Study on evaluation of RB-SiC aspherical mirror high frequency surface quality fabricated with fixed abrasive technology

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The issue of the letter is focused on the RB-SiC aspherical mirror high frequency surface quality which is fabricated with the different type fixed abrasive pellets. The two-dimensional (2D) surface roughness of the mirror is simulated and experimented. The errors between the simulation and the experiment are 5.97%, 3.19%, 3.59%, 37.37% using W1.5, W3.5, W5, W7 pellets respectively. The error emerging reason is analyzed in detail after the comparison. Also the fractal theory is applied on the analysis of the optical mirror surface fabricated with the fixed abrasive technology. The analysis result shows that the good surface quality of the RB-SiC mirror can be obtained quickly with being polished with the fixed abrasive technology. So the fixed abrasive technology is very suitable for the fast optical surfacing, especially can obtain good surface roughness fast in the stage of grinding mirror which is not suitable for being tested with interferometer.

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Generally, the surface error, the ripple and the surface roughness should be tested quantificationally when a SiC mirror is finished. The mirror surface quality is evaluated through the parameters tested.

The surface error which is also called low frequency error is studied for decades[1−3]. So the surface error is not in the letter's extension, it is focused on the high frequency error of the SiC mirror fabricated with the fixed abrasive technology, which is studied through several different methods.

The existence of the high frequency error on the mirror will increase the scattering energy, decreasing the effective energy entering the camera, then the image quality will be decreased. So we should understand exactly what factor and which stage leads to the increase of the high frequency error on the mirror in the fabrication. In the most situation, the study is only focused on the method of testing the high frequency error, but the theoretical study on the high frequency error is seldom. The starting point of the letter is simulating the microcosmic formation the high frequency error in the fabrication process. And also the mirror surface fabricated with pellets is analyzed and evaluated using the fractal theory for the first time.

Because of the complexity of simulating the fabrication process of SiC mirror with diamond abrasive actually, the following important assumption is made: the final mirror surface is formed by the indentation into the SiC mirror with the still diamond particles. In the fabrication of the SiC material, the size and depth of the indentation formed by the diamond particles are totally different. So we are on the assumption that the position distribution of the indentations is uniform, the size of the indentations are in Gaussian distribution, the depth is δ_{w}[4],the cross-section shape of the indentation is shown in Fig. 1.

The unit area is dispersed into $n \times n$ matrix, so there are n^2 computing points we get. According to the actual microcosmic fabrication instance, the final indentation is formed by the larger diameter diamond particle, when the larger diameter diamond particle is pressed into the indentation formed by the smaller diamond particle, whose indentation value is always the deeper depth. When in the process of the simulation, the position of the single computing point is covered by several indentations, the depth is computed as the larger absolute value. The number of the indentations is decided by the abrasive number involved to fabricate the mirror in the unit area on the pellet surface. In processing the surface roughness, the traditional one-dimensional (1D) surface roughness is extended to two-dimensional (2D), the depth of the indentation distributed random in the computing zone, which is denoted as $z\left(x_i, y_j\right)$, so the formula of the surface roughness is changed into

$$R\mathrm{a} = \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} z\left(x_i, y_j\right). \tag{1}$$

Three pictures in Fig. 2 simulated with matlab show the indentation distribution formed by the different diameter diamond particles. According to the distribution of Fig. 2, the simulated value of the surface roughness can be calculated.

In the fabricating experiment, four different types pellets are used, which are $\phi 10 \times 5$, W7, R∞; $\phi 10 \times 5$, W5,

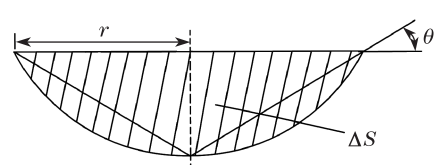

Fig. 1. Sketch of contact area between single abrasive and workpiece.

R∞; $\phi 10 \times 5$, W3.5, R∞; $\phi 10 \times 5$, W1.5, R∞ respectively. The pellet diameter is 10 mm, the thickness is 5 mm, the surface type is flat, the diamond particle diameters in pellet are 7, 5, 3.5, and 1.5 μm. The pellets are felted on the round iron pad whose diameter is 40 mm, and the iron pad is fixed on the single axis polishing machine. The workpiece material is the reaction bonded SiC which is made in our own institute and fixed on the round rotation table. The coolant is de-ion water[5−7].

The fabrication facility is a single axis lens polishing machine which is manufactured by Nanjing machine shop. Its maximum fabricating diameter is 300 mm, the speed extension of the principal axis is 18–50 rpm, the frequency of the pendular axis is 60 Hz, and the fabrication pressure depends on the fabrication load which can be adjusted flexibly.

In the experimental process, the SiC mirror should be polished adequately with one single type pellets in each fabrication procedure, which makes sure that the surface sub-damage crack left in the last procedure will be removed completely. The long fabricating time process ensures that the surface roughness result is stable and reliable.

In the testing experiment of the surface roughness, the instruments is from the DI company, and the type is Dimension$^{\text{TM}}$ 3 100 atomic force microscope. The sampling length is 10 μm, the number of sampling points is 256, and the results are displayed in Fig. 3.

For a better intuitionistic comparison, the local surface profile curves in Fig. 3 are picked up via "section option" in software Nanoscope III 5.12r2, and the sampling length is 10 μm. The results are shown in Fig. 4.

In the whole process of the fabrication, the changing trend of the surface roughness is summarized in Fig. 5.

As shown in Fig. 5, the surface roughness of 42.758-nm RMS is obtained via being fabricated with W7 pellets, the surface roughness decreases to 17.219-nm RMS fast after being fabricated with W5 pellets. After W3.5, W1.5 pellets are used, the surface roughness decreases quickly to 1.591 nm finally.

The theoretical value is acquired via the combination of the indentation depth model[1] and the surface roughness model. The following picture is the comparison

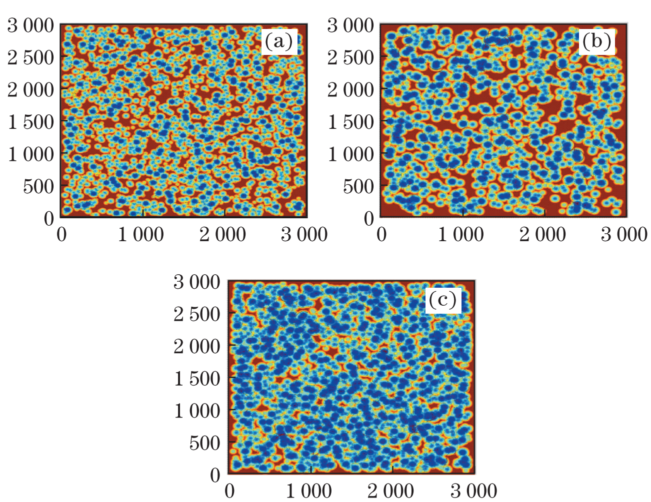

Fig. 2. Simulation of the indentations formed by the different type diamond particles.

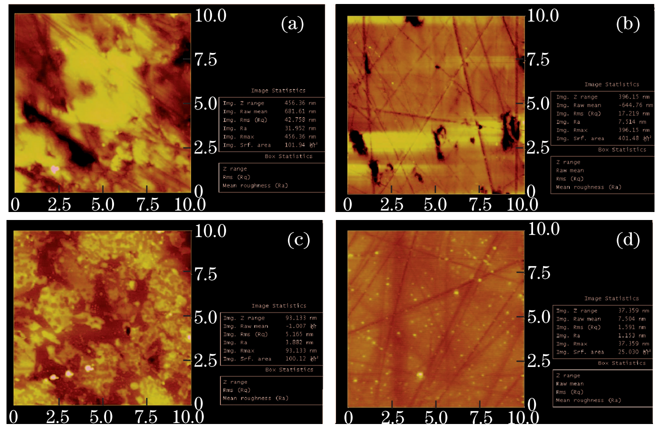

Fig. 3. AFM testing results comparison: (a) W7 fabrication result: RMS = 42.758 nm; (b) W5 fabrication result: RMS = 17.219 nm; (c) W3.5 fabrication result: RMS = 5.265 nm; (d) W1.5 fabrication result: RMS = 1.591 nm.

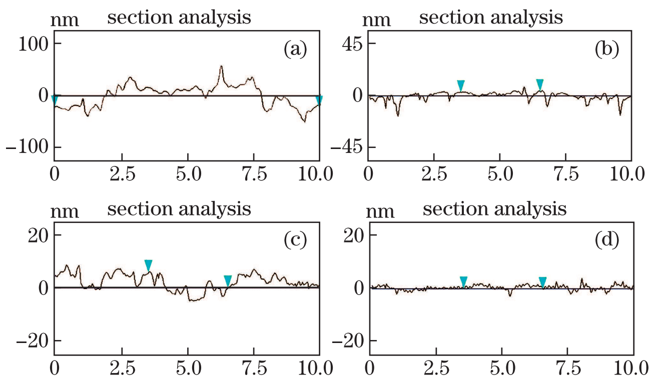

Fig. 4. Profile changing curves by using different type pellets. (a) W7 pellet; (b) W5 pellet; (c) W3.5 pellet; (d) W1.5 pellet.

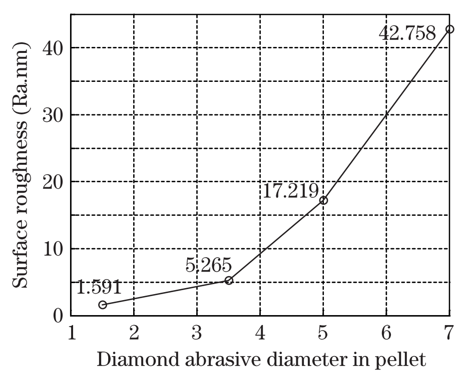

Fig. 5. surface roughness comparison in each working procedure.

result. The curve with the diamond marks in Fig. 6 is the experimental value (below), star marks represent the theoretical value (above).

The following analysis is finished according to Figs. 3 and 6:

1) For the traditional technology, W0.5 diamond slurry is used to get a better surface roughness below 2 nm. But the surface roughness of 1.153-nm RMS is gained with W1.5 pellet, which indicates that a better surface quality will be obtained with the larger diamond in pellet with the fixed abrasive technology.

2) According to the comparison of the simulation and experiment, the trend of the surface roughness curve can be seen that the workpiece surface roughness increases in e-exponential function with the abrasive particle diameter.

3) In the whole experiment, it is found that the fitness between the pellet surface and the workpiece has obvious influence on the workpiece surface roughness. The breaking-on procedure on the pellet surface is necessary before the fabrication.

4) In Figs. 3(b) and (d) , the obvious scratch on the workpiece surface is observed. There are two main reasons via analysis: (1) There are many larger diameter diamond particle than standard level existing in the pellets, so the much more stricter procedure should be introduced in producing pellets; (2) The emerging scratch is caused by the leftover abrasive particles in the last fabrication procedure. The most effective measure is to wash the workpiece seriously between the fabrication procedures.

5) The theoretical values are smaller than the experiments in Fig. 6, and the error ratios between the simulations and experiments are 5.97%, 3.19%, 3.59%, 37.37% respectively. The bigger diamond beyond standard is the main reason, which causes the bigger surface roughness. But the situation above does not get involved in the simulation.

6) Under the condition in which the experimental value is bigger than theoretical value, the result of W7 pellet is much more obvious, whose error ratio is 37.37%. There are much more diamond particles whose diameter is bigger than 7 μm. The removal on the SiC mirror fabricated with this type pellet is brittleness removal, which is the material crack phenomenon. The material crack causes a deeper indentation than the simulation, which has serious influence on the surface roughness.

The geometry characteristic parameters of the optical fabrication surface is an very important index of evaluating the optical mirror surface quality. The statistical parameters, such as RMS and PV values of the surface profile, are used to describe the SiC mirror surface. The evaluating methods above are all based on the Euclidean geometry whose dimension is integer, in which lots of valuable information are filtered automatically except for some few info, so the parameters left cannot reflect the actual situation of the project[8−10].

But as a new mathematical tool, the fractal theory emphasizes particularly on the self-comparability and self-affine[11−13] , which can be applied on the mechanical surface perfectly. Lots of research results are obtained via using this powerful mathematical tool.

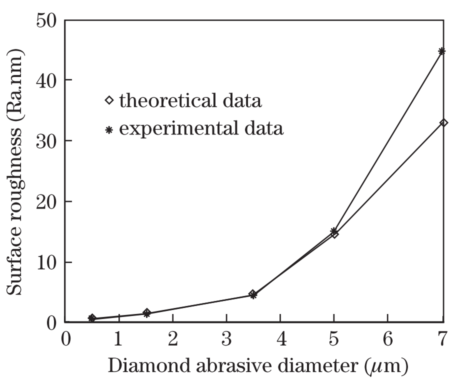

Fig. 6. surface roughness curve of different type pellets.

The process of fabricating the SiC mirror with the fixed abrasive technology is thousands of micro-cutting course with diamond particles which distributes randomly on the pellet surface. The micro-structure of the SiC mirror surface will be invariant when the fabrication time is long enough. Generally, the surface fractal dimension will be a stable value.

The Weierstrass-Mandelbrot (W-M) function in the fractal theory has the character of continuity, not differential everywhere, which has the advantages of describing the optical fabrication surface. It is denoted as

$$Z(x) = l^{D-1} \sum_{n-n_1}^{\infty} \frac{\cos 2\pi\gamma^n x}{\gamma^{(2-D)n}} \quad (1 < D < 2,\ \gamma > 1), \quad (2)$$

where $Z(x)$ is the profile sag value of the fabricating surface; x is the testing coordinate of the fabricating surface; l is the characteristic length coefficient; D is the fractal dimension; γ^n is the module of space frequency, which is corresponding to the reciprocal of the fabricating surface wavelength. It decides the surface frequency spectrum, which lies on the sampling length.

The calculation of the fractal dimension is the key problem of describing the surface profile fractal character. The methods of calculating fractal dimension have structure function method, power spectrum method, box-counting method, wavelet method and so on. But not every method is good at calculating the fractal dimension. For example, the power spectrum method is suitable for describing the self-affine fractal curve, but its exponential relationship is not obvious and the error is worse when it is applied on describing the surface profile. The box-counting method using extension is wide, but the result of applying on self-affine fractal research is not good. However, the structure function method in which the standard profile curve is the W-M fractal function is perfect on the stability and veracity of calculating the fractal dimension. Because of its clear physical meaning, high calculating precision and simple calculating process, the structure function is our option to calculate the fractal dimension of the SiC mirror fabricated with the fixed abrasive technology.

For a certain profile curve of the optical fabrication surface, the structure function is defined as the increment of the variance[14]. It is denoted as

$$\begin{aligned} H(\nu) &= \left\langle [Z(x+\nu) - Z(x)]^2 \right\rangle \\ &= \int_{-\infty}^{\infty} H(\theta)(\mathrm{e}^{\mathrm{i}\theta\nu} - 1)\mathrm{d}\theta, \end{aligned} \quad (3)$$

where ν is random increment of x, is the space average, and $H(\theta)$ is the power spectrum of W-M function.

The discrete power spectrum of W-M function is shown as

$$H(\theta) = \frac{l^{2(D-1)}}{2\ln\gamma} \frac{1}{\theta^{5-2D}}. \quad (4)$$

With the combination of Eqs. (3) and (4),

$$H(\nu) = Bl^{2(D-1)}\nu^{4-2D}, \quad (5)$$

where

$$B = \frac{\Gamma(2D-3)\ln[(2D-3)\pi/2]}{\ln\gamma(4-2D)}. \quad (6)$$

Equation (5) indicates that the structure function is the power function, so the structure function is a beeline in log-log coordinate system. The experimental sag $Z(x)$ is inputted into the computer in solving the equation, the sampling interval is Δt, the sampling number is N. $Z(x_i)$ is rewrote as Z_i, where $\nu = n \cdot \Delta t$. So the discrete structure function is denoted as

$$H(\nu) = \frac{1}{N-n}\sum_{i=0}^{N-n}(Z_{i+n} - Z_i)^2. \quad (7)$$

Whether the structure function obeys the rule of exponential distribution in a certain extension is analyzed via plotting the $H(\nu)$-ν curve in log-log coordinate system. If it obeys the exponential distribution and the local linear zone exists obviously, it indicates that $Z(x)$ has the fractal character in this local linear zone. If not, it indicates that $Z(x)$ does not have the fractal character. Not having the fractal character in the calculation result shows that the final surface roughness fabricated with the fixed abrasive technology is perfect.

For analyzing the experimental profile in Fig. 4 with the structure function, the corresponding structure function curves are obtained according to profile curves in Figs. 4(a)–(d). The results are displayed in Fig. 7 in log-log coordinate system.

In Fig. 7, it is obvious that the linear character of the structure function curve only exists in a lesser local zone, and the rest zone surges obviously. So we can come to an conclusion that as far as the experiment results are concerned, the SiC mirror fabricated with the pellets does not have the obvious fractal character, which is difficult to describe the mirror surface with a smaller fractal dimension. From the other point of view, the facility of obtaining a better surface roughness with the fixed abrasive technology makes the structure function complicated. In addition, because the polishing time is short, the experiment result proves that the fixed abrasive technology has the advantage of fast-polishing in the other point of view.

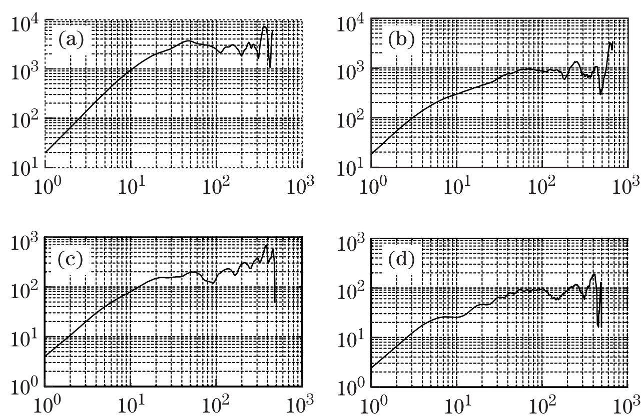

Fig. 7. Structure function of the surface profile fabricated with pellets. (a) W7 pellets; (b) W5 pellets; (c) W3.5 pellets; (d) W1.5 pellets.

In conclusion the letter is based on the high frequency evaluation of the SiC mirror fabricated with the fixed abrasive technology. The computer simulation on the surface roughness is carried out in microcosmic model. Via the comparison of the simulation and experiment, the surface roughness result shows that the error ratios are 5.97%, 3.19%, 3.59%, and 37.37%, respectively, by using different type pellets. Also the reason of the error is analyzed at the same time. In addition, the fractal theory is applied on the analysis of the optical mirror surface fabricated with pellets in the short time. It is found that the mirror surface fabricated with the pellets does not have the obvious fractal character. So we come to a conclusion that the fixed abrasive technology can polish the SiC mirror to a better surface roughness quickly. It is suitable for the fast surfacing in fabricating the SiC mirror.

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