The design and fabrication of porous sintered grinding wheel based on Selective Laser Melting technology

Shubo Zhang¹,², Xuekun Li¹,²,³,⁵, Chenchen Tian¹,², Guoqiang Guo⁴, Liping Wang¹,² and Xinjun Liu¹

¹ Department of Mechanical Engineering, Tsinghua University, Beijing, 100084, China
² Beijing Key Lab of Precision/Ultra-precision Manufacturing Equipment and Control, Tsinghua University, Beijing, 100084, China
³ State Key Lab of Tribology, Tsinghua University, Beijing, 100084, China
⁴ Shanghai Spaceflight Precision Machinery Institute, Shanghai, 201600, China
⁵ E-mail:xli@tsinghua.edu.cn

Abstract. Grinding wheels is one of the most important tools in precision machining, which is usually used to realize high surface quality. The common fabrication method of sintered grinding is hot-pressed process, which has technical difficulty to form high proportional and open pores of wheel. To improve the porosity and interconnected pores of sintered grinding wheel, this paper proposes a new method to design and fabricate porous wheel, which is based on Selective Laser Melting (SLM). This method can proactively control the quantity and status of pores in grinding wheel according to different working conditions. In this paper, two types of porous grinding wheel structures are designed and fabricated by SLM technology, and their mechanical properties are tested through compression experiment and simulated by finite element method. The result indicates this method has potential to fabricate high porosity grinding wheel with enough strength.

1. Introduction
Grinding wheels have been widely used in grinding of various materials, which have unique advantage to acquire high quality surface and machine hard-to-cut material compared with others machining process. But with the development of era, traditional wheel fabricating process cannot meet the improving requirements. Therefore, searching for new design concept and fabrication method of sintered grinding wheels becomes more and more important.

The performance of grinding wheel is mainly dominated by abrasive, bond and porosity. The community never stops researching abrasives and bond material property in order to enhance the sharpness and lifetime of grinding wheel since 19th century [1]. But until 1990s, scholars came to realize the important functions of pores during grinding process, such as providing access to coolants and holding chips removed from workpiece. The functions of wheel porosity in the process of grinding were investigated in [2-3]. It is noteworthy that those useful pores refer to open pores in working layer rather than closed pores. Several methods to increase porosity were proposed based on traditional process. And these methods can be classified into three categories: burn-out, close cell and agglomeration methods. The first methods generate pores by adding easy burn-out ingredients (such as polymer resin [4], sugar [5], etc.). The close cell methods fabricate porous wheel by using alumina
bubble particles as pore-forming agents [6-7]. And the agglomeration methods produce high porous grinding wheel by using pre-formed clusters of grains [8-9]. Unfortunately, neither of them can realize the proactive design of wheel structure.

The commonly method to fabricate sintered grinding wheels is hot-pressed forming process in the past years. In the process of hot-pressed, uniformly mixed abrasives and bond are subjected to the specific pressure and temperature (simultaneously or not) for a period of time (figure 1). After the grinding wheel got cooled down, pore was passively and stochastically introduced in the space where abrasives or bond cannot fill. Even through using some tricks can increase grinding wheel porosity in this fabricating process, those methods had not changed the forming essence of grinding wheel, which is natural packing. So the porosity pores distribution and interconnections of traditional grinding wheels are unable to be controlled directly, only adjusted through a group of indirectly related parameters by skilled technicians. Therefore, it is difficult for traditional process to produce controllable porous grinding wheel. However, a kind of developing fabrication method named Additive Manufacturing (AM) technology, such as Selective Laser Melting (SLM) or Selective Laser Sintering (SLS), emerged since 1980s, which shed a light upon grinding wheel fabrication.

![Figure 1. Wheel structure passively formed in hot-pressed forming process.](image)

The SLM is a rapid manufacturing process that has advantage of fabricating complex 3D parts based on powder bed fusion technology. The SLM process works by dividing a CAD model into layers and bonding the rolled-out powder using laser beam layer by layer to form 3d object. With the further development of additive manufacturing technology, many types of powder are available in the SLM process, such as alloys of steel, aluminium, titanium and so on. Numerous studies have acquired many types of porous structure using metal powder based on the SLM technology [10-11], and provided methodology to tune process parameters and investigate mechanical property [12]. Also, many scientific and technical workers devote to research composite materials made by AM technology [13-14]. Thus it is possible to apply the SLM process on the mixture of metal powder and abrasives for fabrication of grinding wheel.

In this paper, a kind of design concept and process to fabricate porous sintered grinding wheel is developed based on SLM technology. Two types of grinding wheel with porous structures are designed and fabricated, whose mechanical properties and porosity are investigated. And the result demonstrates that this method has potential to produce high porosity grinding wheel with satisfying strength compared to hot-pressed forming process.

2. Design concept

The design concept of traditional sintered grinding wheel has not changed over hundreds years, including three major components of abrasives, bond and porosity [1]. And numerous scholars made great contributions to developing more hard abrasives, searching higher strength bond or improving porosity of grinding wheel. However, the structure of grinding wheels constituted of three components cannot be controlled during the traditional wheel fabrication process. And the influence of those components on grinding performance is coupled owing to uncontrollable wheel structure. Therefore, traditional design concept and fabrication process hinder the further improvement of grinding wheel performance.
AM technology makes it possible to proactively control the grinding wheel structure, thus the design of wheel working layer structure will become a part of design concept. That is to say, wheel structure can be designed in advance rather than passively formed from coupled three components. AM technology has advantage to produce complex structures, so any structures within the range of AM process accuracy are permitted to be designed. The general principles of wheel structure design are satisfying the strength according the force bended during grinding process and making high porosity of wheel. As shown in figure 2, three examples of wheel structures are designed based on three types of lattices, including the octahedron (OC), the truncated octahedron (TO) and the stellated octahedron (SO), TO and SO wheel structures are investigated in this paper. According to the mechanical properties and effective porosity of these structures, the better structure can be determined by working conditions and technical requirements.

3. Experiments

3.1. Materials
The mixed powder used in SLM process includes abrasives and metal powder. Diamond abrasives and aluminum alloy powder are mixed and chosen in this experiment, whose micro morphology is shown in figure 3. The range of grain size of abrasive is from 62um to 75um. The particle size of aluminum alloy ranges from 15um to 30um with spherical shape, and its chemical composition is shown in table 1. The concentration of abrasives is defined as 60%. Uniformly mixed powder should be stored under dry conditions.
3.2. SLM Equipment
The SLM Equipment used to perform the experiments is built by Beijing Longyuan AFS Corporation. The machine is assembled by gas cleaning system, laser transmitting & movement system, working chamber, control system and powder layered system. It uses a Rofin-Sinar Nd:YAG laser source with wavelength of 1.064μm. The maximum output power of laser source is 400W in continuous mode. The moving resolution can reach up to 10μm by using the stepper motor. Powder layers are deposited in one direction using roller. The SLM process must be under the nitrogen or argon gas circumstance to prevent oxidation of part.

3.3. Compressive experiment
The mechanical property of porous structures is obtained by static compression test using compressive testing machine (WDW-100/E) with a 100kN load cell. The constant deformation rate of 2 mm/min is applied to the samples until the strain reaches to 25%. The sample size is 12mm*12mm*12mm. The test is carried out according to the standard method for compression of porous and cellular metals (ISO 13314 [15]). The sample is placed between two flat rigid plates and three samples were tested for every kind of wheel structures. Through the compressive experiment, mechanical properties were acquired such as plateau stress, quasi-elastic gradient, elastic gradient, and first maximum compressive strength and so on.

3.4. Effective porosity measurement
Effective porosity (EP) is an index to weigh the quantity of the interconnected pores in structure, where coolant can flow into during grinding process. Those pores have positive effect in grinding, especially for cooling and lubrication, which cannot be realized by the close pores or trapped pores. The water absorption method is used for the measurement of effective porosity of wheel structure, which is usually used to test bulk density and apparent porosity of ceramic and concrete [16], etc. The principle of the measurement is testing the weight of dry specimens and saturated specimens. Then the volume percentage of the open pores in the specimens is calculated as equation (1):

\[
EP = \frac{(W - D)}{V \times \rho_w} \times 100\
\]

Where EP is effective porosity, W is saturated specimen’s weight, D is dry specimen’s weight, V is exterior volume of the specimen and \(\rho_w\) is water density.

4. Numerical model methodology
Numerical simulation is powerful tools to optimize the design of grinding wheel, including abrasives concentration, wheel structure and so forth. But simulating macroscopic wheel structure with numerous tiny grains consumes huge computing resource. In this paper, the numerical simulation of wheel structure divided into two steps, mesoscopic simulation to get the basic mechanical properties of composite material with 0.1mm ~ 1 mm scale, and macroscopic simulation to simulate wheel structure macroscopic behaviors based on the result of mesoscopic simulation.

4.1. Mesoscopic simulation

4.1.1. Microscopic structural modelling. Digimat FE, copyrighted by MSC, is used to model diamond/ alloy composites. Abrasives need to be modelled firstly. From the microscopic image of abrasive particles (figure 3.a), the diamond particles’ shape is generally presented as irregular truncated octahedron. For simplification, the diamond abrasives shape is modelled as regular truncated octahedron. The overall size (d) of abrasive particles conforms normal distribution, that is \(d \sim N(68.5, 21)(\mu m)\), according to the data provided by diamond factory. So the particles size is generated obeying the same normal distribution. Then abrasive model is imported into Digimat FE, and grain concentration is set as 60 %. The modelled composite is shown in figure 4.
4.1.2. Mechanical properties of grinding wheel constituent materials. The mechanical properties of diamond and aluminum alloy are shown in table 2 based on the data provided by the powder supplier. Because the mechanical properties of SLM processed aluminum alloy is anisotropic, only Z axis (part growing direction) properties is investigated in this paper. Equation (2) provides the uniaxial tensile stress-strain relation of aluminum alloy bond.

\[ \sigma = A e^n = \sigma_0 \left(1 + \frac{e}{e^p}\right)^n \quad (2) \]

where the symbols \( \sigma \), \( A \), \( n \), \( \sigma_0 \) and \( e^p \) are flow stress, the stress constant, the hardening exponent, the yield stress and the plastic strain, respectively. For the aluminum alloy used in this experiment, the stress constant is 457 MPa, and the hardening exponent \( n \) is determined as 0.033.

| Properties                  | Symbol | Unit  | Diamond | Alloy Al (AM) |
|-----------------------------|--------|-------|---------|---------------|
| Density                     | \( \rho \) | g/cm\(^3\) | 3.52    | 2.68          |
| Young’s modulus             | \( E \)  | GPa   | 1050    | 71.7          |
| Poisson’s ratio             | \( \mu \) | --    | 0.19    | 0.33          |
| Yield stress                | \( \sigma_Y \) | MPa   | 2650    | 260           |
| Ultimate strength           | \( \sigma_{UTS} \) | MPa   | --      | 457           |

4.1.3. Interfacial behaviour. Interface behavior between diamonds and binder is consider in mesoscopic simulation of wheel structure. Interfacial behaviors mainly fall into three categories: adhesive behavior, cohesive behavior and friction behavior [17]. Cohesive behavior is only considered in the simulation because of low reaction temperature and bonded behavior of diamond and binder. Breaking glue model is used in simulating debonding behavior at cohesive interface. The outer surface of grains is initially tied to the surrounding binder. The contact states will be suppressed and then the interface of grain-binder will be open up when mechanical load is bigger than specific conditions shown in equation (3):

\[
\begin{cases}
\left( \frac{t_n}{S_n} \right)^2 + \left( \frac{t_s}{S_s} \right)^2 + \left( \frac{t_f}{S_f} \right)^2 > 1 \text{ if } t_n \geq 0 \\
\left( \frac{t_s}{S_s} \right)^2 + \left( \frac{t_f}{S_f} \right)^2 > 1 \text{ otherwise }
\end{cases}
\]  

Where: \( t_n \) is the stress component which is normal to the grain-binder interface, \( t_s \), \( t_f \) are the two shear stress components acting along the grain-binder interface, \( S_n \) is the maximum stress that can be withstood by the interface when subject to normal stresses only, \( S_f \) is the maximum stress that can be withstood by the interface when subject to shear stresses only.

4.2. Macroscopic compressive simulation
In macroscopic simulation, the wheel structure is viewed as uniform and defect-free material, whose mechanical properties are determined by mesoscopic simulation. The pressure along z axis is applied to the samples, which equals to first maximum compressive strength of each wheel structure derived from compression tests.

5. Results and analysis

5.1. Morphology of wheel structures
The overall appearance of TO and SO wheel structures are shown in figure 5, the structures in samples are clearly identifiable. And the surface textures on structures are similar with CAD models, but some subtle textures are obscured due to the limit resolution of SLM process. Figure 6.a shows the diamond
abrasives are firmly bonded into binder. The line scanning energy spectrums of the grain-binder interface was detected (figure 6.b), Al and C elements both exist in two interfaces. And in interface-1, the quantity of Al element gradually decreases while the quantity of C elements gradually increases, which is opposite to interface-2. Thus, it indicates the boundary condition is well bonded without any flaws. Figure 5.c and 5.f show the morphology of two wheel structures after compression, the shear lines are roughly along the diagonal for both structures, which is similar to brittle material.

Figure 5. The morphology of wheel structure samples produced by SLM and after compressed. (a). truncated octahedron (TO) structure and its cell, (b). overall appearance of TO structure sample, (c). shear lines (orange) roughly along the diagonal; (d). stellated octahedron (SO) structure and its cell, (e). overall appearance of SO structure sample, (f). shear lines (orange) roughly along the diagonal.

Figure 6. The interface of diamond and binder. (a) is the micrograph of structure surface, (b) is 5 kinds of elements energy spectrum along the line.

Effective porosity of two grinding wheel structures are tested using water absorption method. As shown in table 3, the effective porosity of TO wheel structure is larger than SO wheel structures. Additionally, the relative error between actual effective porosity and theoretical porosity calculated from CAD model is very large. The reason is that some powder is tripped in structures and the wheel structures are not very precisely fabricated. However, the results of effective porosity have the same trend with theoretical calculation. Therefore, the actual effective porosity still can be seen as reasonable index to figure the porosity of wheel structure.

Table 3. Effective porosity of two wheel structures.

| Structure | overall size [mm] | Strut diameter [mm] | TP   | EP   | Relative error |
|-----------|-------------------|---------------------|------|------|----------------|
| TO        | 12 × 12 × 12      | 0.4                 | 69%  | 52%  | 25%            |
| SO        | 12 × 12 × 12      | 0.4                 | 50%  | 39%  | 22%            |

* TP --- theoretical porosity; EP --- effective porosity.
5.2. Compression result
The mechanical properties of foams and lattice are investigated in [18] by M.F. Ashby. TO and SO structure essentially belong to porous materials, thus their mechanical properties are similar to porous metals’. But the existence of big proportional abrasives in the structure makes them have different behaviors that the stress sharply drops when the strain is big than 0.2 ± 0.05 (varied with structures and samples). That region of stress-strain curve contains quite little useful information directing to design wheel structure. Therefore, the range of strain was uniformly set to 0–0.16. Stress-strain curves (figure 7) were obtained from static compression tests, which are used to derive different mechanical properties. From the curves, quasi-elastic gradient and yield stress $\sigma_y$ are acquired according to the standards [15]. The first maximum compressive strength of TO structure is 52MPa, and the SO’s is 155MPa; the quasi-elastic gradient of TO is 762MPa and the SO’s is 2616MPa. According to the testing results, SO structure has higher anti deformability and compression strength than TO structure.

![Figure 7. Stress-strain curve for TO, SO samples of the static compression tests, thin lines stand for the standard deviation from the means of three samples.](image)

5.3. Numerical simulation
Basic mechanical properties are obtained from mesoscopic simulation, shown as figure 8. The strain ranged from 0 to 0.012 is applied to the composite model along z axis. From the equivalent Von-Mises stress distribution (figure 8.a), concentrating stress always occurs on grain corners. The diamond is still bonded into binder firmly even though some surfaces of diamond are separated from binder partially. The uniaxial stress – overall strain curve of reference point is plotted in figure 8.b, and the equivalent elastic modulus ($E$) and yield strength are acquired, 92GPa and 253MPa, respectively. Obviously, the composite of grains and aluminum alloy has lower yield strength than single aluminum alloy made by the same method (SLM) because of the existence of diamond abrasives. But the equivalent elastic modulus of composite is larger than aluminum alloy’s due to the influence of hard particles.

Given the grain-binder composite mechanical properties, macroscopic compressive simulation results are shown in figure 9. To reduce computer resources, one eighth of TO and SO models are used in compressive simulation, the first maximum compressive strength acquired from compressive test is applied to each structure along z axis. Thus, TO’s pressure is 52MPa and SO’s is 155MPa. A serial of stress concentrating points are labelled in figure 9 and shown in table 4. Generally speaking, the destruction often happened at concentrating points. Although the pressures applied to two structures are different, the typical concentrating points values is similar, the average of these points is 238MPa and 244MPa. Furthermore, the average value of concentrating points prone to be destructed is close to the yield strength of composite. It’s demonstrated that the simulation has a great accordance with test results.
Figure 8. Mesoscopic simulation result, (a). the equivalent Von-Mises stress distribution, (b). stress-strain curve and equivalent elastic modulus ($\tilde{E}$).

Table 4. The values of concentrating points.

| Types | Pressure [MPa] | Typical concentrating points values [MPa] | Average [MPa] |
|-------|----------------|------------------------------------------|---------------|
| TO    | 52             | 239                                      | 238           |
| SO    | 155            | 251                                      | 244           |

Figure 9. The equivalent Von-Mises stress distribution of TO (a) and SO (b) structures.

6. Conclusions

In this research, the design and fabrication method of porous wheel is developed based on SLM technology. The effective porosity of grinding wheel structures can reach up to at least 30% using this method. The design of grinding wheel structure is introduced into wheel design concept. And the porosity can be controlled in accordance with designed CAD model, which is difficult to realize for traditional hot-pressed forming methods. Two wheel structures, truncated octahedron and stellated octahedron, are designed and fabricated using the method involved in this paper. Both of TO and SO structures have their own advantage on the specific aspect. For example, TO structure has larger porosity but lower compressive strength compared with SO structure. However, the choice of two
structures should be judged by the working conditions and technical requirements. The simulation results are well converged with compressive tests, which indicates it is feasible to optimize the design of grinding wheel before fabrication. It can be concluded from this paper that the design and fabrication of porous grinding wheel based on SLM technology is practicable in engineering. Furthermore, the wheel structure can be controlled before wheel fabricated, which is difficulty for traditional process. The next work of this project is testing grinding performance of this kind of grinding wheel.

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