Machining position-attitude optimization in Magnetorheological Finishing (MRF) of off-axis aspheric

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Abstract

The complex manufacturing features of off-axis aspheric make it become a difficult issue in modern optical fabrication. The distinct technical advantages of Magnetorheological Finishing (MRF) tend to achieve high-precision and high-efficiency fabrication of off-axis aspheric. Two machining position-attitude models are proposed in MRF process, which refer to parent mirror coordinate position-attitude model (PCPAM) and child mirror coordinate position-attitude model (CCPAM). Their machining ability, machining difficulty, and machining accuracy are both analyzed and simulated. The results indicate that CCPAM is much more excellent in the machining ability, the machining difficulty as well as the machining accuracy, thereby would be the optimized one. To demonstrate its advantage and feasibility, a rectangle off-axis aspheric mirror is figured with CCPAM. In two MRF iterations of 9 hours, the surface form accuracy improves to 14nm RMS finally.

1 Introduction

With the development of modern technology, the off-axis optical system is more and more widely used in serious applications. MRF is a high-deterministic and high-precision optical manufacturing method [1]. It realizes the material removal based on the shear effect of MR fluid under high-gradient magnetic field, and the accuracy amount of material removal is dominated by varying the dwell time. The technical advantages of MRF make it as a good choice for the fabrication of off-axis aspheric. This paper focuses on the key problem in off-axis aspheric fabrication and aims at high-precision and high-deterministic MRF of off-axis aspheric.

2 Machining position-attitude model

The machining position-attitude model is the position-attitude of an optical element adopted in the fabrication process. Due to its machining features, varies types of machining position-attitude model can be established in off-axis aspheric fabrication.

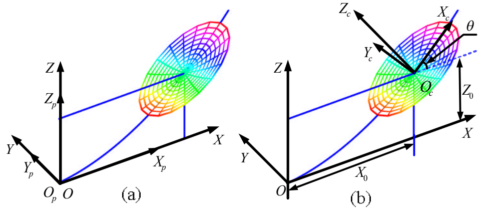


Fig. 1 Machining position-attitude model. (a) PCPAM; (b) CCPAM

As shown in Fig.1, two different machining position-attitude models are proposed in MRF of off-axis aspheric, which refer to Parent mirror Coordinate Position-Attitude Model (PCPAM) and Child mirror Coordinate Position-Attitude Model (CCPAM). The difference of two models is the definition of machining coordinate system, in PCPAM the machining coordinate system is in coincidence with the mirror coordinate system $OXYZ$, but in CCPAM it locates at the geometrical centre.

The off-axis aspheric in PCPAM can be expressed as:

$$z(\rho)=\frac{c\rho^2}{1+\sqrt{1-(1+k)c^2\rho^2}} \tag{1.1}$$

where c is the paraxial curvature, k is the conic constant, and $\rho=\sqrt{x^2+y^2}$ 。
However, it can be expressed in different way in CCPAM, which are as follows [2]:

$$z_c(x_c,y_c)=\frac{\gamma}{\beta+\sqrt{\beta^2-\alpha\gamma}} \tag{1.2}$$

$\tan\theta=\dfrac{c\cdot x_0}{\sqrt{1-(k+1)\cdot c^2\cdot x_0^{\ 2}}}$, $\alpha=c(1+k\cos^2\theta)$, $\beta=\dfrac{1}{\sqrt{1+k\sin^2\theta}}-ck\sin\theta\cos\theta x_c$,
$\gamma=c(1+k\sin^2\theta)x_c^{\ 2}+cy_c^{\ 2}$.

3 Model analysis

3.1 Machining ability

To compare the machining ability, their distribution domains of off-axis aspheric figured in this paper are simulated, as shown in Tab.1. It is found that the CCPAM can reduce the sagitta of off-axis aspheric, and a less distribution domain is needed in CCPAM. Based on the results, it indicates that the stronger machining ability can be obtained when CCPAM is adopted in MRF of off-axis aspheric.

Tab. 1 Distribution domain in different position-attitude models

	AXIS X	AXIS Y	AXIS Z	AXIS A	AXIS B

	max	min	max	min	max	min	max	min	max	min
PCPAM	182	-182	336.9	0	36.93	0	0.199	0	0.109	-0.109
CCPAM	182	-182	150	-150	12.12	0	0.083	-0.093	0.108	-0.108

3.2 Machining difficulty

The manufacturability of aspheric is an interesting issue which can be used to estimate its machining difficulty. Foreman [3, 4] proposed that the manufacturability is based on the hypothesis that the difficulty involved in fabricating an aspheric surface is directly related to the rate at which the radius of curvature along a tangential profile of the surface changes with distance from the optical axis. Based on this definition, we can also estimate the machining difficulty of the two models when the same off-axis aspheric is fabricated. For example, the maximum and minimum tangential radius of curvature is 1868.36mm and 1654.33mm, respectively. Then we can calculate its machining difficulty in PCPAM and CCPAM is 0.6185 and 0.6076, respectively. This result indicates that CCPAM can decrease the machining difficulty compared to PCPAM, which is prone to high-precision off-axis aspheric fabrication.

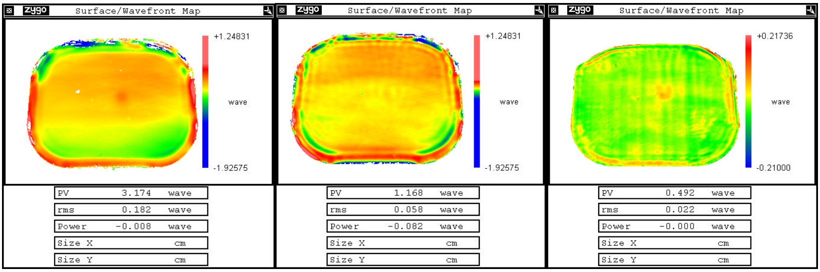
3.3 Machining accuracy

The machining accuracy not only relies on the stability of influence function and the accurate realization of dwell time, but also the accuracy of machine tool as well as machining position-attitude. The rigid theory is adopted to establish the machining accuracy model, and different positioning error is input to observe the normal positioning error (NPE) and tangential positioning error (TPE) of the “polishing tool”. The simulations are conducted by using classical one-factor-at-a-time (OFAT), and the different affecting laws are revealed. The object adopted is also the experimental off-axis aspheric, and the final results show that NPE is the key factor of positioning error caused by X, Y, and C directional position-attitude error, and TPE is the key factor of positioning error caused by Z, A, and B. As the main positioning accuracy in CCPAM is much more excellent than in PCPAM with the same position-attitude error, the CCPAM should improve the figuring accuracy of off-axis aspheric in MRF.

4 Experiments

A rectangle off-axis aspheric whose size is 364mm*300mm is figured by UPF700-7 developed ourselves to verify the analysis. All the results are measured by null test in which Zygo interferometer is used, and CCPAM is adopted in the MRF process.

The initial surface error is generated by CCOS with 3.174λ PV and 0.182λ RMS ($\lambda = 632.8nm$), as shown in Fig. 2(a). Two iterations of MRF in about 6 hours are conducted, and the surface form error improves to 1.168λ PV and 0.058λ RMS, as shown in Fig. 2(b). A further CCOS process is induced to smooth the defects in order to improve the final figuring accuracy, and a second MRF run is conducted later. The process takes about 3 hours, and the final surface accuracy in clear aperture is 0.022λ RMS (14nm), as shown in Fig. 2(c).



(a) (b) (c)

Fig. 2 Surface error of off-axis aspheric. (a)initial surface error; (b)1st MRF process ;(c)2nd MRF process

5 Conclusions

The machining position-attitude optimization is important in off-axis aspheric fabrication, and the CCPAM in MRF of off-axis aspheric is demonstrated. It can reduce the machining difficulty; improve the machining ability and accuracy, which is propitious to figure high-precision off-axis aspheric in MRF process.

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