Research on 3D Printing Process of Metal Powder Based on UV Curing

Xun Liu¹, a, Sixiang Li¹, b, Jianfei Yang¹, 2, *Yu Gao¹, c and Yiping Dou¹, d
¹School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing, China
²Nanjing Normal University Changzhou Institute of Innovation and Development, Changzhou, China

*Corresponding author e-mail: 631056602@qq.com, a610709672@qq.com, bwww1242412@qq.com, c2598773206@qq.com, dyiping.dou@qq.com

Abstract. In this paper, the 3D printing process of metal powder based on digital micro jet was studied. This process used a UV resin with a fast curing speed and high strength as a binder to realize rapid metal powder molding. The influence of process parameters such as nozzle temperature, print pitch, powder coating thickness and printing speed on the forming quality of metal powders was analysed. The adhesion of UV resin and metal powder was obtained by electron microscope. By measuring the density of the model and combined with the molding effect of the model surface, the better process parameters were determined. The results showed that under these process parameters, the bonding effect of UV resin and metal powder can be improved, and the error of molding process can be reduced. It has some theoretical and experimental significance for metal ink-jet printing technology.

1. Introduction

Metal 3D printing, as a prospective technology, has found its wide applications for these areas like biomedicine, automotive, military and aerospace [1], where the manufacture of complex and expensive parts with high-precision is required. At present, there are three main rapid prototyping technologies for directly manufacturing metal parts: electron beam melting (EBM), selective laser melting (SLM) and laser engineering net shaping (LENS). The materials used now in these technologies are usually expensive alloys like aluminum alloys and titanium alloys, or other high-temperature alloys that have some serious drawbacks like porosity and prone to cracking [2]. In addition to the three technologies above, remarkable achievements have been obtained in metal inkjet printing (MIP), which has been developed on the basis of the three-dimensional printing technology (3DP) in recent years. Compared with other metal 3D printing, MIP has a wider range of applicable materials. Besides, the application of adhesive injection will make MIP a prospective and practical technology in the near future.

This paper presents the study on 3D printing process of metal powder, with digital micro jet and UV resin. The influence of process parameters on the forming quality of metal powders is first analysed. Then, the process parameters are optimized through the model density measured and the analysis on the molding effect of the model surface. Solid models are printed for the study in our Laboratory.
Experimental results show that the optimized parameters are very effective at improving the bonding effect of UV resin with metal powder and at reducing the error of molding process.

2. 3D printing process of micro-jet metal

The process flow and schematic of the 3D printing process of micro-jet metal are shown in Fig. 1 and 2, where UV resin, as binder, is sprayed selectively on the paved powder by the digital micro sprinkler nozzle, according to the instructions from computer. With this binder, the metal powder particles can be bonded together. UV resin materials are solidified by UV irradiation. Through layer-by-layer printing, a solid model can be obtained after removing the unbonded powder.

![Figure 1. Process flow diagram.](image)

![Figure 2. Schematic of 3D printing process.](image)
The PZT-JET5010 piezoelectric nozzle, with a minimum size of 0.075mm, is selected, which can accurately dispense 0.01mg grades at specified locations with high precision.

3. Experimental study on 3D printing forming of micro-jet metal

3.1. Metal powder
The metal powder for printing the solid model is the 300 mesh 316L stainless steel powder, the chemical composition of which is listed in Table 1.

| C  | Si  | Mn  | P   | S   | Ni  | Cr  | Mo  | Fe  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
| ≤0.03 | ≤1 | ≤2 | ≤0.035 | ≤0.03 | 10-14 | 16-18 | 2-3 | Bal |

3.2. Binder
The binder for the metal powder above is VeroWhitePlus RGD835 resin, the viscosity and surface tension of which, at different temperatures, are measured as shown in Figure 3. The density of the binder is 1.1064 g/cm³ and stable at the usual working temperature ranging from 20°C to 80°C.

![Figure 3. Viscosity and Surface Tension at Different Temperatures.](image)

3.3. Analysis of interaction and infiltration process between binder and powder bed
The interaction process between the adhesive droplets and the surface of the powder bed is shown in Figure 4. When the droplets are impacted on the powder bed with a certain speed, they will spread and moisten the surface of the powder bed, then penetrate and solidify the powder [3].
In the process of droplet forming and dropping, shown in Figure 4 (a), the droplet is assumed to have a spherical shape with a constant volume after the droplet is sprayed from the nozzle to the surface of the powder bed. UV resin is ejected from the nozzle with an inner diameter of 0.075mm. The equation for estimating droplet diameter \( D \) can be expressed as [4]

\[
D = \left( \frac{6d \sigma}{\rho g} \right)^{1/3}
\]

(1)

Where \( d \) is the inner diameter of the nozzle; \( \sigma \) the surface tension, \( \rho \) the adhesive density, \( g \) the acceleration of gravity.

The ceramic crystal in the piezo nozzle can apply a positive pressure \( F_q \) by vibration to the binder at the nozzle, making the droplet falling rapidly from the nozzle, with a zero initial velocity. If the friction between the liquid and the inner wall of the nozzle is negligible, the velocity \( U_0 \) of the droplet when it reaches the surface of the powder bed can be calculated as follows:

\[
U_0 = \left[ 2gh + 2F_q gh / d \sigma \pi \right]^{1/2}
\]

(2)

Where \( h \) is the vertical distance from the nozzle to the surface of the powder bed.

The percolation process of the droplet is illustrated in Figure 5 [5-6]. When the droplet is impacted onto the powder bed, it starts to diffuse with certain pressure on surface of the powder bed. If the droplet diffusion radius reaches its maximum value, the retraction and vibration of the droplet can be observed and this maximum spreading radius can be kept unchanged after droplet stabilization. In the process of droplet penetration, it is necessary to reduce the impact force of the droplet on the surface of the powder bed and ensure the smoothness of the surface of the powder bed. The effect of droplet impact on the powder bed depends on the Weber number \( We \), the formula of which is as follows [3]:

\[
We = \rho U_0^2 D / \sigma
\]

(3)

For \( We \leq 13 \), the smoothness of the surface of the powder bed will not be affected by the impact of the droplet, which will be formed to spherical shape with a maximum spreading radius through retraction.
and vibration, as shown in Figure 4 (b). Then, as shown in Figure 4 (c) and (d), the droplet starts to infiltrate into a fine hole in the powder bed. After the droplet completely penetrates into the powder bed, the powder is wrapped up to form a hemispherical mixture. The volume $V$ of the mixture is the sum of the droplet volume $V_0$ plus the powder volume $V_1$ attached to the droplet. $V_1$ can be calculated as follows [4]:

$$V_1 = V_0 \left[ (1 - \varepsilon) / \varepsilon \right]$$

(4)

Where $V_0$ the volume of the droplet is infiltrated into the powder bed and $\varepsilon$ is the porosity of the powder bed, which can be expressed as,

$$\varepsilon = 1 - \left( \frac{\rho_{\text{bulk}}}{\rho} \right)$$

(5)

Where $\rho_{\text{bulk}}$ is the bulk density of powder, $\rho$ the density of powder material. $\rho_{\text{bulk}}$ can be measured by scale gauge and digital scale. The penetration diameter of the droplet, $D_p$, can be calculated as follows:

$$D_p = \sqrt[3]{6V / \pi}$$

(6)

If the droplet fully permeates the powder bed, $V_1 = V_0$, the diameter and the penetration depth of the droplet will reach their maximum value. The maximum penetration depth of the droplet is as follows:

$$h_{\text{pen max}} = \sqrt[3]{0.675} V_0^{2/3} / \varepsilon$$

(7)

3.4. Influence of process parameters on the quality of metal mold forming

Through the analysis on results of repeating tests, we find that for a good jetting effect, the nozzle’s temperature should better be maintained at 75°C to reduce the viscosity of the VeroWhitePlus material and to avoid the nozzle from being glued. At 75°C, the corresponding parameters of the binder are: viscosity $\mu=12$ mPas, surface tension $\sigma=19.6$ mN/m and density $\rho=1.1064$ g/cm$^3$.

The printing distance $L$ should be equal to $\sqrt{2} D_{\text{p max}} / 2$ to make sure that each layer print area can be sprayed with same amount of adhesive. This geometrical relationship can be illustrated in Figure 6.

![Figure 6. Print spacing L.](image-url)
The powder-thickness $H$ determines whether the two adjacent layers of the model can be reliably bonded. Therefore, $H$ must be less than the penetration depth $h_{\text{pen, max}}$ of the droplet. Figure 7 is a cross-section of the printed fault model. The white frame shows that there is no penetrant binder in each layer due to the oversize of the powder.

The print speed $S$ refers to the speed of movement of the print head in the XY plane. If the print speed is too fast, the liquid droplets will drift from the right points, as shown in Figure 8 where the uneven droplet injection, rough edge and middle part with excessive binder can be observed clearly. Experimental results from repeating tests show that the optimized printing speed is $80 \text{ mm/s}$ for our models with a nice printing effect.

3.5. Analysis of experimental results

According to the analysis results from 3.3, the process parameters of the model can be set up as follows:

1. According to (1), the diameter $D$ of the droplet is set to be $0.933 \text{ mm}$.
2. Adjust the drive voltage of the sprinkler and the velocity $U_0$ to control the driving pressure $F_q$, which is calculated to be less than $19.624 \text{ mN}$ for $\text{We} \leq 13$, with $h=2 \text{ mm}$, to make it sure that the flatness of the surface of the powder bed is not damaged.
3. The porosity ratio $\varepsilon$ is measured by scale to be $0.412$. The maximum penetration diameter and penetration depth of the droplets are calculated by (6) and (7): $D_{\text{pen, max}} = 1.054 \text{ mm}$, $h_{\text{pen, max}} = 0.548 \text{ mm}$. With the set up above, 9 test pieces are selected and printed for the comparison experiments, considering the factors that the actual droplet is not a regular ball and the volume of the droplet will be slightly different. The main process parameters of the 9 pieces are listed in Table 2, where the density ratio $K_m$ is used to evaluate the printing effect. $K_m$ can be obtained by the equation below,

$$K_m = \frac{\rho}{\rho_{316L}} \quad (8)$$

Where $\rho$, the density is measured by density meter MH-300A and $\rho_{316L}$ is the theoretical density of the 316L stainless steel.
Table 2. Density of test pieces under different process parameters.

| Number | UV lamp power (W) | Print speed S (mm/s) | Powder thickness H (mm) | Print pitch L (mm) | Density K_m (%) |
|--------|-----------------|---------------------|------------------------|-------------------|-----------------|
| 1      | 63.4            | 80                  | 0.4                    | 0.2               | 62.71%          |
| 2      | 63.4            | 80                  | 0.4                    | 0.3               | 60.42%          |
| 3      | 63.4            | 80                  | 0.4                    | 0.4               | 51.52%          |
| 4      | 63.4            | 80                  | 0.3                    | 0.4               | 63.11%          |
| 5      | 63.4            | 80                  | 0.3                    | 0.3               | 69.26%          |
| 6      | 63.4            | 80                  | 0.3                    | 0.2               | 71.13%          |
| 7      | 63.4            | 80                  | 0.2                    | 0.3               | 74.84%          |
| 8      | 63.4            | 80                  | 0.2                    | 0.4               | 63.75%          |
| 9      | 63.4            | 80                  | 0.2                    | 0.2               | 73.22%          |

As may be seen from Table 2, the smaller the powder thickness H or the print spacing L, the greater the density ratio K_m. Picture of No. 3 shows that this test piece is rough and almost broken in the middle part due to the large H and L. Compared with No.3, No. 7 is much better with smooth surface and edge, shown in Figure 10.

![Figure 9. Test piece No. 3.](image)

![Figure 10. Test piece No. 7.](image)

Figure 11 and 12 are the sections of 50 times and 1K times’ magnification of No. 7, showing that the UV resin has been fully bonded to the powder, with less independent spherical powder particles and porosity.

![Figure 11. 50 times magnification.](image)

![Figure 12. 1K times magnification.](image)

4. Conclusion
This paper presents our study on the 3D printing process of metal powder with digital micro jet. The influence of process parameters on the forming quality of metal powders is analyzed first. The optimization of parameters has been carried out through repeating tests based on the analysis results. 9 test pieces, with different process parameters, have been printed for the comparison experiments. The experimental results show that the better printing effect can be obtained by the optimized parameters.
Acknowledgments
This work is financially supported by Natural Science Foundation of Jiangsu Province (BK20151548) and Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX18_1225).

References
[1] Yang J D and Liu H R, Research Development of 3D Printing for Large Complex Metal Parts. Ordnance Industry Automation. 2017, 36 (02): 8 - 12.
[2] Wang P, Huang Z H, Qi W J, Zhou Y X, Xu C J and Liu J Y, Effect of the 3D printing process parameters based on SLM technology on the structural defect of 316 stainless steel. Welding Digest of Machinery Manufacturing. 2016, (02): 2 - 7.
[3] Zhou S G, Simulation and Experimental Study on Piezoelectric Diaphragm-driven Micro droplet Jetting Technology. M.S. thesis, Dept. Electron. Eng, Shanghai Jiao Tong Univ, 2013, Shanghai, China.
[4] Lee A C S and Sojka P E, Drop Impact and Agglomeration Under Static Powder Bed Conditions. American Institute of Chemical Engineers Journal. 2011, 58 (2): 79 - 86.
[5] Stow C D and Hadfield M G, An experimental investigation of fluid flow resulting from the impact of a water drop with an unyielding dry surface. A Mathematical Physical and Engineering Sciences. 1981, 373 (1755): 419 - 441.
[6] Zhu D B, Chu R Q, Zhang X X, Cheng E, Zhang Z Y, Qu Y X, Sun C and Duan G L, Progress in Mechanism of Ceramics Inkjet Printing. Journal of Mechanical Engineering. 2017, 53 (13): 108 - 117.