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The thermal deformation property of silicon mirror with different porosity fabricated by direct laser sintering

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ABSTRACT

The effect of the heat sink's porosity on the thermal deformation of the laser silicon mirror has been investigated in this paper. The water-cooled laser silicon mirror with different porosity structure has been fabricated by direct laser sintering and powder mixture of Cu-based alloy and NaCl. A Twyman-Green interferometer was employed to measure the thermal deformation of the silicon mirrors radiated by a high power laser. It is shown that the thermal deformation of the mirrors surface is related to porosity significantly. As the porosity increases, the thermal deformation decreases at first and then increases. With the heat sink porosity of 30.3%, the smallest thermal deformation of the mirror surface is obtained. The maximum thermal deformation of the mirror is 0.25 μm if the absorbed laser power density achieves to 5.3×10^5 W/m^2.

1. Introduction

In the high power laser system, the resonator mirrors and reflectors absorbs laser energy during laser works, which may result in temperature rising and nonuniform thermal deformations, even destruction of the mirrors. As the laser power and working time increase, the problem becomes more and more serious. When the deformation of the resonator mirror is larger than λ/10 (λ is the laser wave length), the quality of the laser beam will deteriorate drastically and result in expanding focus spot in remote transmission. Therefore, reducing or compensating the thermal deformation of the laser mirrors is become ever more urgent. There are several ways to reduce the thermal deformation of laser mirror [1–3]. However, water-cooling is the most effective and widely utilized method [4–8].

The water cooling mirror with micro pores has attracted more and more attentions for its high heat transfer coefficient and surface area/volume ratio [9]. Previous researches have investigated the heat exchange efficiency of the mirror with porous by theoretical calculation and experiment. In their research, the mirror with porous has excellent properties on reducing the thermal deformation of the laser mirrors [10–12]. Si is widely utilized in high power laser because of its excellent thermal properties and optical machinability. However, existing processes technologies for micro machine the Si reflector mirror with micro porous are hardly to fabricate the complex configuration on the silicon mirror because of the disadvantages of residual stress, shape limitation and inefficiency.

Laser process is widely utilized in industrial application since the laser was developed [13–14]. Direct laser sintering (DLS) is an additive manufacture prototyping technology, which can fabricate 3D metal parts with complex shape and structure from the CAD model and metal powder directly. DLS technique always brings micro pores in the sintered parts because of its nature. Therefore, it has become a new technique to manufacture porous material. The porosity and pore size of DLS can be controlled by varying the laser process parameters and material components [15–18]. However, high porosity sintered part could not be obtained because of too low strength of such samples.

Porogen is generated to utilize for making porosity during manufacture porous materials. Some researcher fabricated lotus root-shape and high porosity structure by direct laser sintering successfully with porogen added [19,20]. So the heat sink with different porosity can be fabricated by DLS with some porogen added. Heat sink with appropriate porosity may also improve the cooling efficiency [21–23] since the micro pores also form flow pass channel as well and the water can flow in these channels.

Based on our earlier research [24], the fabrication of water-cooled laser silicon mirror with porous structure by direct laser sintering was feasible. However, the thermal deformation of the mirror is still regarded as too large. Therefore, fabrication coppery

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heat sink with appropriate porosity on the back of Si mirror is expected to achieve a high heat exchange efficiency and a smaller thermal deformation.

To investigate the influence of the porosity on the cooling effect, a series of water-cooled laser silicon mirrors with different porosity are fabricated by DLS in this paper. The heat dissipation ability of the heat sink with different porosity using a Twyman-Green interferometer to measure the thermal deformation of the silicon mirror under high power laser radiation.

2. Fabrication of coppery heat sink with different porosity on the back of Si mirror by DLS

2.1. Experimentals

The experiments were carried out on the self-developed DLS processing system. As shown in Fig. 1, this system was consisted of a laser, a scanner, a chamber with atmospheric control, a powder delivery system and a control system. The laser was a continuous-wave (CW) CO_2 (l = 10.6 mm) laser with a maximum laser power of 250 W (COHERENT K250). The focus distance of the lens was 300 mm with the focused spot size of 0.3 mm.

The powders utilized in the experiments were a gas atomized 99% purity Cu powder (−200 mesh) with spherical shape, pre-alloyed spherical CuP (phosphor 7.25 wt%, copper 92.75 wt%, −325 mesh) powder , SiO_2 (−200 mesh) powder and NaCl (−200 mesh) powder with irregular shape. Different mass ratios were used as tabulated in Table 1 for different powder mixtures. Powder 1#∼5# were utilized to fabricate transition layers. In the first transition layer, the metallurgical bonding and sufficient bonding force between the silicon substrate and the heat sink layers were obtained since the Cu_3Si alloy was generated [24]. The thermal stress caused by the thermal properties' differences of the Si substrate and coppery heat sink was overcome by the series transition layers were designed as the components gradually changed.

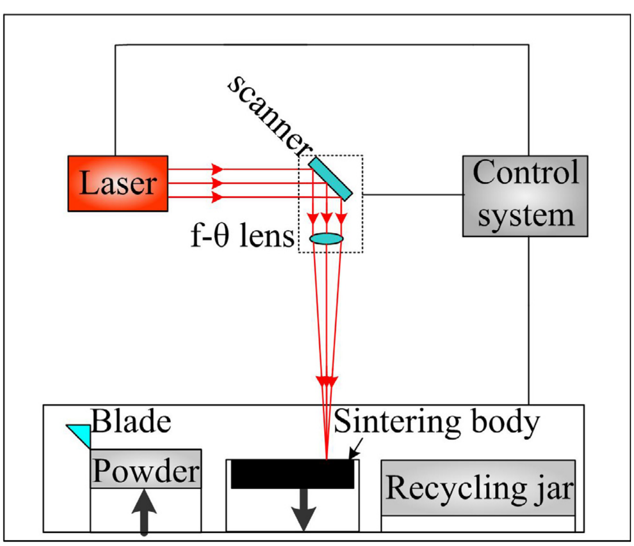

Fig. 1. The schematic diagram of the DLS system.

The sinter process parameters were as follows: the laser power was in the range of 60–100 W, the scan speed was in the range of 100–200 mm/s, the hatch spacing and layer thickness were kept as a constant of 200 μm and 100 μm, respectively. All experiments were performed in the ambient atmosphere.

Fig. 2 is the schematic diagram of the structure of the whole Si mirror. The whole Si mirror consists of components: a mirror and a sealed cap. The mirror includes three parts: Si substrate, transition layers and coppery heat sink. The sealed cap has two roles: one seals the mirror to make sure the water does not leak by using the rubber sealing ring, another is to provide the inlet and outlet. Transition layers were sintered firstly on the silicon substrate, and then a coppery heat sink was sintered on the surface of the transition layers. The shape and size of transition layers were the same as the coppery heat sink layers excepting the thickness. In this experiment, the thickness of the silicon substrate, the transition layers and the coppery heat sink layers were 3 mm, 0.5 mm and 2.5 mm, respectively. The diameter of the substrate, the heat sink layers and the water inlet were 60 mm, 40.5 mm and 1.5 mm, respectively. In the heat sink, the circinate channel width was designed as 0.5 mm and the wall thickness was 2 mm.

2.2. The heat sink with different porosity

Fig. 3(a–e) shows the photo of the silicon mirrors with coppery heat sink fabricated by DLS. It can be seen that no crack and warpage are found on the coppery heat sink. The structure of the heat sinks in Fig. 3 is all the same except the porosity. To investigate the porosity of the heat sink sintered with different mass ratio of NaCl, the mirrors in Fig. 3 have been dealt with ultrasound in water at 60 °C for 3 h. Therefore, the NaCl phase in the sample was removed and became pores, as shown in Fig. 4.

In Fig. 4(a–e), the black area is the pores which are interconnected [24], while the bright area is the sintering body composed of coppery metal. From Fig. 4(a–e), it can be found that the distribution of the irregular pores are approximate uniform, and the black area increase with the mass ratio of NaCl, which indicate that the porosity of the sample increase with the mass ratio of NaCl. The porosity of the samples (a–e), measured by the image method, are 8.8%, 17.7%, 24.6%, 30.3%, 39.4% respectively. Moreover, the size of the pores increases with the porosity.

3. Measurement of the thermal deformation of mirrors surface

3.1. Experimentals

Fig. 5 shows the experimental setup for measuring thermal deformation of the mirror. It consisted of a propagation of laser optical system, liquid coolant flow system, a Twyman–Green interferometer, a CCD camera and a data acquisition card. The sample mirror was obliquely irradiated by a 250 W CW CO2 laser (COHERENT K250). The beam spot on the mirror surface was an ellipse with a short half-axis of 9 mm and a long half-axis of 12 mm, i.e., the laser irradiated area of the mirror was 340 mm^2. The laser

Table 1
Powder composition of the mixed powder.

Powder No	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#
SiO_2 (Wt%)	50	40	30	20	10	0	0	0	0	0
Cu (Wt%)	0	20	30	40	50	60	57	54	51	48
CuP (Wt%)	50	40	40	40	40	40	38	36	34	32
NaCl (Wt%)	0	0	0	0	0	0	5	10	15	20