Influence of resin flow on shrinkage of additive manufacturing coated sand molds

Shu-ming Zhao, * Shan Yao, and Tong Yang

School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China

Abstract: Coated sands are used extensively for additive manufacturing sand molds in the metal casting process, and the packing structure changes caused by the resin flow promote the shrinkage and deformation of the part. During the coated sand heating, the resin on the surface flowing to the contact points of the particles forms the resin neck and causes particles to pack close to each other. In this work, the diameters of the coated ceramsite sand before and after heating were measured based on in-situ experimental observations with image measuring apparatus and blue laser, to obtain the relationship between resin coating thickness and the particle diameter. The particle packing model was established to describe the particles' achievement of a stable state one by one. A re-packing simulation was then performed after reducing the particle diameter according to the resin coating thickness, to obtain the shrinkage ratios at different particle size distributions. It was found that the resin coating thickness increased from 0.8 to 2.3 μm as the particle diameter increased from 107 to 500 μm , for the coated ceramsite sand with the resin content of 2wt.%; the shrinkage ratio decreased first and then increased as the particle diameter increased. The experimental minimum shrinkage ratio was 3.28%, and the corresponding particle diameter was 300–375 μm , while the minimum shrinkage ratio obtained by simulation was 3.43%, and the corresponding particle diameter was 214–300 μm . After mixing the five groups proportionally, the shrinkage ratios of the simulation and experiment dropped to 2.81% and 3.04%, respectively, indicating the best results.

Key words: coated ceramsite sand; resin coating thickness; particle packing; shrinkage ratio; additive manufacturing

CLC numbers: TG221

Document code: A

Article ID: 1672-6421(2018)04-291-08

Sand casting is widely employed for manufacturing metal parts with complex structures, and its key lies in the precise production of a high-performance sand mould or core. Additive manufacturing (AM) technologies can be used to create a complex sand mold or core from the CAD data directly without any mold or tooling. Therefore, it shortens the lead time and saves production costs^[1,2]. It's very suitable for single or small batches of the casting metal parts with complex shapes and internal structures.

Currently, two kinds of AM technologies use lasers as heat sources, i.e. selective laser sintering (SLS) and profile invalidation rapid prototyping (PIRP). These

have been used to produce casting sand molds using sand coated with a layer of thin phenolic resin. The SLS process uses a high energy density laser beam to soften the resin and then the sand is bonded together. Meanwhile, the SLS requires laser scanning of the entire area of the slice^[3,4]. The PIRP process uses a higher energy density laser to scan the profile of the parts so that the resin film at the profile is overheated and carbonized. Thereby, it loses the binding effect and forms the separation surface of the parts, which makes the manufacturing process faster^[5,6]. Many researchers focused on the material preparation and process optimization to improve mechanical properties, dimensional accuracy and surface finish of the sand molds, and investigating the impact of the casting process on development time and cost^[7–11].

The two aforementioned AM techniques for sand molds both require a post-curing process after the sand molds are manufactured. That is, the sand mould is placed in a heating oven and maintained at a certain temperature for a period of time to achieve the ultimate

*Shan Yao

Male, born in 1966, Professor. His research and teaching interests mainly focus on the fields of mathematical modeling and numerical simulation of material processing, laser rapid prototyping method based on powder, and quick casting process.

E-mail: yaoshan@dlut.edu.cn

Received: 2017-08-25; Accepted: 2018-03-19

strength^[8]. Especially for the larger sand mold, the interior is usually hollowed out to reduce the laser scanning area and shorten the manufacturing time, which makes the sand molds filled with loose coated sand. During the post-curing process, the resin coated on the particle surface moves to the contact points of the adjacent particles, forming the resin neck. Meanwhile, the disappearance of the resin film on the surface of the particles causes a decrease in the distance between the particles, which causes macroscopic shrinkage and deformation of the parts. It is necessary to improve the accuracy of sand molds by studying the influence of the resin flow on the particle packing structure.

Particle packing with different size distributions plays an important role in many branches of physics and engineering^[12,13]. Experimental investigations and computer simulations were carried out to study the particle packing in the AM techniques. For example, Zhang et al.^[14–17] employed the sequential addition packing algorithm to investigate the random packing of spherical particles in the SLS process and obtained the optimum packing density and coordination number by choosing different particle size distributions. Parteli and Cheng et al.^[18–20] studied the forces among the particles by the distinct element method (DEM), including gravity, contact force, friction force, and van der Waals interaction (VDWI). Hitti et al.^[21] proposed a new dropping and rolling packing algorithm by means of analytical equations, to investigate the random packing of spherical particles. Bertei and Topic et al.^[22–24] used different sizes of spheres to form complex shapes of particles, and then performed the complex-shaped particle packing simulation.

The objective of this work is to study the shrinkage mechanism in the post-curing process of coated sand molds produced by laser additive manufacturing. Firstly, the resin coating thickness of particles in different sizes was obtained by measuring the change in diameter of the coated ceramsite sand before and after heating. Then, the shrinkage ratio of the particles at different size distributions was calculated by measuring the volume of the coated ceramsite sand parts after heating in a standard mold. A particle packing and re-packing model was established, and experimentally measured resin coating thickness was introduced into the model. Thus, the shrinkage ratio of five groups of particles in the diameter range was calculated. A lower shrinkage ratio can be obtained by optimizing the particle size distribution, so that the accuracy of the additive-manufactured parts can be improved.

1 Experimental procedures

1.1 Measurement of resin coating thickness

As a kind of artificial sand, ceramsite sand has a higher refractory capability than quartz sand. It is possible to lower the resin content to achieve the same strength of coated quartz sand due to its high degree of sphericity, which can reduce the gas production and improve the mold permeability to achieve more environmentally friendly casting applications. In order to approximate the spherical particles in the packing model, the

spherical coated ceramsite sand with the size of 100 to 500 μm (resin content of 2wt.%, provided by Dalian Sanben Casting Materials Co., Ltd.) was used to measure the resin coating thickness. The experiment apparatus is illustrated in Fig. 1(a). The diameter measurement of the coated ceramsite sand was carried out with an image measuring apparatus (Byes3020, China), and the maximum magnification was 500 times. A blue laser at a wavelength of 450 nm was aimed at the viewing area of the objective lens to perform in-situ heating of the coated ceramsite sand placed on the glass slide. The blue laser was filtered out by adding a filter with a wavelength of 500–1,100 nm in front of the objective lens, therefore, the background of the photograph is yellow, to protect the electronic components of the image measuring apparatus and to avoid the effects of intense laser light while observing.

Before the diameter measurement, a small amount of coated ceramsite sand was spread on a glass slide using a spoon, to avoid particles overlapping each other (Fig. 1b). Firstly, the observation stage was moved to a suitable measurement area, then the magnification and focal length of the lens were adjusted. Secondly, the contour of the particles was extracted and fitted into a circle by the software of image measuring apparatus, and the diameter of the coated ceramsite sand before heating was recorded (Fig. 1c). Thirdly, the blue laser was turned on for a short time to melt the resin on the particles' surface in situ. Then the diameter of each of the corresponding particles was recorded again (Fig. 1d). The resin coating thickness was obtained by calculating the variation of the diameter before and after laser heating.

Fig. 1: Schematic of image measuring apparatus (a), coated ceramsite sand on measurement area (b), and observation of coated ceramsite sand before (c) and after (d) laser heating

1.2 Shrinkage measurement of coated ceramsite sand

A mold used for heating the coated ceramsite sand was designed to measure the shrinkage ratio with different particle size distributions. As shown in Fig. 2(a), the mold was 100 mm in diameter and 150 mm in height. The sidewall was designed with

2° of the draft angle to facilitate removal of hardened coated sand parts from the mold. The coated ceramsite sand was poured into the mold and vibrated several times to make the particles dense, and then the top surface of the mold was scratched flat (Fig. 2b). The mold was placed in a heating furnace at a temperature of 180 °C for 150 minutes and then taken out to cool down to room temperature. It was found that the coated sand sank a certain distance (Fig. 2c), which means that shrinkage occurred during the heating. The hardened sand part was then removed from the mold and scanned by a 3D scanner (Handyscan700, Canada) to obtain the volume after heating (Fig. 2d). The actual shrinkage ratio during the heating was obtained by comparing the volume of the scanned hardened sand part with that of the mold cavity.

Fig.2: Shrinkage ratio measurement of coated ceramsite sand: (a) mold used for heating coated ceramsite sand (unit: mm); (b) mold filled with ceramsite sand scraped flat on top; (c) coated ceramsite sand after heating; (d) scanning hardened sand part

2 Particles packing model

2.1 Particles packing and re-packing model

During the process of the coated ceramsite sand heating, the resin coating on the surface of the particles melted and flowed into the contact points to form a resin neck. The diameter of the particles became smaller, resulting in macroscopic shrinkage. The process can be simplified into several steps for simulation: 1) particles with a specified size distribution fall into a box one by one until the box is full filled, and the informations (coordinate and diameter) of each particle are acquired; 2) the diameter

of each particle is reduced due to the change of resin coating thickness, and the coordinate remains the same; 3) the particles are re-packed from the bottom of the box under gravity, forming a new packing structure. The space occupied by total particles which originally equaled the volume of the box becomes smaller.

Zhang et al. [14] presented the sequential addition packing simulation model, which starts with the random selection of a sphere according to a pre-defined particle size distribution, and then dropped the sphere into a dimension-specified box ($X_{\max}$, $Y_{\max}$, $Z_{\max}$), and obtained its final stable position using dropping and rolling rules which are derived from a similar physical process of spheres dropping in the gravitational field to minimize its gravity potential. The above dropping and rolling rules were employed in this work, and a new boundary setting rule was proposed to replace the periodic boundaries (any sphere that leaves the box through one of its four surrounding vertical walls or corners will immediately reenter the opposite wall or corner). As shown in Fig. 3, four equal-dimension balls whose diameters were much larger than the box's dimension (such as 10,000 times) were arranged in pairs, and their ball-centers were put on the floor. The distances between ball 1 and ball 3, ball 2 and ball 4 were $X_{\max}$ and $Y_{\max}$ respectively, forming the space of the box between the four large balls. Meanwhile the walls of the box can be considered as the vertical. While the spheres contact with the four walls of the box, it can be considered that they roll down along the four balls according to the rolling rule.

The program flow chart is shown in Fig. 4. Firstly, the total number of fallen particles was defined (to ensure that the

Fig. 3: Boundary setting rule for packing model

particles were sufficient to totally fill the box). Then the particle was dropped down to a final stable position one by one. After the first packing process, all the particles above the box were removed. Secondly, the shrinkage phenomenon due to heating was achieved by the re-packing process of the existing particles. The diameter of the existing particles in the box was reduced according to the resin coating thickness, and all the particles were sorted according to the Z-axis coordinates from small to large. Thirdly, the particles were dropped down again from the existing position one by one, forming a new packing structure. The shrinkage ratio caused by the re-packing process was

Fig. 4: Flowchart of Particles packing and re-packing model

determined by the change in the total volume of the arrangement (solids and voids), and it was defined as 1 minus the re-packing volume divided by the first packing volume, which was equal to the volume of the box. The re-packing volume was calculated by integrating the space occupied by the particles in the box. The XY plane of the box was divided into the grid according to the maximum diameter of the particle, and the height of each grid was determined by the highest particle in the grid, and then the sum of all the grid volumes was the re-packing volume. Obviously, a lower shrinkage ratio was desirable to the packing structure.

2.2 Simulation sets

In this work, the coated ceramsite sand was sieved to determine its particle size distribution in the course of the experiment, and the shrinkage ratio measurement of each group was performed separately. In order to match the simulation result with the experiment data, each particle size distribution was simulated

by the packing model, as shown in Table 1. The particles were divided into 5 groups according to the sieve mesh size, and the corresponding particle diameter was from 107 μm to 500 μm . According to the experience, we know that the proportion of each group in the coating sands was different, but in the simulation process, it can be confirmed that the particles were randomly but evenly distributed in each particle group.

Table 1: Experimental sieving particle size and parameters used in simulations

	Sieve mesh size				
	30/40	40/50	50/70	70/100	100/140
Particle diameter (μm)	375–500	300–375	214–300	150–214	107–150

3 Results and discussion

3.1 Effect of particle size on resin coating thickness

Figure 5 shows the different appearances of the coated ceramsite sand during the diameter measurement. While the upper-light and back-light were turned on, the topography of particles can be observed in detail, and it can be observed that the surface of the particles gradually becomes smooth during laser heating (Fig. 5a and 5b). With only the back-light turned on, the profile of the particles can be seen clearly and extracted to fit into a circle, thereby accurately calculating the diameter of the particles (Fig. 5c and 5d). Before laser heating, the surface of the coated ceramsite sand was relatively rough (Fig. 5a) and the adjacent particles are in point contact. While the laser was turned on to heat the particles, it was observed that the surface of the particles quickly became smooth and the heated particles moved almost simultaneously (Fig. 5b). After heating, a certain length of resin neck was formed between the particles still in contact. It was found that they were tangent to each other by measuring the distance between the centers of the two particles. All the heated particles were reduced in diameter. It can be explained that the resin rapidly flowed to the contact points under the surface tension during the heating process, such as two particles or the particle and the slide glass, which resulted in a minimum resin surface area. Meanwhile, the particles were pulled together under the action of surface tension. Therefore, the assumptions in the packing model were valid: that the diameter of the particles was reduced due to the fact that the resin flows to the point of contact and the particles were re-packed closely. The resin was not burned nor dissipated, it merely flowed to the contact points of the particles, i.e., the gaps of the particles, and this was no contribution to the macroscopic volume. Therefore, in the calculation of the shrinkage ratio, the impact of the resin can be consequently neglected.

Figure 6 shows the relationship between the particle diameter and the resin coating thickness. As can be seen from the figure, the resin coating thickness becomes larger as the particle

Fig. 5 : Appearance of coated ceramsite sand: before (a) and after (b) laser heating with upper-light and back-light on; diameter measurement before (c) and after (d) laser heating with upper-light off and back-light on

diameter increased. The measured particle diameter was from 107 to 500 μm , and the corresponding resin coating thickness was from 0.8 to 2.3 μm . Analysis shows that the smaller the diameter of the particles, the greater the curvature of the particles, and the higher energy required for the resin to adhere to the surface of the particles. Therefore, the larger particles are more likely to adhere to the thicker resin film, when the particles of different particle sizes are coated with the resin together. The data are linearly fitted and obtained the following formula:

$$t = 0.0036D + 0.424 \quad (1)$$

where t is the thickness of the resin film (μm), D is the diameter

of the particle before heating (μm). This formula was used in the following packing model to determine the amount of reduction in particle diameter in the re-packing simulation.

3.2 Effect of particle size distribution on shrinkage ratio

Packing simulation of monosized particles was performed to validate the present model. It can also be used to determine the dimensions of the packing box needed at the current particle size. Figure 7 shows the relationship between shrinkage ratio and the box dimensions. In this simulation, the box dimensions in the X and Y directions are the same and the particle diameter is set as 500 μm , which is the largest size in particle size distribution. As can be seen from Fig. 7a, the shrinkage ratio decreases with increasing box height, i.e., the dimension in the Z direction (Z_{max}). However, it is noticed that as the box height increases to about 12,500 μm , the shrinkage ratio tends to be stable. It is observed from Fig. 7(b) that the shrinkage ratio almost keeps constant as the box dimension in the X or Y direction increases (the box dimension in the Z direction remains at the value of 12,500 μm). Therefore, the dimensions of 5,000 $\times$ 5,000 $\times$ 12,500 μm^3 will be employed for the rest of the simulation cases of the random particle packing.

The simulation shows that the stable shrinkage ratio is about 4.11% for the monosized packing of 500 μm . Figure 8 shows the 3D packing structure and the 2D cross sectional view at the midplane $y=0.5Y_{\text{max}}$ for the first-packing and re-packing. Circles

Fig. 6: Relationship between particle diameter and resin coating thickness

Fig. 7: Shrinkage ratio for monosized packing: (a) box dimension in Z direction, (b) box dimension in X direction

with different radii were observed on the 2D cross sectional view in Fig. 8(c) and Fig. 8(d), because the random packing particles cut by the vertical plane were at different distances from the plane. It can be seen from Fig. 8 that the particles after the re-packing formed a certain gap at the top of the box, which was due to the downward drop of the particles under the gravity after the particle diameter was reduced.

The shrinking phenomenon in additive manufacturing for sand molds is a serious obstacle that results in low part-quality. One way to overcome the shrinking phenomenon is to use a powder bed with a certain particle size distribution. Therefore, in this work, five groups were simulated according to the particle diameter range of Table 1, and the program was set to be uniformly distributed in each group. The calculated data for the shrinkage ratio is shown in Table 2. Meanwhile, the number of particles filled in the box and the first-packing density is given. In addition, in order to compare with the effect of monosized particle packing, the average particle diameter of each group was used as a simulation object. The shrinkage ratio of monosized particle packing was obtained and shown in Table 2 together. It can be seen that the packing of randomly distributed particles in each group was denser than that of the corresponding monosized particles, i.e. it has a smaller shrinkage ratio. The shrinkage ratio of these five groups of coated ceramsite sand, which were measured experimentally, is also shown in Table 2. Figure 9 shows the shrinkage ratio obtained by simulation and the experimental results. Both

Fig. 8: Packing structure for monosized packing of 500 μm: 3D view for first-packing (a) and for re-packing (b); 2D cross sectional view for first-packing (c) and for re-packing (d)

experimental and simulation data showed that the shrinkage ratio decreased first and then increased as the particle diameter increased. The experimental minimum shrinkage ratio was 3.28%, and the corresponding particle diameter was 300–375 μm, while the minimum shrinkage ratio obtained by simulation was 3.43%, and the corresponding particle diameter was 214–300 μm. Meanwhile, the experimental data of the small particles was greater than the simulation results, which is probably that the agglomeration of small sand particles resulted in more resin content, which led to a greater shrinkage ratio. This indicates that the particle size distribution was effective for shrinkage ratio, but requires a reasonable choice of distribution to obtain the desired results. Therefore, the five groups of particles were mixed proportionally, and the shrinkage ratio was measured experimentally and by simulation.

In the packing simulation, particles were dropped down one by one, and the above five groups of particles need to be mixed in proportion. Therefore, the proportions of the particles were calculated according to the number of particles. However, the grade of coated sand used was based on the mass ratio of the powders. Thus, a conversion between them was necessary, according to the particles number and first-packing density of each group in Table 2. As shown in Fig. 10, the mass-based particle size distribution of the coated ceramsite sand used herein was converted into the number-based particle size distribution used for the packing simulation. Figure 11 shows the packing structure simulated according to the actual particle

Table 2: Shrinkage ratios of different particle size distributions

Serial number	Simulation results							Experimental results
	Particles randomly distributed				Monosized particle			Shrinkage ratio
	Diameter range (μm)	Shrinkage ratio	Particles number	First-packing density	Average diameter (μm)	Shrinkage ratio	Particles number	
1	107–150	4.29%	152,400	0.5441	128.5	4.57%	155,664	5.41%
2	150–214	3.53%	54,254	0.5417	182	3.54%	55,627	4.63%
3	214–300	3.43%	19,019	0.525	257	3.50%	19,458	3.80%
4	300–375	3.48%	8,358	0.5051	337.5	3.61%	8,454	3.28%
5	375–500	3.87%	3,768	0.4856	437.5	4.36%	3,797	3.41%

size distribution. It can be seen from Fig. 11 that the distribution of large and small particles has a good randomness, and no ordered regions were found throughout the packing structure. Table 3 indicates that the simulated and experimental shrinkage ratios reached 2.81% and 3.04%, respectively. This is lower than that of any group in Table 2, while the first-packing density was also greater.

Fig. 9: Simulated and experimental results of shrinkage ratio at different particle size distributions

Fig. 10: Particle size distribution respectively based on powder mass and particle number

Fig. 11: Packing structure for actual particle size distribution: 3D view for first-packing (a) and for re-packing (b); 2D cross sectional view for first-packing (c) and for re-packing (d)

Table 3: Simulation and experimental results for actual particle size distribution

Simulation results			Experimental results
Shrinkage ratio	Particles number	First-packing density	Shrinkage ratio
2.81%	40196	0.5599	3.04%

4 Conclusions

The influences of resin flow on shrinkage of additive manufacturing coated sand core were studied by a combination of experiments and packing simulations. The relationship between resin coating thickness and particle diameter was investigated by using the image measuring apparatus and blue laser to measure the coated ceramsite sand at different sizes. A particle first-packing and re-packing model was established to describe the relationship between shrinkage ratio and particle size distribution, and the simulation results were verified by shrinkage measurement experiment. Accordingly, the following conclusions can be drawn:

(1) For the coated ceramsite sand with the resin content of 2wt.%, the resin coating thickness increased from 0.8 to 2.3 μm as the particle diameter increased from 107 to 500 μm .

(2) The packing simulation showed that the shrinkage ratio was about 4.11% for the monosized packing of 500 μm . The shrinkage ratio of randomly distributed particles in each group was lower than that of the corresponding average monosized particles. The minimum shrinkage ratios obtained by simulation and experiment among the five groups were 3.43% and 3.28%, corresponding to the particle size distribution of 214–300 μm and 300–375 μm .

(3) Through the packing simulation based on the actual particle size distribution of the coated ceramsite sand, the shrinkage ratio was 2.81%. The corresponding experimentally measured shrinkage ratio was 3.04%. These were both lower than any of the five groups of particles, which means that a higher packing density was obtained.

References

- [1] Gustafson R, Spada A T. Prototyping process produces sand molds, cores for production castings. *Journal of Applied Probability*, 2002, 92(2): 38–39.
- [2] Chhabra M, Singh R. Rapid casting solutions: a review. *Rapid Prototyping Journal*, 2011, 17(5): 328–350.
- [3] Pham D T, Dimov S, Lacan F. Selective Laser Sintering: Applications and Technological capabilities. *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture*, 1999, 213(5): 435–449.
- [4] Fan Zitian, Huang Naiyu, Chen Zongmeng. Quick Casting by Selective Laser Sintering (SLS). *Special Casting & Nonferrous Alloys*, 1999, 5: 7–9. (In Chinese)
- [5] Yao Shan, Ye Changke, Ye Jianan, et al. Research on pattern-less quick casting based on laser rapid prototyping for coated sand. *Foundry Technology*, 2006, 27(5): 458–460. (In Chinese)
- [6] Yang Tong, Yao Shan, Zeng Feng. Profile invalidation approaching rapid prototyping. *Rapid Prototyping Journal*, 2010, 16(2): 146–155.
- [7] Wang Pengcheng, Xiao Junjie, Li Jinfu. Manufacture of patternless sand mould based on selective laser sintering resin coated sand. *Foundry*, 2008, 57(2): 117–121. (In Chinese)
- [8] Wen Shifeng, Shen Qiwen, Wei Qingsong, et al. Material optimization and post-processing of sand molds manufactured by the selective laser sintering of binder-coated Al_2O_3 sands. *Journal of Materials Processing Technology*, 2015, 225: 93–102.
- [9] Casalino G, Filippis L A C D, Ludovico A. A technical note on the mechanical and physical characterization of selective laser sintered sand for rapid casting. *Journal of Materials Processing Technology*, 2005, 166(1): 1–8.
- [10] Luo Ning, Lu Zhigang, Cui Xulong, et al. Rapid Prototyping and Rapid Casting Process. *Foundry Technology*, 2003, 24(2): 118–119. (In Chinese)
- [11] Xu Zhifeng, Liang Pei, Yang Wei, et al. Effects of laser energy density on forming accuracy and tensile strength of selective laser sintering resin coated sands. *China Foundry*, 2014, 11(3): 151–156.
- [12] Visscher W M, Bolsterli M. Random Packing of Equal and Unequal Spheres in Two and Three Dimensions. *Nature*, 1973, 239(5374): 504–507.
- [13] Jodrey W S, Tory E M. Simulation of random packing of spheres. *Simulation Transactions of the Society for Modeling & Simulation International*, 1979, 32(1): 1–12.
- [14] Zhou Jianhua, Zhang Yuwen, Chen J K. Numerical Simulation of Random Packing of Spherical Particles for Powder-Based Additive Manufacturing. *Journal of Manufacturing Science & Engineering*, 2009, 131(3): 031004.
- [15] Shi Yu, Zhang Yuwen. Simulation of random packing of spherical particles with different size distributions. *Applied Physics A*, 2008, 92(3): 621–626.
- [16] Dou Xin, Mao Yijin, Zhang Yuwen. Effects of Contact Force Model and Size Distribution on Microsized Granular Packing. *Journal of Manufacturing Science & Engineering*, 2014, 136(2): 021003.
- [17] Zhou Jianhua, Zhang Yuwen, Chen J K. Numerical Simulation of Random Packing of Spherical Particles for Selective Laser Sintering Applications. *ASME 2008 International Mechanical Engineering Congress and Exposition*, 2008: 327–336.
- [18] Parteli E J R. DEM simulation of particles of complex shapes using the multisphere method: Application for additive manufacturing. *AIP Conference Proceedings*, 2013, 1542(1): 185–188.
- [19] Cheng Y F, Guo S J, Lai H Y. Dynamic simulation of random packing of spherical particles. *Powder Technology*, 2000, 107(1–2): 123–130.
- [20] Jia T, Zhang Y, Chen J K, et al. Dynamic simulation of granular packing of fine cohesive particles with different size distributions. *Powder Technology*, 2012, 218(1): 76–85.
- [21] Hitti K, Bernacki M. Optimized Dropping and Rolling (ODR) method for packing of poly-disperse spheres. *Applied Mathematical Modelling*, 2013, 37(8): 5715–5722.
- [22] Bertei A, Chueh C C, Pharoah J G, et al. Modified collective rearrangement sphere-assembly algorithm for random packings of nonspherical particles: Towards engineering applications. *Powder Technology*, 2014, 253(253): 311–324.
- [23] Parteli E J R, Pöschel T. Particle-based simulation of powder application in additive manufacturing. *Powder Technology*, 2016, 288: 96–102.
- [24] Topic N, Pöschel T. Steepest descent ballistic deposition of complex shaped particles. *Journal of Computational Physics*, 2016, 308: 421–437.