Modeling and simulation of powder spreading of Inconel 625 based on 3DP process

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Abstract. Three-Dimensional Printing (3DP) forming technology has the advantages of rapid forming speed, wide range of printing materials, unlimited printing shape and no need for supporting materials. In this paper, the Discrete Element Method (DEM) is used to simulate the powder spreading process of Inconel 625. The influence of powder particle shape, powder ratio, roller size and roller horizontal speed on powder spreading is simulated. The results show that the horizontal velocity of powder laying roller and the shape of powder particles have great influence on the accuracy of powder spreading. The influence of powder characteristics on the forming quality is studied. It is found that if the particle size of powder is smaller, the fluidity will be lower, and the forming quality will be better; if the particle size of powder is larger, the fluidity will be better, but the precision of the part will be reduced. The results provide a theoretical basis for the preparation of Inconel 625 by using 3DP process.

1. Introduction

In 3DP process, the powder particles will collide with each other because of the movement, and the force and displacement will be generated between the particles. Therefore, the powder spreading of 3DP process has complex kinematic and mechanical behaviors. These complex behaviors can be analyzed by DEM.

By using multi-material 3D printing technology, the inter-particle bond properties and agglomerate structure of agglomerates can be accurately controlled and duplicated. Ruihua Ge et al. [1] used the Discrete Element Method (DEM) to simulate the agglomerate crushing process. The results show that for both agglomerate structures, the DEM simulation and experimental results show good agreement at the initial elastic deformation stage. Ruihua Ge et al. [2] also used DEM to simulate the agglomerate breakage with different structures subject to compressive loads. Haeri et al. [3] used the DEM to simulate the spreading of rod-shaped particles in realistic AM settings, and studied the effects of particle shape and operating conditions on the bed quality, characterized by surface roughness and solid volume fraction. A. Kittu et al. [4] used AM particles as analogue soils allows for DEM validations to be performed using a wide range of shapes, more realistically replicating natural sands and gravels. A gypsum-epoxy composite material and a photopolymer material were tested to determine properties...
such as Young’s modulus, Poisson’s ratio, shape, surface roughness, and inter-particle friction angle. From the above analysis, the DEM has been widely used in the study of particle interaction.

In this paper, the powder spreading of 3DP process is simulated by using discrete element method. The laying quality of powder layer is observed by studying different parameters such as powder particle shape, powder ratio, roller size, roller horizontal speed, etc., so as to provide the basis for experimental research and ultimately realize the optimization of powder spreading parameters.

2. Experimental preparation

2.1. Experimental materials
Inconel 625 powder used in this experiment was purchased from Nantong Jinyuan Intelligent Technology Co., Ltd., with an average particle size of 0.05mm. It can be seen from SEM (Fig. 1) that the spheroidization is better. The average particle size of PVA powder as binder is 0.125mm.

![Figure 1. SEM of Inconel 625 powder.](image)

2.2. Theory of particle contact
The printing process in 3DP process involves the interaction between the roller and the powder particles and the interaction between a large number of powder particles. According to the physical characteristics of the actual powder spreading process, the soft ball model is selected as the basic model of the particle system [5] (Fig. 2).

![Figure 2. Model of two soft spheres in contact.](image)
The dotted line in Fig. 2 shows the particle $j$ before collision; the solid line is after collision, $\delta$ is the normal phase overlap, and the moving distance is tangential displacement.

There are two main methods to solve the particle discrete element method based on the soft sphere model. One is the motion equation, which is used to calculate the contact force between particles; the other is the contact force equation, which is used to solve the velocity and acceleration of particles.

In the soft sphere model, the collision process between particles is simplified as the damped vibration of a spring oscillator. The equation of motion is as follows:

$$m\ddot{x} + c\dot{x} + kx = 0$$  \hspace{1cm} (1)

Where $x$ is the displacement away from the equilibrium position; $m$ is the mass of the spring oscillator; $c$ and $k$ are the spring damping coefficient and elastic coefficient, respectively.

For the spherical particle model, according to Hertz contact theory, the normal contact force $F_{nij}$ is expressed as

$$F_{nij} = (-k_n a^2 - c_n v_{ij} \cdot n)n$$  \hspace{1cm} (2)

Where $k_n$ is the normal elastic coefficient of particles; $a$ is the normal overlap; $c_n$ is the normal damping coefficient; $v_{ij}$ is the velocity of particle $i$ relative to particle $j$, $v_{ij} = v_i - v_j$; and $n$ is the unit vector from the center of particle $i$ to the center of particle $j$.

The tangential contact force $F_{tij}$ is expressed as

$$F_{tij} = -k_t \sigma - c_t v_{ct}$$  \hspace{1cm} (3)

Where $k_t$ is the tangential elastic coefficient of the particle; $c_t$ is the tangential damping coefficient; $\sigma$ is the tangential displacement of the particle indirect contact; $v_{ct}$ is the slip velocity of the contact point.

In the process of particle collision, the size of $k_n$ and $k_t$ is related to the amount of normal overlap, so it needs to be calculated in real time according to the actual situation. In order to simplify the calculation, in the soft sphere model, we assume that the elastic and damping coefficients are constant throughout the collision process, and the deformation is ignored.

2.3. Model establishment and simulation parameter setting

2.3.1. Modeling. In order to ensure the accuracy of the experiment, the spherical particle model is adjusted to 0.1 mm. As shown in Fig. 3, the volume of ellipsoidal and rod-shaped models is equal to the spherical volume. The simplified model as shown in Fig. 4 is established to simulate the process that the powder spreading roller and the powder leakage device work at the same time.
2.3.2. Simulation parameter setting. Fill in the properties of Inconel 625, PVA and steel materials according to the material property table (Tab. 1) and the mechanical parameters table (Tab. 2) between the materials. The contact relationship between particles is set as Hertz-Mindlin (no slip) with RVD Rolling Friction, which is suitable for the case of rolling friction between particles in the model. The contact relationship between particles and geometry is Hertz-Mindlin (no slip).

3. Simulation results and analysis

3.1. Influence of particle shape on powder spreading

Under the conditions of the roller radius of 7.5mm, horizontal moving speed of 0.05m/s, rotation speed of 20rad / s, counter clockwise rotation, powder laying thickness of 0.5mm, number of mixed powder particles of 3000(90% of Inconel 625 and 10% of PVA) and simulation time of 1s, the powder spreading effect of spherical, ellipsoidal and rod-shaped (equal volume) particles are simulated respectively. The simulation results are shown in Fig. 5.
Figure 5. Simulation results of different particle shapes.

It can be seen from the simulation results in Fig. 5 that the powder with spherical shape has good densification in the process of powder spreading; there will be voids in the process of powder spreading for ellipsoidal powder particles; and obvious voids and large voids will be generated for rod-shaped powder particles in the process of powder spreading.

In the process of powder spreading of ellipsoidal and rod-shaped powder particles, the gap mostly occurs in the middle of the forming platform, that is, the forming place of general parts. Therefore, using these two kinds of particle shape to lay powder has a great influence on the forming accuracy of parts. Therefore, spherical particles were selected as the powder particle model in the follow-up experiments.

3.2. Influence of powder ratio on powder spreading

In order to enhance the bonding effect of metal powder, PVA powder was added to Inconel 625 as binder. The process of adding PVA powder, PVA powder 5% (mass ratio) and PVA powder 10% (mass ratio) to the increment of PVA powder was simulated respectively. The other experimental factors remained unchanged. The simulation results are shown in Figure 6.

Figure 6. Simulation results of different PVA powder contents.

It can be seen from the simulation results in Fig. 6 that the more PVA powder content, the better the bonding effect and the lower the porosity of the powder layer. But in the process of debinding sintering, PVA powder will be burned, which will produce a large gap, which will have a greater impact on the overall performance of the green part, so PVA powder should be added appropriately. According to the simulation results, the mixed powder containing 5% PVA was selected for printing.

3.3. Influence of the size of powder roller on powder spreading

Three kinds of powder spreading processes with 5 mm, 7.5 mm and 10 mm roller radius were simulated respectively, and the other experimental factors remained unchanged. The simulation results are shown in Fig. 7.
It can be seen from the simulation results in Fig. 7 that the powder roller radius has little effect on the powder spreading, but considering the processing cost of parts, powder spreading efficiency, equipment volume and other factors, the powder roller radius should not be too large or too small. The powder roller with radius of 7.5mm is used for actual printing.

3.4. Influence of the size of powder roller on powder spreading
Three kinds of powder spreading processes with horizontal moving speed of 0.05m/s, 0.15m/s and 0.25m/s are simulated respectively, and other experimental factors remain unchanged. The simulation results are shown in Fig. 8.

From the simulation results in Fig. 8, it can be clearly observed that when the horizontal moving speed of the roller is 0.05m/s, the powder layer is dense; when the horizontal moving speed of the roller is 0.15m/s, the density of the powder layer decreases and there is a gap; when the horizontal speed of the roller increases to 0.25m/s, the gap of the powder layer increases.

When the roller radius, rotation speed, rotation direction, particle number and simulation time of the roller are fixed, the higher the horizontal speed of the roller is, the greater the porosity of single powder laying is, and the pores mainly appear in the middle part of the forming platform, that is, the general green parts forming place. In the later spray bonding, the gap caused by too fast horizontal speed will reduce the bonding degree between powder layers, and the performance of parts will be greatly reduced. If the horizontal speed is too small, the preparation efficiency will be affected. Therefore, the appropriate horizontal speed of the powder spreading roller should be given priority in the actual powder spreading process. According to the simulation results, 0.15m/s is selected as the horizontal moving speed of the roller in the subsequent printing experiment.

4. Conclusions
The 3DP powder spreading process of Inconel 625 powder was simulated by DEM. Under the condition of controlling the corresponding parameters, different parameters such as powder particle shape, powder ratio, roller size and roller horizontal speed are simulated respectively. The conclusions are as follows:
(1) The particle shape of Inconel 625 powder has a great influence on the quality of powder spreading. The more irregular the shape of the powder particles is, the greater the possibility of producing large voids in the powder spreading process, and the powder spreading quality of spherical particles is the best.

(2) The horizontal moving speed of the roller has a great influence on the quality of powder spreading. The faster the horizontal speed is, the larger the gap will be.

(3) Although the content of PVA has no effect on the quality of powder spreading, it will affect the quality of Inconel 625 parts after degreasing and sintering.

(4) The size of powder roller has little effect on the quality of powder spreading.

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References
[1] Ruihuan Ge, Mojtaba Ghadiri, Tina Bonakdar, et al. Deformation of 3D printed agglomerates: Multiscale experimental tests and DEM simulation. Chemical Engineering Science, 2020, 217.
[2] Ruihuan Ge, Lige Wang, Zongyan Zhou. DEM analysis of compression breakage of 3D printed agglomerates with different structures. Powder Technology, 2019, pp.1045-1058.
[3] Haeri S, Wang Y, Ghita O, et al. Discrete element simulation and experimental study of powder spreading process in additive manufacturing. Powder Technology, 2017, pp.45-54.
[4] A. Kittu, M. Watters, I. Cavarretta, et al. Characterization of additive manufactured particles for DEM validation studies. Granular Matter, 2019, pp.1-15.
[5] Wang Yuanyuan, Zhang Sixiang, Yang Weidong. Modelling and simulation study of powder spreading in 3DP process. Journal of Hebei University of Technology, 2018, pp.37-43.