preparation, a 3D model from computer-aided design (CAD) software or 3D scan data from 3D scanner is converted into STL file. The slicing software for FDM process slices the 3D model from STL file and generates G-codes for FDM machine. In fabrication, the generated G-code is sent into the FDM machine and the machine produces the final 3D part, based on the G-codes. During the fabrication process, a filament of polymer material is fed into a heating block via a motor mechanism. The filament is melted, and extruded over a bed or a previous layer.[5, 6]By piling up the extruded filaments, the shape of 3D model is gradually realized by layer-by-layer fashion.The mechanical properties of a part fabricated by the FDM process are significantly dependent on the bonding strength of two successive layers or two neighboring lines in the fusion of the melted filaments.[7]During the fusion process, the mechanical properties are deteriorated by internal voids between layers or lines.[7,8] The deterioration of the mechanical properties is clearly proved by comparing the properties of between parts from FDM and mold.[6]Thus, the reduction of the internal voids is important to improve the mechanical properties of a part from FDM process.

Many researchers proposed various ways to reduce the voids. Galantucci et al.andJayanth et al. compared the tensile strength and surface roughness for ABS through chemical post treatment using different solutions and immersion time. In case of these papers, chemical post treatment reduced the tensile strength although the voids were reduced.[9, 10] Another way to reduce voids is physical post treatment.Kim et al. improved the surface roughness and tensile strength for polylactic acid (PLA) using remelting method according to mold temperature.[11]Parker et al. eliminated the voids for Polyphenylsulfone (PSU), polycarbonate (PC), and ULTEM 9085 according to mold temperature and pressure.[12] However, Kim et al. and Parker et al. cannot be applied to complex three dimensional shapes because they used mold to reduce voids.From the studies, it can be found that temperature and pressure are important parameters to reduce the voids but individual parameter is only considered.

November-December 2019
ISSN: 0193-4120 Page No. 78 – 85

In that regard, hot isostatic pressing (HIP) process attracts the attention of authors because the process uses temperature and pressure simultaneously[13]. However, HIP process is not suitable for polymer because the HIP process is implemented under the condition of high temperature and high pressure and the condition can damage part from FDM process.[14] Similar to the HIP process, there is warm isostatic pressing (WIP) process to use temperature and pressure simultaneously. The WIP process is implemented under the condition of relatively lower temperature and pressure than HIP process. Authors thought that the WIP process is more reasonable to reduce the internal voids of part from FDM. In this study, authors have studied the influence of the WIP process parameters for the change of the internal voids for the reduction of the voids caused by FDM process. To evaluate the influence, tensile specimens are fabricated by FDM process. The tensile specimens are treatedwith various WIP process profiles and are tested.

## II. Materials and Methods

### Specimen fabrication

Acrylonitrile butadiene styrene(ABS) filaments (ABS plus, Stratasys, U.S.A.) were usedin a commercially available FDM system (Fortus 250mc, Stratasys, USA.).The filament has a glass transition temperature($T_g$)of108°C and a diameter of 1.75 mm. Figure 1shows atoolpath in the side view ofthe x–y plane. The raster angle is+45/-45° that is thenext layer additively manufactured on the previous layer. The contour number, layer width, and layer thickness were set to 1 time, 0.4 mm, and 0.25 mm, respectively. Theapplied nozzle temperature, chamber temperature, nozzle diameter, and flow rate were set according to the manufacturer's recommended parameters.As shown in figure 2(a), the specimen wasfabricated through FDM along the z-axis direction. A support structure was built for the stable fabrication on the overhang of the model structure. Thus, the completed part comprises support and model structures, as shown in figure 2(b).The surface of the part formed through FDM after removing the support is shown in figure 3.

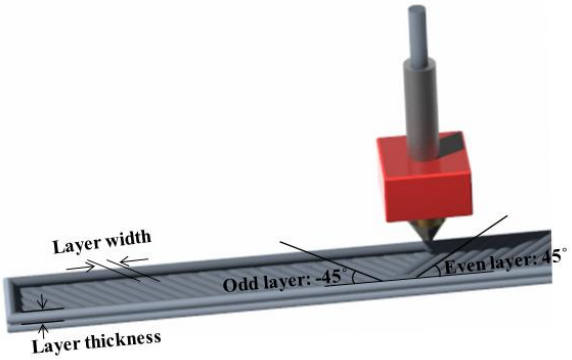



Figure 1.Schematic of fused deposition modeling according to toolpath inside view of x–y plane.

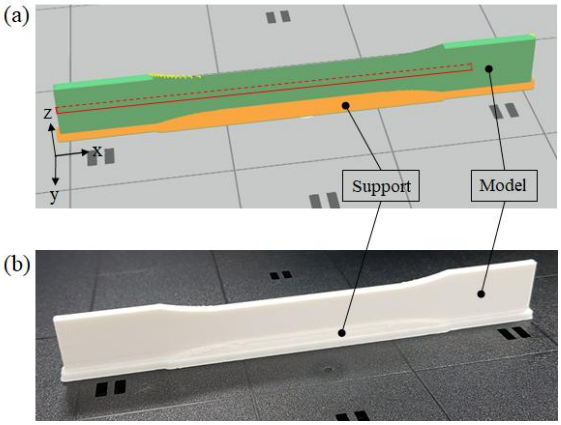



Figure 2. (a)Support and model shapesfrom slicing software and (b) part fabricatedby FDM.


Figure 3. The photograph(left) of fabricated part and microscopic image(right) of surface after support was removed.

November-December 2019
ISSN: 0193-4120 Page No. 78 – 85

### WIP Process

The WIP instrument is shownin figure 4(a). The chamber temperature, pressure, and processing time can increase up to 300°C,100 bar, and 6 hours, respectively. The chamber volume is approximately 4400 $cm^3$.During the WIP process, all specimens were placed inside the chamber, as shown in figure 4(b). The WIP was performed inthree steps, as shown in figure 5. First, nitrogen is injected to increase the pressure of the chamber up to the target pressure. Next,the chamber is heated to increase the temperature up to the target value. In this study, three process parameters are considered as processing time, temperature and pressure. The test conditions for the WIP process are summarized in Table 1. After the processing time, the cooling was performed using nitrogen gas in chamber.

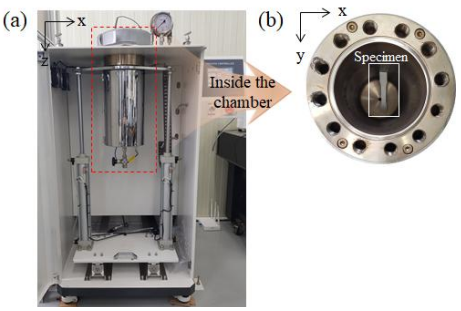



Figure 4.Photographs of (a) the WIP instrument and (b)specimeninside the chamber.

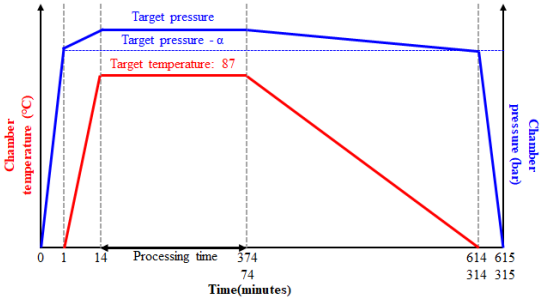



Figure 5. Chamber temperature, pressure, and processing time profile in WIP process.

Table1. The test condition for the WIP process

| | | | | | |
|---|---|---|---|---|---|
| Target temperature (°C) | 87 (0.8 x $T_g$) | | | | |
| Target pressure (bar) | 10 | 30 | 50 | 70 | 90 |
| Processing time (hours) | 6 and 1 | | | | |

### Tensile Test

All of the tensile specimens were designed according to the ASTM D638 type 1 standard. They were set onto a universal testing instrument (DTU-900, Daekyung tech, S. Korea). The tensile test was conducted at a tensilerate of 5 mm/min. Each test was performed using three specimens at different conditions.The test results were expressedby in terms of the average value and standard deviation.

### Thermo-Gravimetric Analysis(TGA) test

Thermo-Gravimetric analysis(TGA)test was conducted to confirm polymer thermal degradation. The polymer thermal degradation by the weight reduction rate was determined according to the processing time with fixed pressure and temperature. The heating rate and initial weight were set to 10°C/min and 19.4877 g, respectively. The weight reduction ratewas expressedin percentage.

## III. Results and Discussion

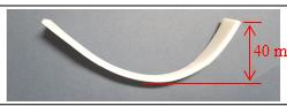
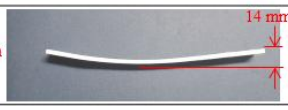
### The determination of temperature for WIP treatment

All of the polymers studied have a glass transit temperature ($T_g$) in which the polymer chains were soft andexhibited mobility.[15]Thus, it is important to determine the reasonable temperature for WIP process. To determine the temperature, WIP treatment is performed under

November-December 2019
ISSN: 0193-4120 Page No. 78 – 85

various temperatures (0.8, 0.9 and 1.0 $T_g$), pressure (90 bar) and processing time (6 hours). The results of WIP treatment are shown in table 2. As shown in table 2, the specimens at 108°C($T_g$) and 97°C(0.9 $T_g$) exhibited significantwarpage because the polymer became soft. Meanwhile, in the specimen at 86°C(0.8 $T_g$) warpagedid notappear. It means that the WIP treatment should be conducted under 0.8 $T_g$ to prevent warpage during the process. For the next WIP treatment, temperature is fixed at 86°C.

Table2.Warpage of the specimenswiththe chamber temperature during the WIP process.

| Chamber Temperature (°C) | 108 ($T_g$) | 97 (0.9 x $T_g$) | 86 (0.8 x $T_g$) |
|---|---|---|---|
| Warpage |   |   |  |

**Effect of WIPtreatment**

Figure 7(a)compares thetensile strengths of specimens without and with WIP treatment under pressures(10, 30, 50, 70, and 90 bar) and processing time (6 hours).The tensile strength of the specimen without WIP treatment was 33.67 MPa. However, the tensile strengths with WIP treatmentwas 1.66~7.27% lower than strength of specimen without WIP treatment. The results can be explained as the thermal decomposition of polymer. The thermal decomposition of polymercan be categorized into two cases.First, the polymer is exposed to a temperature higher than the inherent degradation temperature of the polymer[16]. Second, the polymer is maintained at a low temperature for a long time.[17] In this experiment, it seems that thermal decomposition appears due to the second reason. To prove this phenomenon, TGA test was performed86°Cas time progressed, as shown in figure 7(b).The dotted line and full line indicate the original weight and reduction ratio as time progresses for ABS, respectively. The weight of ABS began to decrease from approximately 1.6 hours. This implies that the safe state of WIP treatment is from 1.6 hours at 86°C and the processing times of 6 hourscan reduce the weight of ABS by approximately 0.05%. Thus, it can be understood that the weight loss is the reason for the deterioration of tensile strength, as shown in figure 7(a).

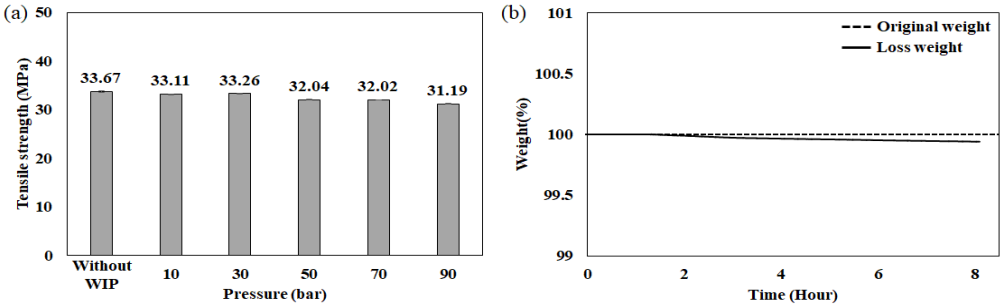



Figure 7.(a) Tensile strengthwithout/withWIP treatmentfor6hours processing time and (b) TGA curve of ABS.

Figure 8(a) shows the change of the tensile strength without and with WIP treatment under pressures(10, 30, 50, 70, and 90 bar), processing time (1 hour) and temperature(86°C). From figure 8(a), it can be found that the chamber pressure of 10 bar is

not enough to cause the change of the bonding strength of specimen or the reduction of voids and the pressure should be at least over 30 bar to increase the tensile strength under the test condition. In addition, it can be observed that the measured tensile strength increases up to 11% by the increase of the chamber pressure, comparing to the measurement of specimen without WIP treatment. Figure 8 (b) shows the change of the voids with the conditions for WIP treatment. In the cases of with WIP and 10 bar, the void sizes are very similar. In other cases, it can be observed that the void sizes decrease with the increase of the pressure. However, with the increase of the pressure, the void sizes decrease but the tensile strengths are almost similar.

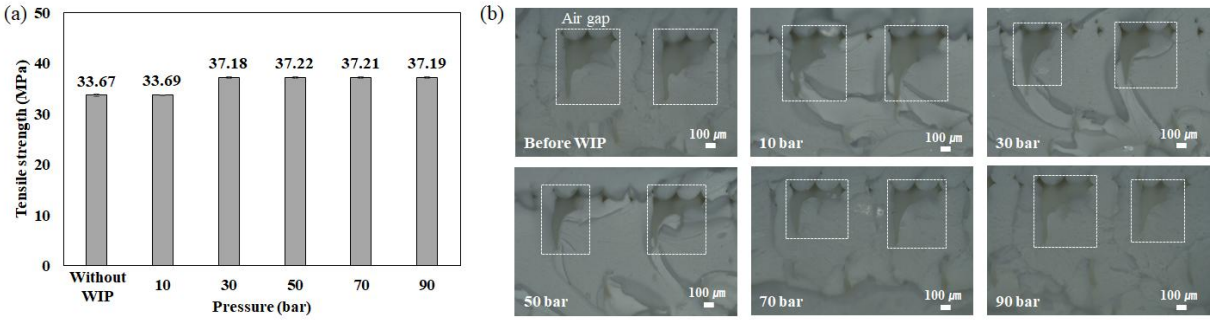



Figure 8. (a) Tensile strengths without/with WIPtreatment for 1hour processing time and (b)morphologychange in air gaps for the specimenformed through FDM according to different chamber pressures

**Discussion**

In this study, authors investigated the influence of the WIP process parameters for the voids of a part fabricated from FDM process.In polymer process, temperature is most important parameter because all polymer process start from softening the polymer. Thus, the determination of the temperature for WIP treatment should be preceded. In this study, for the determination of the process temperature, candidate temperatures are determined based on $T_g$. The temperature of 86 °C (0.8 $T_g$) is determined as the process temperature to prevent warpage. Thus, in this study, the process temperature is considered as constant. It would be the main reason of the small improvement of the strength because the main source for the determination of the behavior of the polymer is kept as a constant as shown in figure 8(a). Hence, with the increase of the pressure, the void sizes are slightly decreased but the tensile strengths are almost similar.

Thus, to obtain the further improvement of the strength, the voids should be fully removed. Two approaches could be considered to fully remove the voids. One is to increase the process temperature. As shown in Section 3.1, the process temperature is determined as the condition without the appearance of the warpage. In this study, the specimens are freely placed in the chamber during the treatment.In the increase of the pressure on the temperature of near Tg, specimens could be easily warped. If specimens are fixed by a tool in the chamber, the tool can help the reduction of the warpage. Another is to increase the process pressure. As shown in figure 8(b), the void sizes are gradually decreased with the increase of the pressure. However, the influence of the pressure for the void size become smaller with

November-December 2019
ISSN: 0193-4120 Page No. 78 – 85

the increase of the pressure. Over a certain pressure, the influence could be converged into a certain level. Thus, if one of them should be chosen, the former would be more preferred. In addition, in terms of the location of voids, the increase of the process temperature would be more helpful. During the FDM process, the appearance of the voids is random. Among the voids, the voids placed in the middle of a part is hard to load the pressure. Thus, for the increase of the effective depth of the pressure, it could be said that the increase of the process temperature is necessary.

In the design of the WIP treatment profile, the degradation should be considered. As shown in figure 8 (a), the increase of the pressure can improve the strength. However, in figure 7(a), even though the process pressure increases, the strength decreases due to the degradation. It means that the decrease of the strength caused by the degradation of the polymer is larger than the increase of the strength by the increase of the process pressure. Thus, the processing time should be strictly determined to prevent the deterioration of the strength.

## IV. Conclusion

Among AM technologies, FDM is preferred owing to its advantages such as low-cost hardware system, simple operating mechanism and a range of materials. However, parts formed throughFDMcontainthe internal voids thatcan degrade their mechanical properties. This study proposes the use of the WIP treatment to reduce thosevoids. The influence of the process parameters for the WIP treatment was investigated based on the change of the tensile strength and the change of the void size based on image analysis. Furthermore, the WIP process profile was verified applicable to the polymer used. From this study, the conclusions could be obtained as follows.

(1) When the specimens are freely placed in the chamber, the reasonable process temperaturewas86 °C (0.8 $T_g$)

(2) The degradation of the polymer specimen caused by a long exposure of lower temperature is more dominant to deteriorate the strength of the specimen

(3) The increase of the pressure can reduce the voids but the improvement of the strength cannot be obtained over a certain pressure.

In this study, authors propose the use of the WIP treatment to reduce the internal voids and can find the possibility of the usefulness of the WIP treatment as one of post-processing processes. However, there are many unsolved problems to build the optimal profile for the WIP treatment. For future work, authors will focus on finding ways to build the optimal profile of WIP treatment based on the analysis of the influence of the process parameters for the change of the void size.

## V. Acknowledgment

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