https://doi.org/10.2352/ISSN.2169-4451.2018.34.162

Real-time X-ray visualization of ink penetration into powder bed for binder jetting process

Shin Mizutani[1], Daichi Yamaguchi[1], Takeshi Fujiwara[2], Masato Yasumoto[2], Ryunosuke Kuroda[2,3]; [1] Ricoh company, Ltd., 2-7-1 Izumi, Ebina-shi, Kanagawa, 243-0460 Japan, [2] NMIJ, National Institute of Advanced Industrial Science and Technology (AIST), Central 2, 1-1-1 Umezono, Tsukuba-shi, Ibaraki 305-8568, Japan, [3] OPERANDO-OIL, National Institute of Advanced Industrial Science and Technology (AIST), 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8589, Japan

Abstract

We have developed an in-situ X-ray imaging system to visualize penetration dynamics of small ink droplets into powder bed in binder jetting process. The imaging system consists of a micro focus X-ray source, an ink depositing device by remote control and a high resolution flat panel detector. The whole process of the ink penetration, such as ink penetration through the powder bed and powder bed densification, was visualized in sequence applying this system. The results show that the difference of the amount of ink cause the change of the powder bed densification and the penetration distance in depth and plane direction. The real-time visualization of the ink penetration dynamics can be useful to clarify the mechanism of the defects in the fabricated objects, such as internal porosity and weak bonds between the layers.

Introduction

Binder jetting (BJ) is one of the Additive Manufacturing (AM) process, in which the ink as binder is deposited from inkjet heads onto the powder bed, and the powder particles are bonded by the deposited ink. BJ is the excellent in terms of high productivity and low printer price. However, objects fabricated by BJ may have some defects including porosities, density non-uniformity, or insufficient bonding between thin powder layers because of its inability to fully densify the powder bed [1]. Although these defects decrease density and accuracy of the fabricated objects, the mechanism causing the defects has not been investigated so far. To improve quality of the objects, it is necessary to clarify the mechanism of the fabrication process by visualizing the ink penetration into the powder bed.

Several works of observing the liquid penetration into the powder bed have been reported previously. Hopgood et al., Nguyen et al. and Marston et al., observed the droplets immersing into the powder bed optically [2][3][4]. Although the change of droplets on the surface of the powder bed can be imaged, it is impossible to evaluate the penetration depth or spreading distance into the powder bed. Munuhe et al. and Davis et al. visualized the droplets penetration inside the powder bed by X-ray CT [5][6]. Although shapes of the penetration area inside the powder bed can be obtained, it is impossible to visualize the droplets penetration dynamically.
Zhao et al. and Lun et al. observed the solidification process of laser sintering using synchrotron radiation [7][8]. Although dynamic evolution of the melt pool in laser powder bed fusion processes were observed, these studies were conducted by a large-scale experiment facility, synchrotron, and it is difficult to apply these observation techniques to practical feedback for fabricating technology development. Tan et al. and Garcia et al. analyze ink penetration dynamics by simulation [9][10]. Although the penetration profiles were shown with different droplet impact speed and the liquid-liquid interface in the powder bed with different wetting properties, the powder particles are fixed so it is impossible to simulate the agglomeration of the powder caused by the ink penetration.

Based on the above backgrounds, attempts were made to visualize the ink penetration process of the BJ method by X-ray. We installed a unique inkjet experimental machine inside the X-ray apparatus. Thus, we could visualize the ink penetration dynamically by the micro focus X-ray and the high resolution flat panel. Results are reported below.

Experimental procedure

Manufacturing process

Figure 1 describes the whole process of BJ method. The powder is supplied by a "recoater" which is a rotating roller, and the ink is deposited onto the surface of the powder bed. We prepare stainless steel 316L powder. Each particle is coated with a water-soluble resin containing polyvinyl alcohol (PVA). The ink deposited from the inkjet head dissolute the PVA to solidify the powder particles. Repeat the above steps to fabricate a target object. The fabricated object is in a low strength state called a green body, so it is necessary to dry, degrease and sinter the fabricated object.

In this study, attention is paid to the process in which powder is densified when the ink penetrates into the powder bed. The details of the specific imaging system will be described below.

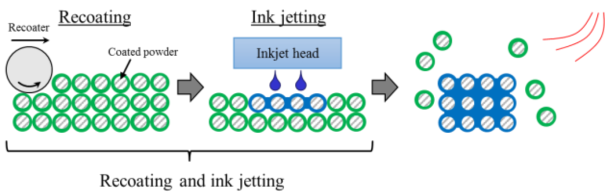


Figure 1. *Schematic diagrams of binder jetting system*

X-ray imaging system

The X-ray imaging system consists of micro focus X-ray, acrylic cell filled with powder, inkjet system and high resolution flat panel. X-ray penetrates the powder filled in the cell and reaches the flat panel. The amount of X-ray passing to the detector depends on the powder density. The different amount of X-ray affects the image contrast. Since the powder bed density varies before and after the ink penetration, the penetration region is visualized.

The inkjet system is originally designed for this research, and the nozzles are arranged at 150 npi, that is, at an interval of about 170 μm in the direction parallel to the X-ray traveling direction (Figure 2). The powder-filled cell has a width of about 3 mm with respect to the X-ray traveling direction. In other words, image in which deposited ink are overlapped at a pitch of 150 dpi on the 3mm wide powder bed is obtained. By adjusting the distance between the micro focus X-ray tube, the acrylic cell and the X-ray flat panel detector, the magnification ratio of the image is about 20 times.

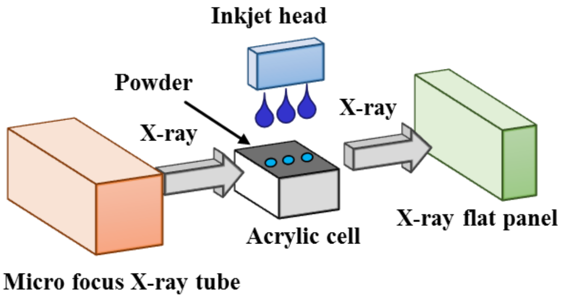


Figure 2. *Schematic diagram of X-ray imaging system for the ink penetration into powder bed*

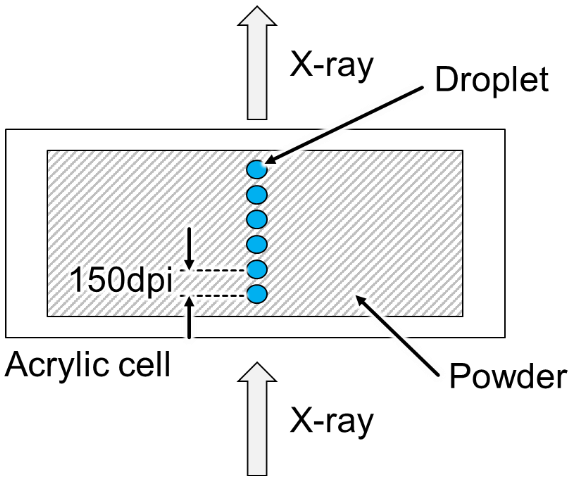


Figure 3. *Top view of positional relation between X-ray and droplets*

The inkjet system can be driven from the outside of the X-ray apparatus, and can deposit the ink onto the surface of the powder bed during X-ray irradiation. The imaging speed of the flat panel is 3 fps. In that frame rate, the ink penetration and densification process can be sufficiently visualized as described below. For clear recognition of the state change of the powder bed caused by ink penetration, contrast of the obtained image is adjusted after image processing is performed.

Validation of visualization

A comparison experiment was conducted for the validation of the X-ray visualization. The droplets with different amounts of ink were deposited onto the surface of the powder bed by our BJ prototype machine [11]. Then, the droplet diameters on the surface of the powder bed were measured and compared with the width of the penetration area of the X-ray visualization. Four different amounts of ink (160 pl, 320 pl, 480 pl, 640 pl) were used to measure the diameter of the droplets. Figure 4 shows an observation example of the ink droplets on the surface of the powder bed.

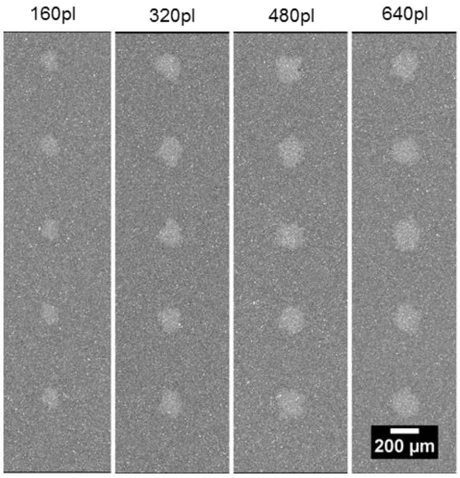


Figure 4. *Top view of surface observation*

It was validated by static visualization whether density changes caused by ink penetration could be detected before visualizing the ink penetration dynamically. A box-shaped sample for validation was fabricated by the BJ prototype machine. Line shaped parts and non-solidified parts were fabricated inside the sample (Figure 5). Since the contrast between the line shaped parts and the non-solidified powder could be detected, it was assumed that the ink penetration area can be detected even by dynamic imaging (Figure 6).

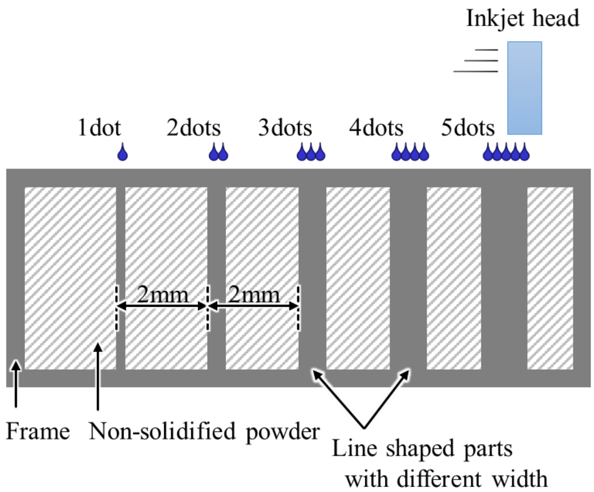


Figure 5. *Conceptual image of the fabricated sample for validation*

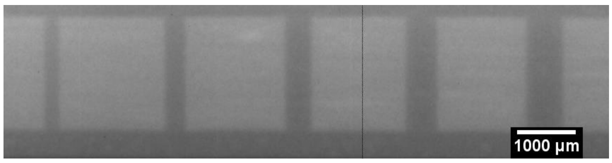
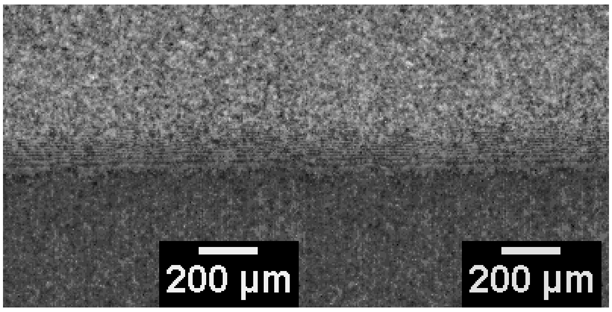


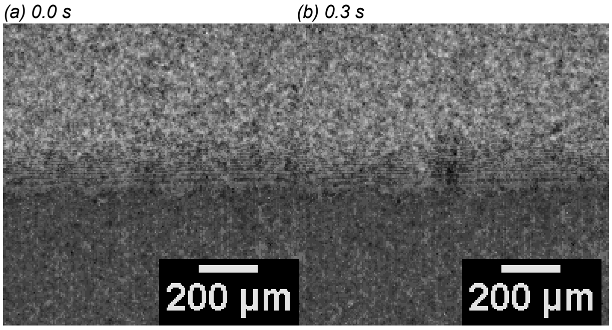
Figure 6. *Static image of line shaped parts and non-solidified powder*

Results and Discussion

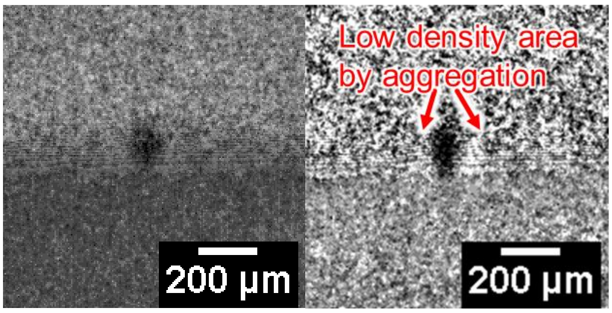
Figure 8 shows an example of visualization results of densification process when the powder density was 29% and the amount of ink was 308 pl. The powder density is a relative density to true density of the stainless steel (approximately 8 g/cm3). The amount of ink was the total amount of microdroplets of 7.7 pl per drop deposited at 50 Hz for 0.8 seconds from the inkjet head. The image contrast shows the amount of transmitted X-ray reaching the detector, and the brighter it indicates the larger the amount of transmitted X-ray, that is, the lower the density.



(a) 0.0 s *(b) 0.3 s*



(c) 0.6 s *(d) 0.9 s*

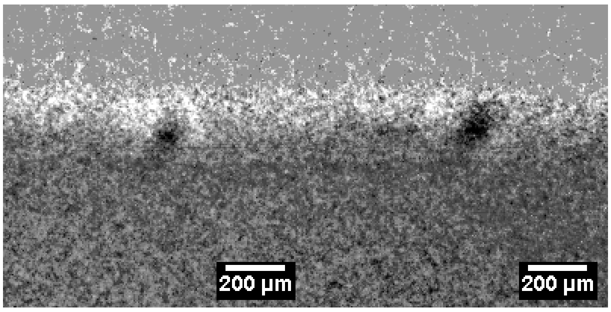


(e) 1.2 s *(f) highlight of the low density area*

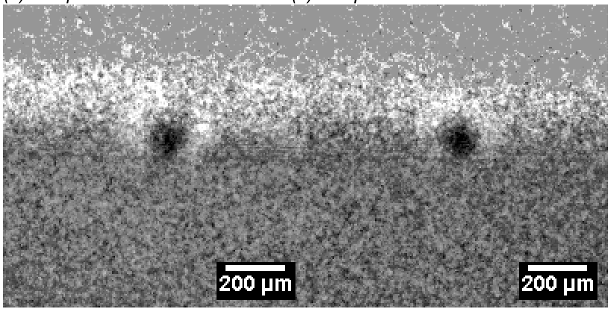
Figure 8. Sequence of X-ray snapshot images of the ink penetration into powder bed

In Figure 8, a dark area of about 100 μm appears in the powder bed within about 1.2 seconds. It is thought that X-ray image shows the result of densification due to the ink permeation and powder solidification by PVA dissolution. On the other hand, the periphery of the dark area is brightened. It is presumed that the ink agglomerates the powder in planar direction while the ink penetration progressing to both depth direction and planer direction.

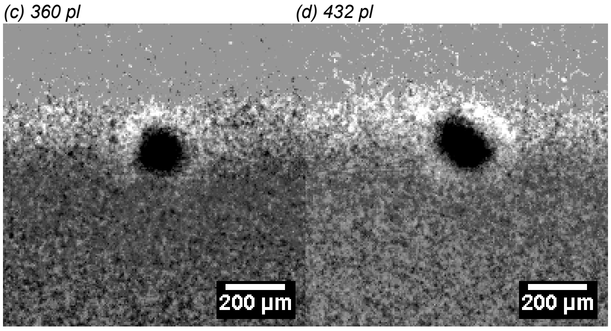
Figure 9 shows visualization results of the different amount of ink. Six different amounts of ink (216 pl, 288 pl, 360 pl, 432 pl, 504 pl, 576 pl) were used to measure the diameter of the droplets. As the amount of ink increases, the dark area becomes darker, indicating that the powder density is higher. In addition, as the amount of ink increases, the dark area becomes larger, indicating that the ink penetration area is widened.



(a) 216 pl *(b) 288 pl*



(c) 360 pl *(d) 432 pl*



(e) 504 pl *(f) 576 pl*

Figure 9. *Ink penetration area of the different amount of ink*

The comparison of size of the ink penetration area by X-ray visualization and the ink droplet diameters by surface observation are shown in Figure 10. Because the two series of droplet sizes are roughly same, the validity of the proposed observation system is confirmed.

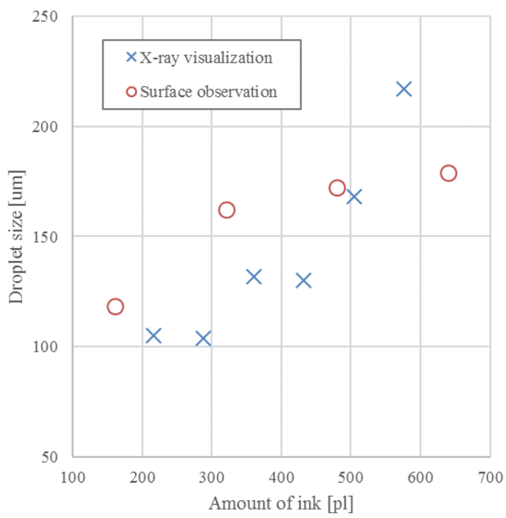


Figure 10. *Comparison of droplet size between X-ray visualization and surface observation*

Conclusion

In the present paper, we proposed a unique X-ray imaging system consisting of micro focus X-ray, inkjet head and high resolution flat panel detector. The ink penetration dynamics into the powder bed in BJ method is visualized by the proposed imaging system. We have found that the amount of ink affects the ink penetration dynamics. The system can be used to clarify the mechanism of the defects in the fabricated objects. By eliminating the defects, quality improvement of the objects is expected.

References

[1] T. Do, "Process development toward full-density stainless steel parts with binder jetting printing." International J. of Machine Tools & Manufacture, 121, 50 (2017)

[2] K. P. Hapgood, "Drop penetration into porous powder beds." J. Colloid and Interface Sci., 253, 353 (2002)

[3] T. Nguyen, "Drop penetration time in heterogeneous powder beds." Chem. Eng. Sci., 64, 5210 (2009)

[4] J. O. Marston, "Experimental study of liquid drop impact onto a powder surface." Powder Technol., 203, 223 (2010)

[5] T. Munuhe, "Using micro-ct to investigate nanofluid droplet sorption in dry powder beds", Powder Technol., 305, 232 (2017)

[5] N. B. Davis, "Microstructure of single-droplet granules formed from ultra-fine powders", Powder Technol., 305, 19 (2017)

[7] C. Zhao, "Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction", Sci. Report, 7, 3602 (2017).

[8] C. Lun, "In situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing", Nature Communications, 9, 1355 (2018).

[9] H. Tan, "Three-dimensional simulation of micrometer-sized droplet impact and penetration into the powder bed", Chem. Eng. Sci., 153, 93 (2016).

[10] E. J. Garcia, "Simulation of liquid-liquid interfaces in porous media", Colloids and Surfaces A: Physicochem. Eng. Aspects, 496, 28 (2016).

[11] T. Sasaki, Printing and Fabrication 2016 (NIP32), Proc. PICS, pg. 139. (2016).

Author Biography

Shin Mizutani received his Master of engineering degree in Computational Physics, the University of Tokyo in 2012 and entered Ricoh company, Ltd. He has been working on the analysis and modelling of physical phenomena in Additive Manufacturing process.