Forming technology of non-heat source binder jetting metal powder and its final treatment process

Li Wang
wanligime@mail.xjtu.edu.cn

Ruanzhi Zhang
Tai Ze
Zhaofa Zhang
Zhenghao Liu
Shixing Chen
Bingheng Lu

Research Article

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Abstract

The binder jetting (BJ) forming process is an additive manufacturing method based on discrete stacking and microdrop jetting technology. It has the advantages of low cost and high degree of automation; further, it has no special requirements pertaining to the shapes or structures of machining parts. However, at the present stage, all BJ processes involve hot curing, which leads to high molding and maintenance costs. To solve this problem, polyvinyl alcohol powder was used as the main material of the binder formed via the BJ process. The wetting of the powder bed by ink droplets was simulated, and the ink formula and printing process parameters were optimized. The final metal part was formed via defatting and sintering, resulting in a tensile strength of 323 MPa and density of 85.6%.

1. Introduction

With properties such as high strength, high hardness, high-temperature resistance, and corrosion resistance, metallic materials have application prospects in many fields, such as aerospace, marine engineering, and biomedical and automotive manufacturing. However, traditional metal processing methods generally require forging, pouring, turning, milling, planning, grinding, clamping, and other mechanical processes, increasing the production costs of enterprises. Additionally, they involve many processing steps and are time-consuming, demanding for operators, and harmful to the environment. Most importantly, owing to the inherent shortcomings of traditional machine tool processing, metal parts with complex shapes and structures and high precision levels, such as propeller blades and automobile engine cylinder blocks, cannot be rapidly manufactured. Binder jetting (BJ) is an additive-prototyping method based on discrete stacking [1]. With the support of computer-aided design, jet three-dimensional (3D) printing technology turns 3D virtual models into physical products in a short time and according to the application requirements. Owing to its advantages of low production costs, a short production cycle, high flexibility, automation and rapidity, no special requirements for the shapes or structures of processed parts, and high precision, jet 3D printing technology has been widely used in manufacturing, medicine and health, architectural design, and other industries, and its development prospects are infinite and broad [2–4].

The BJ 3D printing process was developed by Sachs et al. at the Massachusetts Institute of Technology in 1992 and was then known as 3DP [5]. The principle is illustrated in Fig. 1. According to the two-dimensional cross-sectional data from the 3D model, the computer controls the nozzle to inject the binder onto the surface of the powder bed as required to form the part, achieving a single layer of powder bonding. Such layers are stacked to obtain the final part. Compared with the selective laser sintering 3D printing process, which is also suitable for metal forming, the microjet bonding 3D printing process has the advantages of a higher forming speed, a higher the efficiency [6] (by a factor of >10 when a printing head with a width of >65 mm is used), no residual stress after bonding, a high yield of castings, and lower equipment and operation costs. It is suitable for industries that need customization and timely delivery to the market—particularly for parts in the aerospace and medical fields with small batches and high added value.
At the current stage of the metal BJ process, the main binder used is ethylene glycol (EG). It has good water solubility, a relatively low cost, and good stability. **Table 1** presents some of the binder agents applied at this stage.

**Table 1** Binders used for the BJ process.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Powder</th>
<th>Curing temperature (℃)</th>
<th>Curing time</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGBE/IPA/EG</td>
<td>316/420</td>
<td>195</td>
<td>2 h</td>
<td>[7]</td>
</tr>
<tr>
<td>EG/DEG</td>
<td>316L + 316L nano</td>
<td>200</td>
<td>2 h</td>
<td>[8]</td>
</tr>
<tr>
<td>ExOne LB 04</td>
<td>420 + Cu nano</td>
<td>200</td>
<td>2 h</td>
<td>[9]</td>
</tr>
<tr>
<td>N.A.</td>
<td>316</td>
<td>175</td>
<td>3 h</td>
<td>[10]</td>
</tr>
<tr>
<td>PM-B-SR1-01 ExOne</td>
<td>420 + Si₃N₄</td>
<td>170</td>
<td>2 h</td>
<td>[11]</td>
</tr>
<tr>
<td>PM-B-SR1-04 ExOne</td>
<td>Ti + Al</td>
<td>200</td>
<td>2 h</td>
<td>[12]</td>
</tr>
<tr>
<td>EGME/EG ExOne</td>
<td>Inconel 625</td>
<td>175</td>
<td>N.A.</td>
<td>[13–14]</td>
</tr>
<tr>
<td>PM-B-SR2-05</td>
<td>Cu</td>
<td>190</td>
<td>2 h</td>
<td>[15]</td>
</tr>
</tbody>
</table>

As indicated by **Table 1**, the metal printing and forming process involves thermosetting, which leads to a complex metal forming process, increasing the cost of metal forming and reducing the printing efficiency. The existence of heat sources in the forming process increases the complexity of the forming equipment and the maintenance cost of the equipment at a later stage[16]. In this study, polyvinyl alcohol (PVA) powder was used as the main material of the adhesive to reduce the heat-setting process in the metal forming process. The surface quality of the metal forming parts was predicted via penetration simulations, and the accuracy of the simulation results was verified. The optimum parameters of the forming process were determined using the single-factor experimental variable method, and the densification of the printed parts was achieved via thermal degreasing and sintering.

2. Materials and methods

2.1. Materials

In the experiments, 316L stainless steel metal powder supplied by 3D Systems was used. The sphericity and average particle size were measured using a HELOS & RODOS dry air dispersion laser particle sizer (Sympatec, Germany), as shown in **Fig. 2**. The powder density was 4.21 g/cm³, with a true density of 7.98 g/m³, and the powder porosity was 47.26%.

PVA was used as the main material of the adhesive. PVA is a nontoxic and tasteless white powder with a flake micromorphology. Because its main chain contains -CH-CH (OH)- groups, it is a water-soluble polymer with several strong hydrophilic hydroxyl groups. PVA has good adhesion and film-forming
characteristics. With an increase in the degree of alcoholysis, its solubility in water decreases significantly. When the alcoholysis degree is 88%, the water solubility is at its highest. For example, in “pva1788,” 17 represents the degree of polymerization (1700–1800), and 88 represents the degree of alcoholysis (88% ± 2%). PVA has a decomposition temperature of approximately 240 ℃; thus, it is easy to decompose, gasify, and discharge from a printing blank during heat treatment. In this study, pva1788-300 PVA powder was used.

2.2. Powder preparation

For powder pretreatment, a V-type 3D mixer was used to mix the dried and weighed metal powder with PVA powder for 2.5 h, and then a KQM-X/B planetary ball mill was used for ball milling at a speed of 120 r·min⁻¹ for 15 min. After the pretreatment, the PVA powder with a small particle size was fully and evenly mixed with the metal powder. The morphologies of the metal powder, pva1788-300 PVA powder, and mixed powder were examined using an optical microscope, as shown in Fig. 3.

2.3. Preparation of ink and laboratory equipment

The spray was prepared by mixing deionized water and absolute ethanol at a certain mass ratio. A self-developed microjet bonded metal forming printer with a forming size of 230 × 230 × 200 mm³ was used, and the powder laying was performed using a roller. The experimental setup is shown in Fig. 4.

2.4. Penetration simulation

2.4.1. Establishment of multiphysics field simulation model

Droplet penetration simulations were conducted using COMSOL Multiphysics. The metal spherical particles were viewed as a stacking method for a population of isometric spherical particles, and a positive rhomboidal particle arrangement was selected, as shown in Fig. 5. The porosity of the powder bed was controlled by setting the distance d between the particles. The porosity was calculated to be 47.26% when the distance between the particles was d = 9.57 μm.

The simulations were performed using the two-phase flow and level set modules of COMSOL. The level set method was used for fluid simulation, and the controlling equation was the Navier–Stokes equation, which can accurately describe a microporous liquid flow. It is expressed as follows:

\[
\rho \frac{\partial u}{\partial t} - \nabla \cdot \mu \left[\nabla u + \left(\nabla u^\top\right)\right] + \rho (\mu \cdot \nabla)u + \nabla P = F,
\]

\[
\nabla \cdot \mu = 0
\]

where ρ represents the density of the solution, P represents the pressure, u represents the percolation velocity, and F represents the volume force (including gravity and the surface tension of the horizontal set method of treatment).
The material properties were assigned, the boundary conditions were set, and the mesh was divided. The boundary conditions are presented in Table 2. The calculation model designed in COMSOL is shown in Fig. 6.

**Table 2** Boundary conditions.

<table>
<thead>
<tr>
<th>Boundary type</th>
<th>Boundary condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>No slip</td>
<td>( u = 0 \text{ m/s} )</td>
</tr>
<tr>
<td>Particle-based</td>
<td>Lubricated-wall contact angle</td>
<td>( \pi/6 )</td>
</tr>
<tr>
<td>Exit</td>
<td>Initialization phase</td>
<td>—</td>
</tr>
<tr>
<td>Droplet</td>
<td>Outlet pressure</td>
<td>0 Pa</td>
</tr>
<tr>
<td>Gravity</td>
<td>Gravity vector</td>
<td>(-9.8 \text{ m/s}^2)</td>
</tr>
</tbody>
</table>

2.4.2. Analysis of infiltration simulation results

The main purpose of the penetration simulation was to examine the penetration pattern of liquid droplets in the powder bed. The simulation clouds obtained are shown in Fig. 7(a), and the relationship between the penetration thickness and the print speed is shown in Fig. 8.

The printhead used in this study was provided by Epson. The diameter of the spray holes was 30 µm, distance between the spray holes was 143 µm, and spray frequency was 10,000 times/s. By observing the spray effect of the spray nozzle under normal working conditions, the spray droplet size of the spray nozzle was found to be approximately 20 pL; that is, the volume of ink sprayed by a single hole per unit time was 0.2 mm³. The simulation results indicated that the penetration depth of ink droplets in the powder bed was related to the nozzle speed. For example, when the speed was 11 mm s\(^{-1}\), the penetration thickness of the droplets was approximately 0.27 mm, resulting in an inverted triangle-like penetration area when viewed from the cross section of the moving direction of the nozzle (Fig. 7(b)). Accordingly, the space model that needed to be infiltrated after the ink droplets are ejected from a single hole fall to the powder bed in unit time is shown in Fig. 7(b). The overall volume is

\[
11 \times 0.27 \times 0.5 \times 0.143 = 0.212355 \text{ mm}^3
\]

When the powder is loosely packed and left standing, the porosity of the powder bed (containing PVA) is approximately 45%; that is, 55% of the powder is filled in the unit volume, and the remaining 45% is the powder gap, which is filled by air. Thus, the infiltration volume of powder is calculated as

\[
0.212355 \times 55\% = 0.1168 \text{ mm}^3.
\]

The powder bed system used in this study comprised 316L stainless steel and PVA. When their mass ratio is 100:1, their volume ratio in the powder bed is approximately 16:1 according to the density
relationship. Therefore, the osmotic volume of PVA is approximately 

\[ \frac{0.1168}{17} \approx 0.00687 \text{ mm}^3 \]

The quality is

\[ 1.28 \times 0.00000687 \approx 0.00000879 \text{ g} \]

At room temperature (20°C-35°C), the solubility of PVA in water is 10 wt%. Therefore, to dissolve the PVA powder, the amount of water sprayed per unit time in a single hole should be \( \geq 0.0000879 \text{ g} \). The density of water at room temperature is 1 g/cm\(^3\) and that of ethanol is 0.8 g/cm\(^3\). When the mass ratio of water to ethanol is 4:6, the mass of water sprayed in a single hole per unit time is approximately 0.000696 g, which is inadequate for dissolution. When the mass ratio of water to ethanol is 1:1, the amount of water sprayed per unit time is 0.000889 g, which satisfies the requirements for dissolution and solidification. As the content of ethanol is identical to that of water, ethanol can be used to fill approximately 45% of the pores in loose powder, which is consistent with the ink requirements of this study. When the water content increases further, although the requirements for wetting the powder can be satisfied, the conditions are not conducive to the volatilization of liquid without a heat source, reducing the curing speed. Additionally, the higher water content increases the surface tension of the ink, which is not conducive to the typical operation of the nozzle. The optimum ink formula was verified via printing experiments.

2.5. BJ process

The process parameters that influence the forming of metal parts include the saturation of the binder, the thickness of the printed layer, and the ratio of the powder.

The experiment was performed using the single-factor control variable method. With a metal powder–PVA powder mass ratio of 100:1 and a printing-layer thickness of 0.24 mm, molding experiments with an adhesive saturation of 55%, 85%, 115%, and 145% were conducted. The resulting prints were denoted as A1, A2, A3, and A4, respectively (Fig. 10). When the adhesive saturation was 115%, three groups of experiments with printing-layer thicknesses of 0.12, 0.18, and 0.24 mm were conducted, and the results are denoted as B1, B2, and B3, respectively, in Fig. 14. Finally, three groups of proportioning experiments (metal powder–PVA powder mass ratios of 100:0.5, 100:1, and 100:3) were conducted with 115% adhesive saturation and a printing-layer thickness of 0.18 mm. The results are denoted as C1, C2, and C3, respectively, in Fig. 18.

2.6. Post-processing

The post-treatment part of the metal BJ process after forming mainly included two steps: degreasing and sintering. Degreasing involves the decomposition of PVA powder by heat, and the degreasing process is conducted at 350 °C in N\(_2\) for 2 h. The core of the post-treatment process for the metal formed parts lies in the sintering of the metal, and the parameters of the metal sintering process include the sintering
atmosphere, sintering temperature, and holding time. The sintering process used in this study is shown in Fig. 9.

Sintering experiments were performed on the metal parts under vacuum conditions at three temperatures: 1300, 1340, and 1380 °C. After sintering, the mechanical tensile specimens were subjected to tensile tests using a biomechanical tester, and their densities were measured using a densitometer.

3. Results and discussion

3.1. Simulation results

As indicated by the results of simulation clouds (Fig. 7(a)), there were circular penetration areas on both the lower and side surfaces of the molded part; consequently, these surfaces had the worst quality. There were no circular areas on the upper surface; thus, the surface quality was higher. The surface measurement results for an actual printed part are presented in Fig. 12. As shown, the upper surface had the best quality.

The relationships among the printed-layer thickness, binder saturation, and print speed were examined. When the printhead moved at 15 mm/s, the penetration thickness was 0.24 mm, and the binder saturation was $L_{AB} : L_{AC} = 87.5\%$ (Fig. 8). Measurements of the jet quantity, print quantity, and powder porosity of the printhead revealed that when the printhead moved at 15 mm/s, the difference between the simulation result and the measured value (85%) of the adhesive saturation was 2.94% (a small difference); thus, the simulation results matched the actual penetration. The three relationship diagrams obtained through the simulation can be used to guide the selection of the process parameters.

3.2. Effects of forming process parameters

Printed parts obtained with different binder saturation levels for a given layer thickness and powder composition is shown in Fig. 10.

When the adhesive saturation was 55%, the prints were broken. The dimensions of the A2, A3, and A4 prints were measured, and the dimensional accuracies for these prints are shown in Fig. 11. The surface quality was characterized for the three groups with different levels of binder saturation, and the surface extremes obtained are shown in Fig. 12.

The print with the most accurate size and the best surface quality was obtained when the adhesive saturation was 115%.

When the adhesive saturation was too low (55%), because the ink did not fully penetrate the printed layer, the part that played a bonding role was small, resulting in weak bonding between the layers. Thus, after the parts were removed, delamination is likely to occur, as shown in Fig. 10(A1). Additionally, the low adhesive saturation leads to a low adhesive content in the same printed layer, and the bonding effect of the same layer of metal powder is poor. In general, both low and high adhesive saturation lead to poor
surface quality and a low dimensional accuracy. With lower adhesive saturation, the adhesive was not strong enough to hold the necessary powder material together, and some powder particles fell off the part, resulting in a jagged surface and poor surface quality (as shown in Fig. 13). When the adhesive saturation was too high, excess powder stuck to the surface, resulting in bulges and poor surface quality (as shown in Fig. 13). Therefore, the correct amount of adhesive is needed to obtain good surface quality.

Three sets of experiments with different printed-layer thicknesses conducted at 115% adhesive saturation yielded the three sets of images shown in Fig. 14. At the selected printed-layer thickness of 0.12 mm, dislocations occurred between the layers. This is because with a thinner printed layer and higher print speed at the same adhesive saturation, fewer bond points were printed in the same print area (as shown in Fig. 15), and the adhesive force was weaker; thus, the printed layer was more likely to shift when subjected to horizontal forces during the spreading of the powder.

The dimensional accuracies of the prints obtained with layer thicknesses of 0.18 mm (B2) and 0.24 mm (B3) are shown in Fig. 16. The surface quality was characterized for the two groups with different layer thicknesses, and the surface extremes are shown in Fig. 17. With a small difference in dimensional accuracy, a higher surface accuracy was obtained with a thinner printed layer. Thus, the optimum printed-layer thickness was 0.18 mm.

Different powder ratios were used for printing experiments, and the metal parts obtained are shown in Fig. 18. When the PVA powder was mixed into the metal powder, a lower content of PVA powder was better for reducing the impact of the powder on the metal part. Thus, the optimum metal powder–PVA powder mass ratio was 100:1.

3.3. Effect of post-treatment process parameters

In the BJ process, after the metal powder is formed, a post-treatment process is often required. The post-treatment part of the metal BJ process includes degreasing and sintering. The purpose of degreasing is to remove the adhesive from the metal printed parts, and the metal powder is pre-sintered to increase the adhesive strength of the parts.

In this study, the degreasing temperature was determined via thermogravimetric analysis of PVA. Considering that metal powder is easily oxidized at high temperatures, a N\textsubscript{2} atmosphere at 350 °C was selected for degreasing. Through measurements, a curve for the relationship between the weight loss of the sample and the holding time was obtained, as shown in Fig. 19.

As shown in Fig. 19, the weights of the metal parts exhibited a sharp decrease in the holding time period of 0–1 h. The weight change between 1 and 2 h was small, and after 2 h, the weight remained in a stable stage. The PVA was essentially in a stage of complete decomposition at this time. The results indicate that 2 h is a reasonable and economical degreasing holding time. To maintain the bonding force of the degreased parts, pre-sintering was conducted after the degreasing.
Sintering is the last part of the BJ process and is the key step for comprehensively evaluating the performance of products. In this study, supersolids liquid-phase sintering (SLPS) was adopted. Considering the problem of metal oxidation, a vacuum atmosphere was adopted in the sintering process. The solid-phase sintering node of 316L metal powder is 1080 °C; thus, the sintering temperature of SLPS must be higher than this temperature. Tensile tests were performed on three groups of metal parts at different sintering temperatures, and the results are shown in Fig. 20. The tensile strengths of the metal parts reached 323 MPa (elongation: 19.6%) at 1380 °C. Subsequently, the microscopic morphologies of the metal parts at different temperatures were examined, as shown in Fig. 21.

As indicated by Fig. 21, when the metal parts were sintered at 1300 °C, they had large holes. Each 40 °C increase in the sintering temperature reduced the number of holes and made them smaller, because the increase in the sintering temperature accelerated the material transfer during the sintering, which promoted the sintering between the particles and reduced the numbers of pores and defects within the material.

With degreasing and sintering under the optimum parameters, the metal parts shrank. To analyze the changes in the dimensions of the printed metal parts after the sintering, six metal parts (24 × 4 × 5 mm³) were printed (Fig. 22) and post-processed under the optimum degreasing and sintering process parameters. Their lengths, widths, and heights were measured using vernier calipers before and after sintering, and the average values were calculated. The experimental results are presented in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Before sintering/mm</th>
<th>After sintering/mm</th>
<th>Shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>24.1</td>
<td>21.4</td>
<td>11.2%</td>
</tr>
<tr>
<td>Width</td>
<td>0.40</td>
<td>0.35</td>
<td>12.5%</td>
</tr>
<tr>
<td>Height</td>
<td>0.51</td>
<td>0.42</td>
<td>15.6%</td>
</tr>
</tbody>
</table>

As indicated by Table 3, the sizes of the metal parts were significantly reduced after degreasing and sintering. The shrinkage in the length and width directions was approximately 12%, and that in the height direction was approximately 15%. These results are explained by the method used for embedding powder (aluminum oxide) in the process of degreasing and sintering. When metal parts shrink at a high temperature, owing to the weight of the aluminum oxide powder, they are extruded in the vertical (height) direction; thus, the shrinkage in the height direction exceeds that in the length and width directions.

We used Archimedes’ drainage method to measure the densities of the metal parts. The mass of the metal parts when dry was 3.96 g, and the weight of the drained water was 0.58 g when the metal parts were all placed in deionized water. The bulk density of the metal parts was calculated as 6.83 g·cm⁻³, and the density of 316L stainless steel is 7.98 g·cm⁻³; thus, the calculated density of the metal parts was
85.6%. The density of the parts reached the level that can be achieved under ordinary conditions in industry.

4. Summary and conclusions

For solving the problems of the high costs (including maintenance) and low printing efficiencies of metal BJ printers, a method of non-heat source in the metal BJ process is proposed, which significantly increases the printing efficiency compared with the metal BJ printer currently on the market. By studying the morphology of droplet penetration into the powder bed, the reason for the significant differences in surface quality among formed parts was determined. Through research on the forming process, the complete and rapid forming of metal printing parts was realized. With post-treatment, the densities of the metal parts reached the level that can currently be achieved via the metal BJ process with a heat source. The study is summarized as follows.

First, PVA was selected as the main adhesive material, and the mold powder was obtained by mixing PVA with metal powder. By mixing deionized water and absolute ethanol with jet ink, the formation process of microjet adhesive technology can be realized without a heat source.

Second, COMSOL physical field simulation software was used to simulate the droplet penetration process, analyze the spreading of the binder after the penetration of the powder bed, and obtain the relationships among the nozzle speed, penetration thickness, and binder saturation. According to the simulation results, the optimal mass ratio of water to ethanol in the ink was calculated (for a metal powder–PVA mass ratio of 100:1).

Third, the optimum printing process parameters were determined via the single-factor experimental variable method. The optimal level of adhesive saturation was 115%, and the optimal thickness of the printed layer was 0.18 mm, confirming the calculation result that the printing effect is the best when the mass ratio of metal powder to PVA powder is 100:1 if absolute ethanol and water are mixed at a mass ratio of 1:1.

Finally, the tensile strength of the metal was tested at different sintering temperatures, and the optimum sintering temperature was 1380 ℃. The tensile strength of the metal reached 323 MPa (elongation: 19.6%), and the denseness of the metal reached 85.6%.

Declarations

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Conflicts of interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

Li Wang: Conceptualization, Methodology

Ruanzhi Zhang: Writing & Editing

Ze Tai: Investigation, Data Curation, Writing - Original Draft

Zhaofa Zhang: Project administration

Zhenghao Liu: Project administration

Shixing Chen: Project administration

Bingheng Lu: Supervision

References


Figures
### Figure 1

Schematic of the microjet bonding 3D printing process

<table>
<thead>
<tr>
<th>Particle Size</th>
<th>Cumulative Distribution (Q3/%)</th>
<th>Frequency Distribution (Q3*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X10.3 = 21.72 µm</td>
<td>100</td>
<td>2.5</td>
</tr>
<tr>
<td>X16.3 = 24.51 µm</td>
<td>90</td>
<td>1.5</td>
</tr>
<tr>
<td>X50.3 = 35.78 µm</td>
<td>80</td>
<td>1.0</td>
</tr>
<tr>
<td>X84.3 = 49.61 µm</td>
<td>70</td>
<td>0.5</td>
</tr>
<tr>
<td>X90.3 = 54.92 µm</td>
<td>60</td>
<td>0.0</td>
</tr>
<tr>
<td>X99.3 = 71.40 µm</td>
<td>50</td>
<td>0.0</td>
</tr>
<tr>
<td>SMD = 32.47 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMD = 37.16 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copt = 10.27%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Figure 2

Particle size distribution and sphericity of the metal powder.

### Figure 3

Morphologies of (a) metal powder, (b) PVA, and (c) mixed powder under an optical microscope.
Figure 4

BJ metal printer.

Figure 5

Schematic of the orthorhombic particle arrangement.
Figure 6

Infiltration simulation calculation model.

Figure 7

(a) Infiltration simulation clouds; (b) space model of the powder bed to be infiltrated by ink droplets
Figure 8

Relationship between the penetration thickness and the print speed.
Figure 9

Sintering process.
Figure 10

Printed parts at different binder saturation levels (A1: 55%; A2: 85%; A3: 115%; A4: 145%).
Figure 11

Dimensional accuracies with different binder saturation levels (A2: 85%; A3: 115%; A4: 145%).
Figure 12

Surface quality of parts with different binder saturation levels (A2: 85%; A3: 115%; A4: 145%)
Figure 13

Schematic of the bonding effect.

Figure 14

Printed parts for different layer thicknesses (B1: 0.12 mm; B2: 0.18 mm; B3: 0.24 mm).
Figure 15

Maps of bonding points for different layer thicknesses (a: 0.24 mm; b: 0.12 mm).

Figure 16

Dimensional accuracies for B2 and B3 (B2: 0.18 mm; B3: 0.24 mm).
Figure 17

Surface quality for B2 and B3 (B2: 0.18 mm; B3: 0.24 mm).

Figure 18

Parts obtained with different powder mass ratios (C1: 100:3; C2: 100:1; C3: 100:0.5).
Figure 19

Relationship between the weight loss and the holding time.
Figure 20

Relationship between the tensile strength and the sintering temperature.

Figure 21

Microstructures of metal parts after sintering. (a: 1300 °C; b: 1340 °C; c: 1380 °C)
Figure 22

Measurement of the dimensions of metal parts. (a: before sintering; b: after sintering)

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