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Coated Powder Based Additive Manufacturing using Inkjet Technique

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Abstract

A new binder jetting process for fabricating metal or ceramic parts has been developed by using coated powder and inkjet technique. In this study, we have developed metal and ceramic particles coated with 100 nanometer thickness of water soluble resin in conjunction with a new concept of ink which includes cross linking agent that acts on the coated resin but does not include any binding ingredients. In this paper, we present a methodology of our new binder jetting process and an overview of mechanical and physical properties of 316L stainless steel parts created by our process.

Introduction

In the Additive Manufacturing field, powder bed fusion (PBF) processes such as selective laser sintering (SLS) or electron beam melting (EBM) are mainly applied to fabricate metal parts. However, these devices are still used in very limited applications like surgical implants, aerospace equipment due to their high introduction and running cost. Basic principle of their fabrication process requires high-energy beam sources and controlled atmosphere with inert gasses. This would be the cause of the high cost.

On the other hand, binder jetting process is largely applied to fabricate gypsum or casting sand. Binder jetting process has some incontrovertible merits compared with the powder bed fusions. No support structure is needed during the forming process. Fabricating productivity is potentially higher than PBFs [1]. There are, however, a few practical applications for metal or ceramic materials with binder jetting apparatus [2-3]. One reason is that post processes of degreasing and sintering are necessary to achieve high density parts [4]. Those are certainly burdensome tasks. Furthermore, jetting ink including binding components is severe for inkjet technology to ensure high reliability. Binders are easily dried and hardened in and around the nozzles of inkjet heads. This may cause lack of fabricated parts and weaken them.

We have been developing new fabricating process to settle these problems. We focus on keeping the reliability of jetting operation of ink high and shorten the time required for post heating process.

The main aim of our study is to make prototype parts quickly and inexpensively without molds in the powder metallurgy industry. In this industry, almost of all the companies or laboratories have heating furnaces which commensurate with their own demands or materials. These facilities can be utilized as they are used for degreasing and sintering parts created by our new process.

Methods

In this section, we explain a series of our process including materials, printing machine, and a fabricating principle.

We prepare stainless steel 316L powder. It is a commercially available grade. Particle size distribution D50 value of the powder is approximately 14 micrometers and any particle size distribution adjustment is not applied.

Each particle is coated with roughly 100 nanometer thickness of water soluble resin. The resin composes primarily of PVA. We have a couple of methods and devices for coating particles. The best way that depends on the powder characteristic such as density, shape, and safety is selected. After coating, powder pass through cracking machine to loosen some agglomerates.

The main component of the ink is water. Cross linking agent is added to harden fabricating parts. Small amount of humectant and viscosity modifier are added to it. We use the word "ink" for convenience throughout this paper. But this liquid do not include any color pigments.

We build original binder jetting machine using our commercially available 2D inkjet printer (Figure 1). This printer has four inkjet heads for full-color printing originally. Since we do not need color for purpose of this study, every head is filled with the same ink as mentioned above. Each head has 384 nozzles and its substantial resolution is 300npi (nozzle pitch is approximately 84 micrometers). Heads are precisely aligned with each other as shown in Figure 2.

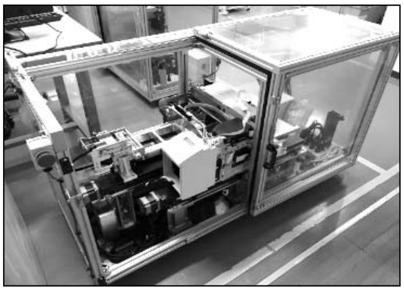

***Figure 1** A photograph of binder jetting machine*

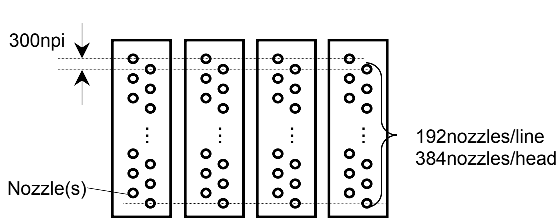

***Figure 2** A schematic view of inkjet heads array layout*

Two powder tubs which are adjacent to each other are settled beneath the moving inkjet heads. The bottom plate of the tubs are movable along vertical axis independently. Layer spreading and subsequent ink jetting sequence are schematically shown in Figure 3. This procedure is a typical binder jetting method [3].

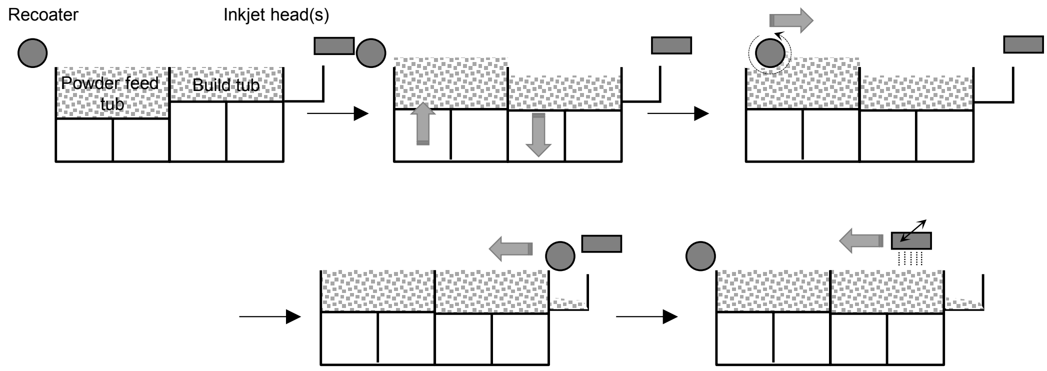

Figure3 *Layer spreading and subsequent ink jetting sequence*

Every single layer thickness is 84 micrometers. The bottom plate of the powder feed tub moves up to 200 micrometers. On the other hand, the bottom plate of the build tub moves down to 84 micrometers. Powder layer is generated by using a recoater (counter rolling bar) which moves 1-axis over the tubs. Rotation speed of the recoater is set to 15rpm. Moving speed is set to 150-200mm/s. Excess powder is trapped at the saucer.

Inkjet heads come over the build tub and jet the ink droplets. Typical droplet volume is approximately 50 picoliter per nozzle. Because all four heads receive same sliced print data from the printer system, one voxel in the powder layer gets 200 picoliter within a several hundred milliseconds.

The water in the ink melts the coated water soluble resin no sooner than the ink touches to the particles. The crosslinking agent in the ink acts on the resin and makes molecular bondings three-dimensionally (Figure 4).

We produce 30mm × 10mm × 3mm rectangular specimens by using the materials and methods as mentioned above. We call these specimens “green body”. These parts become metallurgic via post processing of degreasing and sintering. We measure porosity and mechanical strength of the green body and sintered parts. We also observe the metallic structure of the sintered parts.

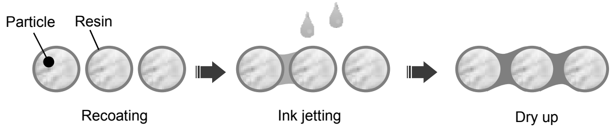

Figure 4 *A conceptual diagram of binding mechanism*

Results and discussions

Coated particle SEM image is shown in Figure 5. Relatively black part observed on the particle is the resin. Figure 6 shows a cross sectional view of one particle. We see very thin resin layer on the stainless steel (white part) body. As plotted on Figure 7, three-points bending strength of the green body depends on the amount of the resin in the powder. It is clear that there is a linearity. We stress that only 1wt% of resin is sufficient for getting green bodies strong enough to handle. This amount of resin is significantly less compared with the conventional powder injection molding methods.

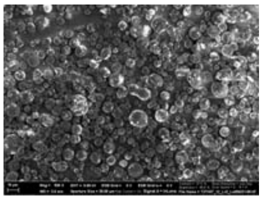

Figure 5 *Coated particle SEM image*

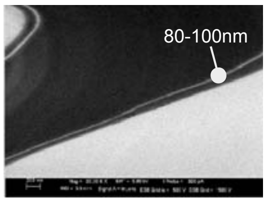

Figure 6 *Cross sectional SEM image of 316L stainless steel particle (D~15um) coated with nanometer (80~100nm) thickness of resin*

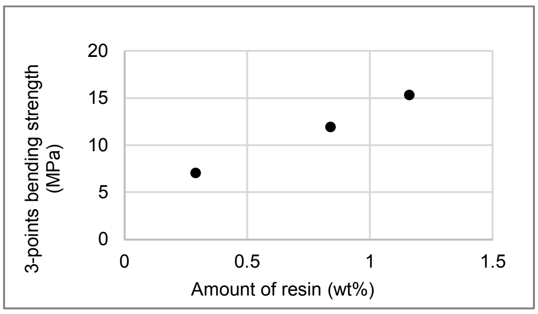

Figure7 *Three points bending strength of the green bodies*

Figure 8 shows the relation between the ink volume jetting in to a voxel in the powder layer and the porosity of the parts. It is certain that the porosity of green bodies and sintered parts decrease as the ink volume increases. Cross sectional photos of sintered parts are shown in Figure 9. We see a characteristic stripe structure corresponding to the layer thickness on the left side of Figure 9. Less ink volume creates this structure. In contrast to this, in the case of increased ink volume condition, we obtain less porosity parts as shown in the right side of Figure 9. We discuss this interesting phenomena in the next section.

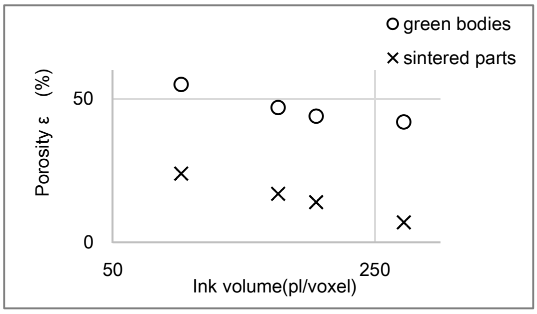

***Figure 8** Porosity of the green bodies and the sintered parts*

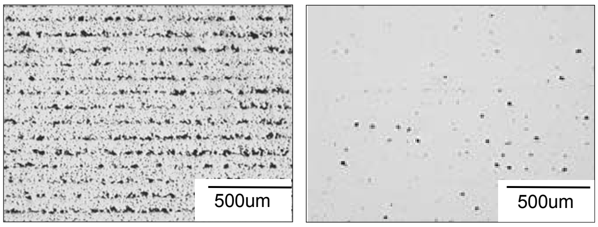

***Figure 9** Comparison of ink volume effects on the internal structure of the sintered parts*

Tensile strength of the sintered parts are shown in Figure 10. From this figure, one immediately sees that the porosity and tensile strength of orthogonal to the build direction have a linearity. We think this result is consistent with the research so far conducted. By contrast, tensile strength to the build direction is weaker than that of orthogonal to the build direction. The linearity to the porosity is not clear. One reason is that some cracks corresponding to the build layer are still remain in the parts. We are now trying to improve this anisotropy of the tensile strength.

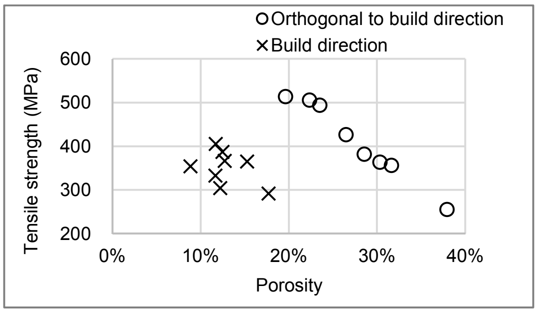

***Figure 10** Tensile strength of the sintered parts*

We now discuss the results obtained in Figures 8 and 9 in connection with an interaction between the ink and the powder. A microscopic schematic view of the ink and the particles behavior is shown in Figure 11. Before ink jetting, packing density of the powder is nearly equals to the bulk density of the intrinsic value of the powder. Because there is no tapping force or vibrations while recoating.

While the ink penetrate the powder, the air in the voxel is almost replaced by the ink. The ink surface forms meniscus and the liquid pressure is lower than the atmosphere pressure. This state called a capillary. Particles in this state move toward center of the voxel by the liquid bridge force. This force arises from surface tension and capillary effect of the ink. The force at the neck of the bridge F is given by the sum of the surface tension and the suction as below [5].

$$F = 2\pi r_2 \gamma + \pi r_2^2 \Delta P \qquad (1)$$

With

$$\Delta P = P_a - P_l = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (2)$$

Where P_a, P_l and γ are pressure of air, pressure of ink and surface tension between air and ink, respectively. r_1, r_2 represents curvature radii of meniscus.

In the case of less ink volume, particles in the voxel of the each layer are independently bound by the force formulated by (1) and the gap appears between the layers. It seems that this gap becomes the origin of the characteristic stripe structure which is shown on the left side of Figure 9. In contrast to this, in the case of increased ink volume condition, the ink jetted on a layer reaches to the beneath of the layer. This excess ink acts on the particles between the layers and makes the gap obscure. According to Nguyen Hoang Long [6], the liquid bridge force is also the function of the ink volume (3), where V, r_0 are volume of ink, radius of particle, respectively. So that much ink weaken the binding force and contribute to decreasing the gap.

$$F = \left(2 - \sqrt[4]{\frac{2V}{\pi r_0^3}}\right)\pi r_0 \gamma \qquad (3)$$

Let us finally show some photos of example parts produced by our methodology in Figure 12. In the order left to right, parts are made from SUS316L stainless steel, glass, and titanium.

Conclusion

In this study, we developed metal and ceramic particles coated with approximately 100 nanometer thickness of water soluble resin and quite a new concept of ink. This water based ink includes cross linking agent acts on the coated resin. But it does not include any binding ingredients. This ink may contribute to prevent nozzles of inkjet heads from clogging and to improve reliability of jetting the ink.

Commercially available inkjet printer system which is used in mass production is utilized for producing green bodies in this experiments. Considerably less expensive binder jetting machines can be provided by using our low-cost mass production of printer system.

Optimum combination of the materials are selected so as to achieve high strength of the green body. The degreasing process time will be shorter than ordinary powder injection molding processes (metal injection molding (MIM) or ceramic injection molding (CIM)) because total amount of organic substances is much less than these conventional processes.

We also provide an overview of the mechanical and physical properties of 316L stainless steel parts produced by our novel process and device. The tensile strength is comparable to a MIM parts.

The methodology of fabricating parts and the properties of the processes such as powder characteristics, recoating parameters, and ink jetting conditions are mentioned. We also discuss the ink volume and behavior in the powder which impact on characteristics of the parts. As we showed, this method can be applied to various materials which are sinterable.

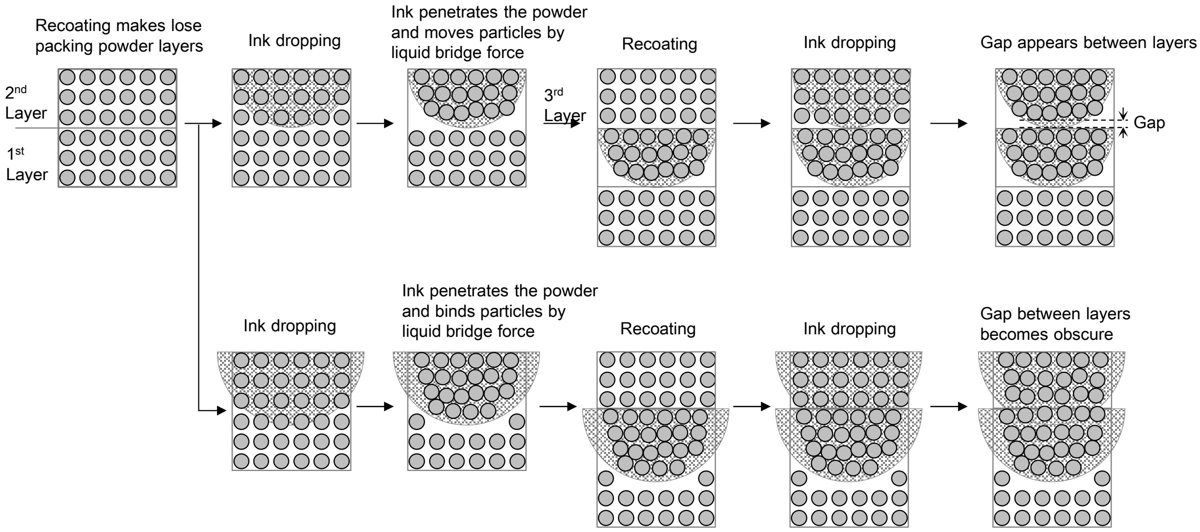

Figure 11 *A microscopic schematic view of ink and particles behavior*

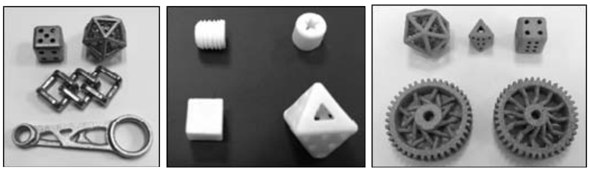

Figure 12 *Sintered part examples of 316L stainless steel (left), glass (center), and titanium(right)*

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Author Biography

Takafumi Sasaki received his Master degree in nuclear physics from the Kyushu University (2003). Since then he has been working in the development division at Ricoh in Japan. His work has focused on the development of inkjet heads and additive manufacturing process.