A study on reduction of processing time and improvement of strength by using photopolymer resin in the 3DP process with powder base

Dong Soo Kim[1] and Sungwoo Bae[2] ([1] Department of Creative Convergence Engineering, Hanbat National University. 125, Dongseodaero, Yuseong-gu, Daejeon, 305-719, South Korea, [2] Industrial-University Cooperation Foundation, Hanbat National University, 125, Dongseodaero, Yuseong-gu, Daejeon, 305-719, South Korea, baesw@hanbat.ac.kr)

Abstract

The 3DP technology is one of the additive manufacturing technologies that have recently come into the spotlight and are being applied to various fields. This technology has the advantage of enabling high speed printing which, is done on the basis of the ink-jet technology and the system to be constructed at a low cost. However, it has also the negative side that requires extra time for curing after 3D shape fabrication. On the other hand a post-processing period is meant to increase the mechanical strength of the product. Therefore, in this study, an innovative 3DP process is recommended to improve the strength of product without any post-processing. To verify the feasibility of the proposed process, a 3DP system was developed to test the mechanical strength experiment of the fabricated specimens. As a result, it was confirmed that the specimens fabricated by the proposed process had three times higher compression and yield strength than post-processed systems for improving the strength through the conventional thermal bubble jet process. To this effect, a proposed 3DP process would remarkably reduce the total fabrication time because there is no dry time and post-processing time after fabrication in the proposed process.

Introduction

To meet the rapidly changing market, the developing cycle of each product has been reduced. That is, under the slogan of "Time to Market", the technology of additive manufacturing (AM) has been developed up to the present level. Recent AM technology has been expanding to some application areas such as Fused Deposition Modeling (FDM) Streolithography Apparatus (SLA) Selective Laser Sintering (SLS) Laminated Object Manufacturing (LOM).Three dimensional printing (3DP) [1,2]. The 3DP technology has recently received a growing interest and is one of the AM technologies being applied in various fields [1,3]. The technology allows high-speed printing based on the ink-jet technology and has the merit of possible low-cost construction. However, after fabrication is completed, a protracted curing time requiring a post-processing to increase the mechanical strength is a limiting factor. Hence, the study sets out to; propose the use of a novel 3DP process, capable of enhancing the strength of the product without any post-processing.

System construction

The mechanism for the AM system comprise of 5 axes as shown in Figure. 1 including; a servo control part for X, the Y axes, a roller part for feeding powder, a feeding room and a building room moving up and down to laminate with a definite thickness. The servo control part for printing comprises of the Y-axis requiring high speed conveying, and the X-axis mounted with the roller part and a printhead. In particular, a timing belt system was adopted to realize a low cost and high speed system. The roller part includes a roller and feeding room for feeding powder, a guide for preventing powder from leaking in the building room, and a device to eliminate the powder that attaches on the roller.

The function of the roller is to form a powder bed according to a layer thickness for the building room and to provide a flattened surface. The thickness of the powder bed is determined by the control precision of the Z-axis. However, the flatness is affected by the particle size and uniformity of the powder, the turning speed of the roller, conveying speed and surface roughness and the like.

The thickness of one layer for feeding powder of the feeding room is usually setup 1.5 times thicker than the layer thickness of the building room to prevent leakage In addition, the turning speed of the roller was set up at 180 [rpm]. The experimental result found that the optimized powder bed was formed when the feeding speed of the roller was 0.25 to 0.3m/s.

To control the AM system, a PC based position control system utilizing the Multi Motion Controller (MMC) board was used. Moreover, a control experiment for SMCSPO algorithm was conducted by using both models for torque and speed by a method of analogue electrical voltage output [4,5].

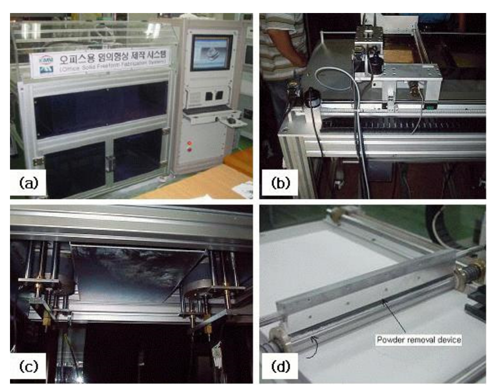

Figure 1. Developed a AM System based 3DP process. (a) AM system , (b) servo motor part for x and y axes, (c) linear motor for z axis, (d) powder removal device (roller part)

3DP process

The AM system for the proposed type was developed on the basis of a 3DP process technique. The 3DP process print is the lowest level of a sectional information of a two dimensional shape where a certain amount of powder is laminated again followed by printing the sectional information corresponding to the next layer, where the three- dimensional fabrication process is achieved through a repeat process [4]. A binding solution of low viscosity is selectively printed on the powder bed using a print head. As such, the printing areas are cured by the binding solution. After the printing process of all layers is completed, the first ‘green part’ is completed by removing sections that are not bound. However, for the binding solution to be injected through the ink-jet print head it is restricted to a material in the extreme case of low viscosity almost similar to the water, thus, the cured part has also difficulty in expecting a high strength. Consequently, a post-process to improve the strength of the product is regarded as important, in a 3DP process [5]. For the post-process, an outer form becomes stronger by laying over instant bonding agents on the outer surface of the structure. Conversely, a method for increasing internal bonding force by using a waxing device is also used.

Problems in 3DP process

As for the conventional thermal bubble jet type 3DP process, two problems are pointed out in general. The first one requires a separate curing time after layer printing, by which total fabrication time is extended. On the other hand the conventional process requires the curing time of the binder ejected selectively on the powder bed per every layer. The curing time range is between 30minutes to 2 hours depending on the layer thickness, form and size for the product.

The second one requires a post-process. Essentially, a fabricated 3DP process has a low strength; this makes it impossible to use a concept model without any post-process. The fabrication time is not only extended in the range of 30 to 60 minutes, but also puts into consideration dimensional deformations of the part due to shrinkage that may be developed depending on some variables of the process and size of the product. Besides, depending on the skills of the workers, the post-process time and the precision of the product are affected. As such, a new process would be required to solve those problems.

Characteristic of proposed process

In this study, the proposed new process can improve the strength of the object and reduce the total fabrication time. It also come with many advantages such as low cost, high speed and variable, selective materials and the like, which the conventional thermal bubble jet type 3DP process has.

The conception drawing of the proposed process is as shown in Figure 2, similar to the conventional thermal bubble jet type 3DP process. The binding solution on the powder bed is replaced by photopolymer resin, and the printed resin is cured by the UV lamp every layers. Because as for the conventional process, binding between the powders is achieved by the binding solution of low viscosity, stronger binding force could not be expected.

Furthermore, by forming the next layer without any drying process after injecting the solution, some inconvenience having to wait for a long drying time is felt. When it comes to the proposed process, a separate delaying time after finishing is not needed to complete the curing in each layer with the UV lamp. Also because the fabricated object has a certain level of strength, it makes the features capable of being used without any post-process.

Curing model

In the photopolymer curing process, the cured layer normally turns to absorb a part of the incident radiation. The UV beam penetrates right down into the powder bed with photopolymer, attenuated gradually by the absorption. The exposure will decrease exponentially with the depth, which follows the Beer-Lambert exponential law of absorption. In practice, the polymerization does not occur when the exposure is below the threshold value; this is primarily due to oxygen inhibition, which imposes a minimal threshold to start the polymerization. The exposure threshold is known as the "critical exposure," Ec. The depth of cured photopolymer by UV light can be derived from the Beer's law. In mathematics, the cured depth of the resin is proportional to the natural logarithm of the UV exposure that is larger than the threshold, otherwise, it equals zero.

$$C = \begin{cases} D_p \ln(E/E_c) & E > E_\mathrm{c} \\ 0 & E \le E_\mathrm{c} \end{cases} \tag{1}$$

Where C refers to cured depth, E refers to UV light exposure, in addition, Dp refers to the penetration depth of the resin, which is purely a resin parameter and independent of the exposure. In practical fabrication, if the average exposure is below Ec, no resin is cured, otherwise if the average exposure falls into the range Ec<Eav<2Ec, the resulting prototypes have not sufficient mechanical strength [12].

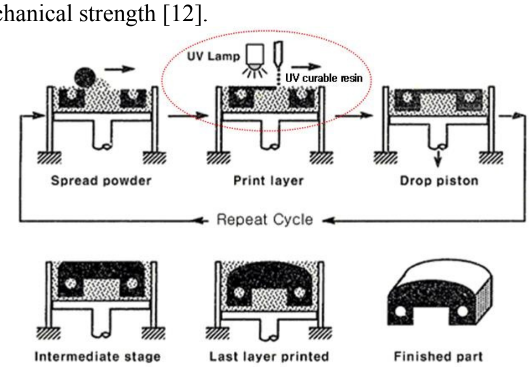

Figure 2. The sequence of proposed 3DP process

Process rate

The proposed new three-dimensional printing process comprises of; the powder bed, resin printing, infiltrating of resin into the inside of the powder, UV curing, and the total process rate is different depending on the combinations of those three technologies.

The powder bed forming speed is at 3 to 5 [s/layer], and is determined by the moving speed for feeding and building room of Z axis, and that of the X axis. In the case of using multiple nozzles for the resin printing, a high speed printing may be possible. However, for the present study, a dispenser from the Mushasi Company was utilized. The result showed that it might be possible to print with a resolution of 400dpi. This confirms that the resin infiltrating speed is not only determined by the viscosity and surface tension of the resin, but also by the void fraction of the powder bed and hydrophilic, which may be approximated as a Eq. 1 by Washvurn equation [10].

$$V = \frac{r\gamma \cos\theta}{4\mu h} \tag{2}$$

Where, r is a half diameter of the void fraction. and are the surface tension and viscosity respectively. is a contact angle of the resin keeping in touch with the void fraction, and h is a penetrating depth of the resin. The void fraction of the powder bed used in the experiment is 4 [㎛], and the surface tension and viscosity of the resin are 62 [mN/m] and 12 [mPa.s] respectively. In the case of 200 [㎛] layer thickness, the penetration speed V is about 32 [㎛/s] according to Eq. 1.

And the print of a micro drop ejected through the printer head attached to the conveying part is determined by Stokes law[10]. A time required for reaching a normal condition being ejected from the nozzle tip end of the print head, i.e. the relaxation time is as shown in Eq. 3.

$$\tau = \frac{1}{18}\frac{d^2}{\eta}\rho \tag{3}$$

Where, d is drop diameter, is drop density, and is the viscosity of air. And the high-speed area of a drop print ejected in the vertical direction may be obtained from Eq. 3.

$$v(t) = \tau g + (v_i - \tau g)e^{-t/\tau} \tag{4}$$

Where, is initial ejecting speed. Furthermore, a drop position corresponding to an approximated time based on the relaxation time may be calculated by Eq. 4.

$$D(t) = \tau g t + \tau(v_i - \tau g)(1 - e^{-(t/\tau)}) \tag{5}$$

Figure 3 shows calculating results of the speed and distance values to each micro drop time according to drop diameters. In case a distance between the nozzle end tip and the powder bed is about 1 [㎜], it was confirmed by a high-speed camera that a time required for an ejected drop to reach the powder bed was about 120 [㎲].

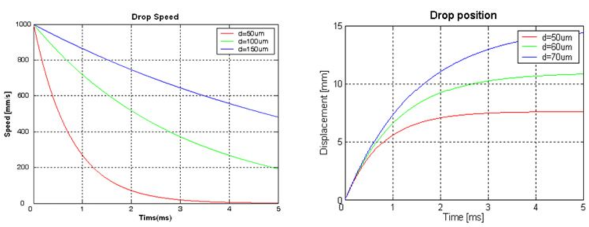

Figure 3. Speed and position of ejected microdrop

Geometrical control

As for the proposed three-dimensional printing process, geometrical control elements are the dimensional errors of the product and the feature size of a minimum shape object. Those two problems affect the strongly interaction between the powder and the resin. Affecting variables include; the material, surface condition, size, distribution, shape object of the powder and packing density, the material, viscosity, surface tension of the resin, the size, speed and frequency of the droplet and each temperature for the powder and the resin, and the like.

The resolution of a fabricated object is mainly determined according to the powder and droplet size, the spreading and infiltration, structural position errors. The size for powder used for the experiment is 5 to 10 [㎛], and the size of the droplet is about 100 [㎛], Less the size of the droplet and the minimum shape object size.. Nonetheless, the resin infiltration is determined according to the viscosity and surface tension, the surface energy of the resin at the boundary between the resin and powder bed, and contact angle, the distribution of the void fraction at the powder bed.

The errors of the product are mainly determined by those of layer thickness, position errors of the droplet, the reproducibility of the droplet spreading, shrinking problems during curing, Z-growth phenomenon. The errors of the layer thickness and the position errors of the droplet are basically linked directly with structural problems. As for the AM system developed for the experiment, the accumulated error of the layer thickness is within a range of 100 [㎛] and the maximum positional errors for the droplet is about 50 [㎛] including those of X, Y servo control parts. For the reproducibility of spreading, the errors may be different depending on the bed surface conditions even if the density of the powder bed is definite, and the applied material is the same. Some shrinkage may be developed when the resin is cured, it becomes different depending on the density of the powder bed and the ejected resin amount. Finally, the Z-growth phenomenon is a typical one appearing during the fabricating process for the layer base, where the resin amount more than the layer thickness is required for binding both of an upper and a lower layer. The result shows that unnecessary portions are cured as the resin ejected to the lowest layer infiltrates into the powder in the lower part as more as it is needed.

Fabrication model and Mechanical test

To verify the possibility for the proposed process, an experimental device as shown in Figure 4 was prepared. The dispenser diameter was 120 [㎛], the feed pressure, was at 2 to 3 [bar], and the heating temperature of the nozzle was set at 95 [℃]. MHL 250 model of 250 [W] was used for the UV lamp.

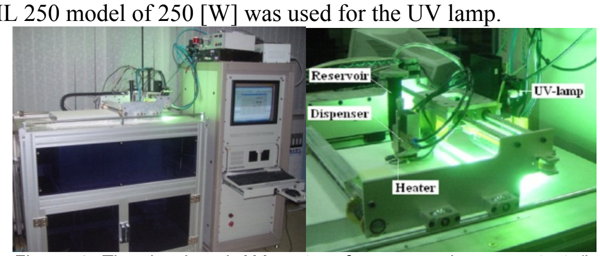

Figure 4. The developed AM system for proposed process test (left; Proposed UV curing system, right; Dispenser and UV-lamp unit)

For measuring the strength, the test for fabricating specimen was conducted using an AM system developed as shown in Figure 5.

After printing the resin by using the dispenser as shown in Figure 5, the printed resin was cured by using the UV lamp for each layer. According to the result, a separate curing time is no more required after completing all the layer printings. Furthermore, there is no post-process. The non-cured powder has only to be eliminated by air spray.

Figure 6(a) shows specimens prepared by the proposed process. For a comparison test, Z310printer® an equipment for 3DP process from Z-Corporation was used. The variables for the fabrication were specified as default values from Z-Corporation and the same specimens as shown in Figure 6(b) were prepared. The test result shows that cleaner surfaces were obtainable from the specimens prepared by the proposed process.

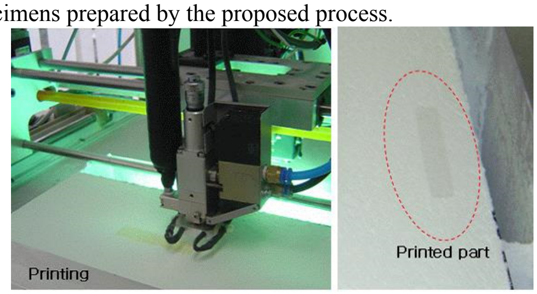

Figure 5. The fabricating process of part in the proposed process

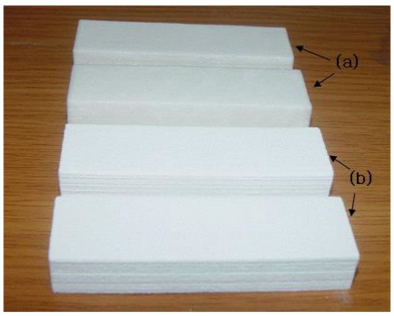

Figure 6. Fabricated test part by (a) developed the AM system and (b) Z310printer®

A series IX® automatic material testing system from Instron corporation, as shown in Figure 7 was used for each test for bending strength and tensile strength. Test specimens were used as shown in Figure 6(a) and (b), and the specimens prepared by Z310® that were not possible to test without any post-process, were tested after having passed a post-process for improving the strength.

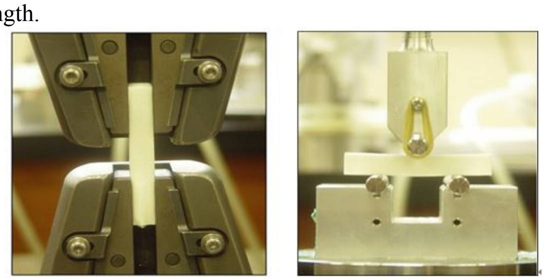

Figure 7. Tensile and compression test in Instron corp.

The compression test result showed that maximum 75 [N] was obtained from the specimens prepared by Z310® model, meanwhile 210 [N] more than about three times thereof was obtained from developed the AM model applied by the new process. And the tensile test result showed that developed the AM model had 1,000 [㎪] yield stress as shown in Figure 8, which was three times higher than that of Z310® model.

At the maximum stress, a five times higher value than that of Z310® was obtained in Figure 9. As the fabricated structure maintains a definite level of strength, it was possible to use directly without any post-process to improve the strength. By and large, it was found that the total processing time could be reduced significantly. Further, problems such as dimensional errors and damages of fine shape objects and the like, could be prevented in advance, and that various, selective material powders could be used for the manufacture of some products for the industrial fields. .

All the specimens prepared by the developed equipment from two types of tests could obtain about three times higher strength than that of post-processed one according to the conventional process. Therefore, in the case of applying the proposed process, the drying and post-process is no longer required. Therefore, a favorable effect is expected for the total fabrication time.

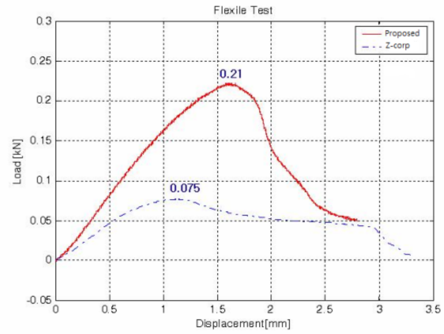

Figure 8. Compression test curve

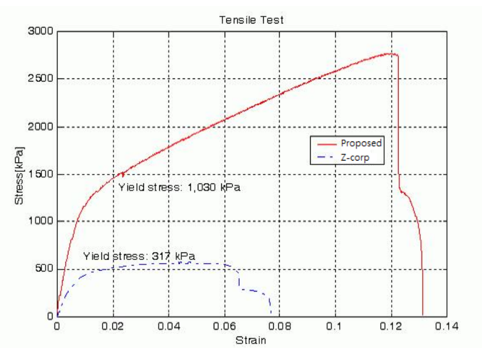

Figure 9. Strain-Stress curve

Conclusions

In this study, a 3DP process was proposed for its efficacy to eliminate some of the problems experienced by the conventional thermal bubble jet printer. The study, pointed out problems for the conventional thermal bubble jet type 3DP process and presented the new process that can improve the strength of the object and reduce the total fabrication time. The process variables including resin jetting volume, jetting speed, layer thickness, and powder bed forming were evaluated. To verify the feasibility of the proposed process, we tested the tensile strength and bending strength experiments. The results established that the specimens fabricated by the proposed process had about three times as higher compression and yield strength than those of post-processed one for improving the strength after fabricating by the conventional process. The experiment indicated that fabricated parts in proposed process have enough strength of so much so that do not need post-processing. As such, the study culminated to the total fabrication time because it is no dry time and post-processing time after fabricated in the proposed process.

References

[1] Terry T. Wohlers: Wohlers Report 2013, Wohlers Associates, 2013.

[2] X. Yan and P. Gu, “A review of rapid prototyping technologies and systems,” Computer Aided Design, vol. 28, no. 4, pp. 307–318, 1996.

[3] C.C. Chang, "Rapid prototyping fabricated by UV resin spray nozzles", Rapid Prototyping Journal, Vol. 10 Iss: 2, pp.136 – 145, 2004.

[4] Ki Sung You, Min Cheol Lee, “Sliding mode controller with sliding perturbation observer based on gain optimization using genetic algorithm”, Int. Journal KSME, Vol. 18, No. 4, pp.630-639, 2004.

[5] H.J. Lee, J.S. Kim, M.C. Lee, D.S. Kim and W.H. Lee, “High Speed and Accuracy Control of Timing Belt System for SFFS of Office”, Proceeding of the KSPE autumn annual meeting, pp. 339-342, 2004.

[6] Paul A. Williams, “A New Process To Fabricate Prototypes Directly From CAD Model”, PhD. Thesis, MIT, pp. 12-17, 1990.

[7] Bredt, J.F., “Binder Stability and BinderlPowder Interaction in Three-Dimensional Printing”. PhD. Thesis, MIT, 1995.

[8] Lee, W. H., Kim, D. S. and Lee, M.C., 'Development of a SFF System Based on Three Dimensional Printing Process,' 2005 Society of CAD/CAM engineer, pp. 550-557, 2005.

[9] Eric R. Lee, “Microdrop generation”, CRC press, pp. 15-29, 2003.

[10] Parker C. Reist, “Aerosol science and technology”, McGraw-hill, 1993.

[11] W.H. Lee, D.S. Kim, and T.M. Lee, “A Study of SFFS for Office Type using Three-dimensional Printing Process”, Proceeding of the KSPE autumn annual meeting, pp.1128-1131, 2004.

[12] Jacobs, P.F.: "Rapid Prototyping & Manufacturing Fundamentals of Stereolithography," Society of Manufacturing Engineers, Dearborn, MI, 1992.

Author Biography

Dong Soo Kim received her BS and PhD in Mechanical Engineering from the University of YungNam, Daegu, Korea 1998 and 2000, respectively. Since then he has worked in the Printed Electronics Research Division at KIMM in, Daejeon, Korea and then from the 2011, he worked in the Department of Creative Convergence at Hanbat National University in, Daejeon, Korea. His work has focused on the development of printing machine and new process issues.