Study on process and manufacturability of metal-bonded diamond grinding wheel fabricated by selective laser melting (SLM)

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Abstract. Selective laser melting (SLM) technology is used to fabricate metal-bonded grinding wheel based on mixed powders consisted of metal powders and diamond abrasives. Taguchi method is adopted to obtain the optimal SLM process parameters for grinding wheel considering laser power, scanning speed and layer thickness. Specimens are fabricated with different SLM process parameters for compression and three-point bending tests. Materials characterization and manufacturing limit test are performed on the specimens fabricated by the optimal SLM process. Results indicate that laser power of 250W, scanning speed of 2.5m/s and layer thickness of 20μm are determined as the optimal SLM process in terms of comprehensive mechanical property and formed surface quality. Moreover, diamond abrasives are firmly embedded into aluminium binder with good bonding condition for SLM-fabricated composite. Furthermore, manufacturability of SLM-fabricated composite is evaluated by manufacturing limits of several common structures. In summary, work in this study fully proves the feasibility of SLM-fabricated metal-bonded grinding wheel and provides a solid basis for the further investigation on the novel grinding wheel with customized porous structures.

1. Introduction

Grinding is vital for excellent surface finish and grinding wheel plays a significant role in grinding process [1]. Furthermore, grinding is the most useful process to generate high quality functional surface made from hard-to-machine materials, such as Inconel 718 [2], cold die steel [3] and metal matrix composite [4]. Outstanding abrasives holding strength and excellent mechanical property contribute to the extensive application of metal-bonded grinding wheel [5]. Nevertheless, the porosity and micro structure cannot be actively controlled due to the hot pressing technique, which is the main traditional fabrication method for metal-bonded grinding wheel. The micro structure and pores are passively formed owing to the essence of hot pressing technique: powder accumulation and pressing forming [6].
Additive manufacturing (AM) attracts more and more attentions because of its potential applications. Multiphase composite as well as complex structures can be fabricated by AM, making it a potential method for developing new materials and new structures [7]. With help of AM technology, novel fabrication method of grinding wheel can be realized. Some attempts have been conducted on the feasibility of AM grinding wheel. Maekawa et al. proposed a new method of fabricating metal-bonded grinding or polishing tools by the greentape laser sintering method [8]. Yang et al. adopted CNC laser machine and customized feeding device to fabricate the metal-bonded diamond cup wheel with regular grain distribution [9]. Unfortunately, the AM process in above attempts must rely on the customized equipment, which cannot be realized with common AM process and equipment.

In this paper, the novel fabrication method of metal-bonded grinding wheel based on selective laser melting (SLM) technology is proposed. SLM is the most popular AM process for metal and alloy. Actually, lots of research works have been performed on SLM process for the fabrication of metal matrix composites [10-12]. However, big challenge exists for the fabrication of grinding wheel due to the special composite consisted of metal matrix (binder) and inclusions (abrasives). The abrasives are very different from ordinary inclusions in terms of shape, size and function, making it harder to form the composite of grinding wheel than common composite, so the SLM process needs further optimization. Actually, many optimization methods can be used for SLM process optimization, such as factorial design, central composite design, response surface method, Taguchi method and so on [13]. Particularly, Taguchi method is extensively applied to optimize SLM process due to its high efficiency and low cost [13]. Li et al. adopted Taguchi method to study the effect of SLM process on the relative density of titanium alloy [14]. Khaimovich et al. adopted Taguchi method and grey relational analysis to optimize the SLM process for thin-walled nickel-chromium parts which are prone to thermal warpage [15]. Sun et al. applied Taguchi method to optimize the SLM parameters such as laser power, scanning speed, powder thickness, hatching space and scanning strategy for the maximum density of titanium alloy [16]. Therefore, Taguchi method is proved to be effective for SLM process optimization.

In this study, Taguchi method serves to design experiment and obtain the optimal SLM process parameters considering different factors such as laser power, scanning speed and layer thickness for SLM-fabricated grinding wheels. To evaluate the quality of SLM-fabricated composite with different parameters, morphology observation and mechanical property test are performed. In addition, material characterization and manufacturing limit test are conducted on the SLM-fabricated composite with the optimal parameters. All the works provide the basis for the fabrication of metal-bonded grinding wheel with SLM process.

Figure 1. Raw materials and fabrication principle for metal-bonded diamond grinding wheel: (a) diamond abrasives; (b) alloy powders; (c) SLM principle.
2. Materials and methods

2.1. Materials and fabrication principle

To fabricate the composite for grinding wheel, mixed powders consisted of diamond abrasives (Figure 1(a), particle shape: irregular truncated octahedron, particle size: 65-75μm) and AlSi10Mg powders (Figure 1(b), particle shape: sphere, particle size: 15-53μm) serve as raw materials for SLM process. The fabrication principle of grinding wheel is depicted in Figure 1(c). The laser wavelength and spot diameter are 1064nm and 70μm respectively. When the new layer of mixed powders is prepared, the laser beam melts the AlSi10Mg powders selectively. Subsequently, melted aluminum alloy solidify as the binder of grinding wheel wrapping abrasives in it. The whole grinding wheel will be formed after numerous repetitions of above procedure.

2.2. Orthogonal experiment design

Orthogonal experiment was adopted to obtain the optimal SLM process for the special composite. Orthogonal experimental design was proposed by Genichi Taguchi and widely applied in multi-factors and multi-levels experimental design. In this study, laser power (levels: 250W, 300W and 350W), scanning speed (levels: 2m/s, 2.5m/s and 3m/s) and layer thickness (levels: 20μm, 30μm and 40μm) were determined as three factors for the orthogonal experiment, so L9(3^4) orthogonal table was chosen for the arrangement of experiment and shown in Table 1. To evaluate the mechanical property of this special composite, nine groups of specimens for compression and three-point bending test were fabricated by SLM with process parameters shown in Table 1.

Table 1. Orthogonal experiment design based on Taguchi method.

| Experiment group | Factor level combination | (A) Laser power (W) | (B) Scanning speed (m/s) | (C) Layer thickness (μm) |
|------------------|--------------------------|---------------------|--------------------------|--------------------------|
| 1                | A1B1C1                   | 250                 | 2                        | 20                       |
| 2                | A1B2C2                   | 250                 | 2.5                      | 30                       |
| 3                | A1B3C3                   | 250                 | 3                        | 40                       |
| 4                | A2B1C2                   | 300                 | 2                        | 30                       |
| 5                | A2B2C3                   | 300                 | 2.5                      | 40                       |
| 6                | A2B3C1                   | 300                 | 3                        | 20                       |
| 7                | A3B1C3                   | 350                 | 2                        | 40                       |
| 8                | A3B2C1                   | 350                 | 2.5                      | 20                       |
| 9                | A3B3C2                   | 350                 | 3                        | 30                       |

2.3. Mechanical property test

Specimens for the mechanical test were fabricated by SLM, including compression specimens with size of Ф8mm(Diameter) * 8mm(Height) and three-point bending specimens with size of 6mm(Width) * 4mm(Height) * 40mm(Length). Nine groups of specimens are corresponding to the nine groups of SLM process parameters shown in Table 1. Every group consists of three compression specimens and three bending specimens, shown in Figure 2(a). The universal mechanical test machine was used for the compression and bending test and depicted in Figure 2(b) and Figure 2(c).

As shown in Figure 2(b), the lower platen was fixed and the upper platen moved down at the speed of 1mm/min in the compression test. The stress-strain curves were derived from the compression force and displacement of upper platen. Every group includes three specimens for compression test, so the total number of compression specimens is up to 27 for nine groups according to Table 1.

As shown in Figure 2(c), the specific fixture served to perform the three-point bending test. The span between two support rollers was defined as 30mm and the loading rate was defined as...
0.5mm/min of load roller. The force-displacement curves were recorded during test. Similarly, every group includes three specimens for bending test, resulting in 27 bending specimens in total referring to Table 1.

![Figure 2](image1.jpg)

**Figure 2.** Specimens and equipment for the mechanical test: (a) compression and bending specimens; (b) compression test equipment; (c) three-point bending test equipment.

### 2.4. Material characterization and manufacturability test

To characterize the SLM-fabricated composite, scanning electron microscope (SEM) and optical microscope (OM) were utilized to analyse the surface morphology and metallographic microstructure. The sample used for the metallographic analysis must be polished and etched.

To evaluate the manufacturability of SLM-fabricated grinding wheel, manufacturing limits of several features and structures were fabricated with the optimal parameters obtained from orthogonal experiment. The features and structures for manufacturing limit test are shown in Figure 3. Figure 3(a) displays the strut structures whose diameters change from 0.1mm to 1.0mm with increment of 0.1mm. Figure 3(b) shows the cantilever structures whose diameters change from 0.1mm to 1.0mm with increment of 0.1mm and inclination angles change from 10° to 60° with increment of 10°. Figure 3(c) presents the small hole structures, including square holes whose side lengths change from 0.1mm to 1.0mm with increment of 0.1mm and circular holes whose diameters change from 0.1mm to 1.0mm with increment of 0.1mm. Figure 3(d) exhibits the thin wall structures whose wall thicknesses are in the range of 0.1mm-1.0mm with increment of 0.1mm. Figure 3(e) indicates a series of arched bridge structures with radius of 2mm to 14mm and thickness of 0.5mm. Figure 3(f) demonstrates the spiral structures with rising angles changing from 10° to 50° and increment of 10°. The diameters of spiral structure and spiral line are 8mm and 2mm respectively.

![Figure 3](image2.jpg)

**Figure 3.** Different features for the manufacturing limit test: (a) strut; (b) cantilever; (c) small hole; (d) thin wall; (e) arched bridge; (f) spiral.
3. Results and analysis

3.1. Material characteristics

To investigate the material characteristics of SLM-fabricated composite, surface morphology and metallographic photo are obtained based on SEM and OM, shown in Figure 4. Figure 4(a) and Figure 4(b) indicate the surface morphology of as-built and polished composite. It reveals that the diamond abrasives are firmly embedded into aluminium alloy binder with good bonding condition. Figure 4(c) and Figure 4(d) depict the metallographic microstructure on the side plane and scanning plane respectively. The side plane is the plane parallel to building direction and the scanning plane is the plane perpendicular to building direction. It displays the scaly melting pool and staggered scanning path on the side plane and scanning plane respectively. Additionally, uniformly distributed abrasives and a few void defects are presented as well.

![Figure 4. Surface morphology and metallographic analysis of SLM-fabricated composite: (a) as-built surface; (b) polished surface; metallographic photo of (c) side plane and (d) scanning plane.](image)

3.2. Mechanical properties

3.2.1. Compression analysis. Compression stress-strain curves are presented in Figure 5(a) for nine groups of specimens fabricated with nine groups of parameters in accordance with Table 1. Three specimens for each group are tested. Mean value (heavy continuous line) and error bar (fine dotted line) are calculated and shown in Figure 5(a). It indicates that four stages exist for the stress-strain curves, including elastic stage, initial yield stage, crack propagation stage and densification stage. Because of a few voids formed in the composite, the initial elastic stage possesses a low elastic modulus. When the voids are compacted, a high elastic modulus appears. As the strain increases, the corresponding stress slows down the pace of growth and the composite comes into the initial yield stage. As the strain increases further, bonding interface fails and cracks, resulting in many cracks of matrix generating around abrasives. Therefore, the stress decreases or fluctuates in the crack propagation stage. With further compression, abrasives may fracture and cracks are compacted, resulting in solidification of composite. Based on the 0.2 % strain principle, the elastic modulus and yield strength are derived from the curves.

3.2.2. Three-point bending analysis. Three-point bending test is a measurement for the transverse rupture strength widely used in grinding wheel strength test. The force-displacement curves are presented in Figure 5(b) for nine groups of specimens fabricated with nine groups of parameters referring to Table 1. Similarly, mean value (heavy continuous line) and error bar (fine dotted line) are
depicted in Figure 5(b). It indicates that the force loaded on the middle of specimen increases linearly with increasing displacement until a sudden drop because of the initial crack generation. The critical force (peak value) and corresponding maximum deflection (critical displacement) are utilized to calculate the flexural modulus and flexural strength.

3.2.3. Determination of optimal parameters. Mean values of mechanical indexes influenced by different process factors and levels for SLM-fabricated specimens are listed in Table 2. The mechanical indexes include elastic modulus (EM), yield strength (YS), flexural modulus (FM) and flexural strength (FS). The process factors include laser power (LP), scanning speed (SS) and layer thickness (LT). To search for the optimal SLM process parameters, analysis of variance (ANOVA) is performed in SPSS software based on orthogonal experimental results and corresponding statistical data are presented in Table 3. Type III sum of squares, degree of freedom and mean square are derived from original experimental data. Besides, F test is conducted at the confidence level of 90% to evaluate the significant influence of process factors (LP, SS and LT) on the mechanical indexes (EM, YS, FM and FS). It indicates that EM is significantly influenced by SS and LT rather than LP, so only SS and LT are considered when determining the optimal process for EM. According to Table 2, the largest EM occurs at SS of 2.5m/s and LT of 20μm respectively among their levels, which are determined as the optimal process for EM. According to Table 2, the largest EM occurs at SS of 2.5m/s and LT of 20μm respectively among their levels, which are determined as the optimal process for EM. Similarly, YS is only significantly influenced by LT, so LT is the main influencing factor for YS and the optimal value is 20μm for YS referring to Table 2. However, FM, FS and surface quality are all significantly influenced by LP instead of SS or LT referring to Table 3 and Figure 6. Interestingly, LP of 250W behaves the best for all the three indexes mentioned above, which can be derived from Table 2 and Figure 6. Hence, LP of 250W, SS of 2.5m/s and LT of 20μm are determined as the optimal SLM parameters in terms of comprehensive mechanical property and formed surface quality.

Figure 5. Mechanical test result: (a) compression stress-strain curves and (b) three-point bending force-displacement curves for nine groups of SLM-fabricated specimens.

Figure 6. Surface quality of SLM-fabricated composite with nine groups of process parameters.
Table 2. Mean values of mechanical indexes with different SLM process factors and levels.

| Process factor | Level of factor | Mean of EM (Gpa) | Mean of YS (Mpa) | Mean of FM (Gpa) | Mean of FS (Mpa) |
|---------------|----------------|------------------|------------------|------------------|------------------|
| Laser power   | 250.0          | 5.4              | 334              | 17.4             | 246              |
|               | 300.0          | 5.5              | 347              | 6.6              | 95               |
|               | 350.0          | 5.1              | 339              | 6.0              | 92               |
| Scanning speed| 2.0            | 5.0              | 333              | 10.0             | 132              |
|               | 2.5            | 5.8              | 353              | 10.6             | 153              |
|               | 3.0            | 5.2              | 333              | 9.3              | 148              |
| Layer thickness| 20.0           | 5.8              | 399              | 10.5             | 174              |
|               | 30.0           | 5.2              | 314              | 9.2              | 120              |
|               | 40.0           | 5.0              | 306              | 10.2             | 139              |

Table 3. Analysis of variance (ANOVA) for orthogonal experimental results.

| Process factor | Mechanical index | Sum of squares | Degree of freedom | Mean square | F test | Significance |
|---------------|-----------------|----------------|-------------------|-------------|--------|--------------|
| Laser power   | EM              | 0.187          | 2                 | 0.093       | 3.111  | 0.243        |
|               | YS              | 256.222        | 2                 | 128.111     | 0.153  | 0.867        |
|               | FM              | 245.340        | 2                 | 122.670     | 20.497 | 0.047        |
|               | FS              | 46346.933      | 2                 | 23173.466   | 60.627 | 0.016        |
| Scanning speed| EM              | 0.927          | 2                 | 0.463       | 15.444 | 0.061        |
|               | YS              | 786.889        | 2                 | 393.444     | 0.471  | 0.680        |
|               | FM              | 2.370          | 2                 | 1.185       | 0.198  | 0.835        |
|               | FS              | 765.584        | 2                 | 382.792     | 1.001  | 0.500        |
| Layer thickness| EM             | 0.887          | 2                 | 0.443       | 14.778 | 0.063        |
|               | YS              | 16041.556      | 2                 | 8020.778    | 9.601  | 0.094        |
|               | FM              | 2.570          | 2                 | 1.285       | 0.215  | 0.823        |
|               | FS              | 4477.834       | 2                 | 2238.917    | 5.857  | 0.146        |

3.3. Manufacturability characterization

To evaluate the manufacturability of SLM-fabricated composite for grinding wheel, manufacturing limits of several structures are investigated. The formed structures are exhibited in Figure 7. Compared with CAD models in Figure 3, the forming quality is satisfactory in terms of dimensional accuracy and surface integrity. Corresponding manufacturing limits are listed in Table 4. It reveals that the inclination angle does not affect the limits of strut and cantilever structures because the smallest diameter appears identical. Additionally, the rising angle (range: 10° to 50°) of spiral structures does not change the limits but affects the surface finish. The smaller the rising angle is, the worse the surface finish is. Similarly, the arched bridge structures with radius of 2-14mm are all well-formed. The surface finish at the top of arched bridge becomes worse as the radius increases. The results show that thin wall with thickness less than 0.3mm, circular hole with diameter less than 0.2mm and square hole with side length less than 0.3mm cannot be fabricated by SLM. In summary, these manufacturing limits for SLM-fabricated composite provide the basis for the design of metal-bonded grinding wheel with controllable porous structures.

Table 4. Manufacturing limits of SLM-fabricated composite.

| Structures          | Strut | Cantilever | Circular hole | Square hole | Thin wall | Arched bridge | Spiral |
|---------------------|-------|------------|---------------|-------------|-----------|---------------|--------|
| Manufacturing Limits | 0.3mm | 0.3mm      | 0.2mm         | 0.3mm       | 0.3mm     | 2-14mm        | 10°-50° |
3.4. Applications in grinding wheel

In this study, selective laser melting is used for the fabrication of metal-bonded grinding wheel based on the mixed powders consisted of diamond abrasives and metal powders. Results indicate that SLM-fabricated composite is well formed with good bonding condition and can serve as grinding wheel material, proving the feasibility of SLM-fabricated grinding wheel. Indeed, as an AM technology, SLM can be utilized to fabricate arbitrarily complex structures. Therefore, metal-bonded grinding wheel with customized shape and controllable porous structures can be designed and fabricated with this method, which will be studied in further research. That is to say, pores and micro channels inside grinding wheel can be actively designed and realized instead of passively formation, which benefits the porosity, debris space and heat dissipation of grinding wheel and gives a new thinking and methodology for design and fabrication of customized grinding wheel. The research on SLM process and manufacturability provide a solid basis for the further investigation. Actually, disadvantages and restrictions of proposed method exist. Owing to the limitations of SLM process, size of abrasives may be restricted. Moreover, the production efficiency may be restricted if the grinding wheel is too big or the porous structure is too complex. Besides, further investigation on fabrication process and heat treatment are needed to diminish cracks or voids defects inside the as-built SLM composite. Therefore, lots of works need to be done to realize the practical industrial applications of SLM-fabricated grinding wheel.

4. Conclusions

In this study, SLM fabrication process and manufacturability of metal-bonded grinding wheel are investigated. The main findings are exhibited as follows:

(1) Diamond abrasives are firmly embedded into aluminium alloy binder with good bonding condition for SLM-fabricated composite. Scaly melting pool and staggered scanning path can be distinguished from metallographic microstructure.

(2) Four stages exist for compression stress-strain curves, including elastic stage, initial yield stage, crack propagation stage and densification stage. Force increases linearly with increasing displacement until a sudden drop because of initial crack generation during three-point bending test.

(3) Laser power of 250W, scanning speed of 2.5m/s and layer thickness of 20μm are determined as the optimal parameters in terms of comprehensive mechanical property and formed surface quality. Manufacturability is evaluated by testing manufacturing limits of several structures.

(4) Work in this study fully proves the feasibility of SLM-fabricated metal-bonded grinding wheel and provides a solid basis for the further investigation, such as grinding wheel with porous structure, making it a potential method to fabricate high performance novel grinding wheel.

Figure 7. Manufacturing limits and surface finish of structures: (a) top view and (b) side view.
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