Ultra-smooth combined polishing process for nickel-phosphorus alloy components

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KEYWORDS: Nickel-phosphorus alloy, Magnetorheological polishing, Small tool polishing, Combined polishing process, Full-band error

As a metal coating material commonly used in optical components, nickel-phosphorus (NiP) alloy has excellent machinability, wear resistance and corrosion resistance, and is suitable for extreme ultraviolet optical systems. Single point diamond turning(SPDT) is the most typical processing method of nickel-phosphorus alloy, but it will leave periodic turning tool marks, resulting in poor roughness. Therefore, further ultra-smooth polishing is required after turning. In this paper, the ultra-smooth polishing process of nickel-phosphorus alloy is studied in detail, and a combined polishing process is proposed. By combining two polishing processes, magnetorheological polishing(MRP) and small tool polishing(STP), the full-band error convergence of nickel-phosphorus alloy can be realized effectively. Firstly, the polishing effects of magnetorheological polishing and small tool polishing on nickel-phosphorus alloy were studied respectively. Then, a nickel-phosphorus plane mirror with a diameter of 50mm was processed by combining these two polishing processes. The low-frequency surface error of Sq 0.012λ, mid-frequency roughness of Sq 0.730nm and high-frequency roughness of Sq 1.62nm were achieved. The method of combining magnetorheological polishing with small tool polishing proposed in this paper uses magnetorheological polishing to quickly remove the turning tool marks, reduce low and medium frequency errors, and then uses small tool polishing to clean the iron powder left by magnetorheological polishing, reduce medium and high frequency errors while maintaining low frequency surface accuracy. The experimental result shows that the combined polishing process has strong feasibility, and the processing effect is much better than that of the single polishing process, which broadens the optional route of ultra-smooth polishing of ultra-ultraviolet optical components.

NOMENCLATURE

λ: The wavelength of He-Ne laser used in the interferometer, λ=632.8nm.

1. Introduction

Nickel-phosphorus alloy coating is widely used in the surface modification of advanced optical mirrors, such as EUV collector. Nickel-phosphorus alloy has excellent machinability which can be used for infrared applications only by single point diamond turning. However, SPDT will leave periodic spiral tool marks on the surface, which will produce diffraction and stray light in reflection application, limiting the use of this component in the field of visible light and ultraviolet light. Therefore, it is necessary to use the ultra-smooth polishing process to remove the tool marks after SPDT and further improve the surface quality.

At present, researchers have used a variety of polishing processes to polish nickel-phosphorus alloys, such as float polishing [1], electrochemical polishing [2], magnetorheological polishing [3-5] and small tool polishing [6], and have achieved good polishing effect. However, most studies only use white light interferometer to evaluate the roughness, which cannot satisfy the requirement of extreme ultraviolet optical components for full-band error [7].

In this paper, according to the sampling frequency of different measuring equipment, the low, medium and high frequency surface roughness are divided. The low spatial frequency roughness(LSFR) is measured by laser interferometer(Equipment: Zygo-Verifire). The size of the workpiece is 50 mm, and the number of sampling points is about 500×500. Therefore, the spatial frequency range that can be evaluated is $2.0e^{-5}$ ~ $5.0e^{-3}$ μm^{-1}. The medium spatial frequency roughness (MSFR) is measured by white light interferometer(Equipment: Zygo-Nexview NX2). The selected objective lens is 50× and the zoom multiple is 1×. The measurement range is 0.174×0.174mm and the number of sampling points is 1000×1000. Therefore, the evaluated spatial frequency range is $5.8e^{-3}$ ~ $2.9\mu m^{-1}$. Atomic force microscopy (Equipment: Bruker-Dimensional FastScan Bio) is used to measure high spatial frequency roughness (HSFR). The measurement range is 5x5μm and the number of sampling points is 256×256. So the evaluated spatial frequency range is 0.2 ~ $25.6\mu m^{-1}$. By combining the data from these three sources, the full-band error evaluation with spatial frequency of $2e^{-5} \sim 25.6\mu m^{-1}$ can be realized.

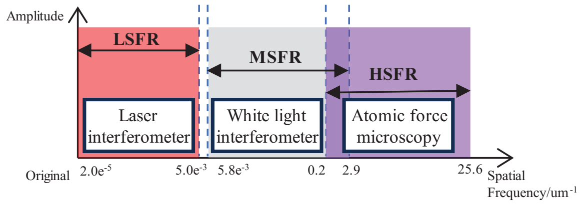


Fig.1 Division of surface error frequency band

In this paper, the combined polishing process of magnetorheological polishing and small tool polishing is studied to polish the nickel-phosphorus alloy components. By removing the turning tool marks and improving the full-band surface error, the processed components can reach the application level of extreme ultraviolet optics. In the second chapter, the experimental settings are introduced in detail, including turning conditions, magnetorheological polishing conditions and small tool polishing conditions. In the third chapter, all the experimental results are analyzed.

2. Experimental settings

The commercial electroless nickel-phosphorus plating with the phosphorus content of 11.4wt% and thickness of 150 μm was applied to 7075 aluminum substrates with a diameter of 50 mm which is summarized in Table 1. It is a kind of amorphous nickel-phosphorus alloy with high phosphorus composition, whose hardness is low and is suitable for single point diamond turning. Furthermore, it is non-magnetic and does not affect the magnetic field distribution, so it can be processed by magnetorheological polishing.

Table 1 Parameters of the experimental workpieces

Phosphorus content	Plating thickness	Substrates material	Diamater
11.4wt%	150μm	7075 aluminum	50mm

The workpieces are turned by a commercial Moore Nanotech 250UPL ultra-precision machine lathe and the SPDT machining parameters are showed in the Table 2. Two nickel-phosphorus plane mirrors were processed, one for magnetorheological polishing and the other for small tool polishing. The nickel-phosphorus composition and turning parameters of the two nickel-phosphorus mirrors were exactly the same. And the processing results are shown in Fig. 2.

Table 2 Machining parameter of SPDT

Spindle speed	Feed speed	Tool nose radius	Cutting depth
1000rpm	1mm/min	0.015mm	10μm

It can be clearly seen that periodic tool marks have been left on the surface of the workpiece, and the residual height is about 2nm. A peak point with the frequency of $1\mu m^{-1}$ can be seen in the PSD curve. According to Fig. 5 and Fig. 6, the MSFR and HSFR after SPDT have reached nanometer-level accuracy, which can fully meet the requirement of infrared optics.

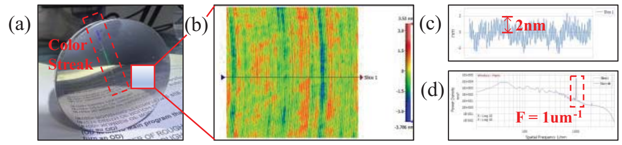
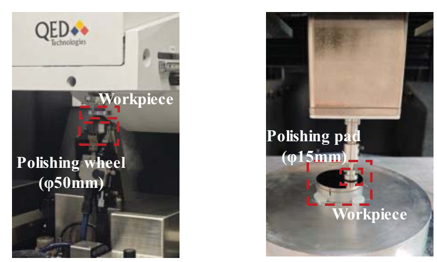


Fig.2 Turning tool marks diagram (a) physical map and color streak, (b) white light interferometer image, (c) Slice 1 section line, (d) PSD curve

After SPDT, the workpiece is polished by magnetorheological polishing and small tool polishing respectively to study the characteristics of the two polishing processes. The specific polishing processing parameters have been obtained by the pre-experiment, as shown in Table 3 and Table 4. Specifically, the magnetorheological machine lathe is Q-flex 300 MRF Polishing Machine of QED Technologies International, LLC from the United States, and the magnetorheological fluid is commercial D11 and C30 polishing fluid. D11 is used to quickly remove tool marks and improve the surface accuracy due to its high removal rate to nickel-phosphorus alloys. C30 is used to uniformly remove the material, thereby improving the surface roughness. And the small tool polishing lathe is APP-600 Polishing Machine of LangXin (Suzhou) Precision Optic Co. Ltd from China, and the commercial S45 polishing fluid is selected as the polishing fluid whose abrasive is silica and the nominal diameter of the grain is 45nm. The pH of the polishing fluid is 10, so the essence of small tool polishing is chemical mechanical polishing. The polishing results are presented and analyzed in Chapter 3.



(a) (b)

Fig.3 Polishing scene (a) magnetorheological polishing, (b) small tool polishing

Table 3 Processing parameters of magnetorheological polishing

Machine Tool	Polishing fluid	Wheel diameter	Magnetic field	Pressing depth
Q-Flex300	D11/ C30	50mm	2500GS	30%

Table 4 Processing parameters of small tool polishing

Machine Tool	Polishing fluid	Tool diameter	Tool rotation speed	Pressure
APP-600	S45	15mm	90rpm	0.05Mpa

3.Results and discussions

3.1 Magnetorheological polishing

By comparing Fig.5 (a) and (b), after magnetorheological polishing, the low and medium frequency roughness is obviously improved, but the high frequency roughness is seriously deteriorated. By analyzing the results from atomic force microscopy, it can be found that there are many white spots on the surface of the workpiece which are fine iron powder embedded by magnetorheological polishing. And it is difficult to remove the embedded iron powder by conventional rinse methods such as cloth wiping or ultrasonic cleaning. Therefore, it is necessary to take iron powder cleaning measures to improve the high frequency roughness of the surface after magnetorheological polishing, so that the workpiece can meet the application requirements of extreme ultraviolet light optics.

After magnetorheological polishing, the turning tool marks is completely removed, and there is no color streak on the surface of the workpiece, which can also be reflected from the disappearance of the peak value of $f = 1\mu m^{-1}$ in the PSD curve, indicating the high efficiency of magnetorheological polishing. Therefore, using magnetorheological polishing as the first polishing process after turning can improve the processing efficiency.

3.2 Small tool polishing

According to Fig.6, after small tool polishing, the low frequency surface error has almost no change, the medium and high frequency roughness of the workpiece has been improved, and the turning tool marks still exist, but the depth is slightly reduced. This is due to the low efficiency of the small tool polishing, and scratches appear on the surface of the workpiece. After polishing, the surface is clean and few abrasive particles are embedded. Therefore, small tool polishing can be used as the next process of magnetorheological polishing. While maintaining the low frequency surface accuracy, the residual iron powder of MRP can be removed, and the medium and high frequency roughness of the workpiece surface can be further improved.

3.3 Combined polishing process

According to Fig.5, after magnetorheological polishing and small tool polishing, the surface accuracy of Sq 7.535nm(0.012λ), the medium frequency roughness of Sq 0.730nm and the high frequency roughness of Sq 1.62nm are obtained. The full-band error is greatly improved, the turning tool marks are completely removed, and the embedded impurity seen under the atomic force microscope is completely cleaned. The workpiece can satisfy the application requirements of extreme ultraviolet light optics.

Fig. 4 Nickel-phosphorus surface after combined polishing process

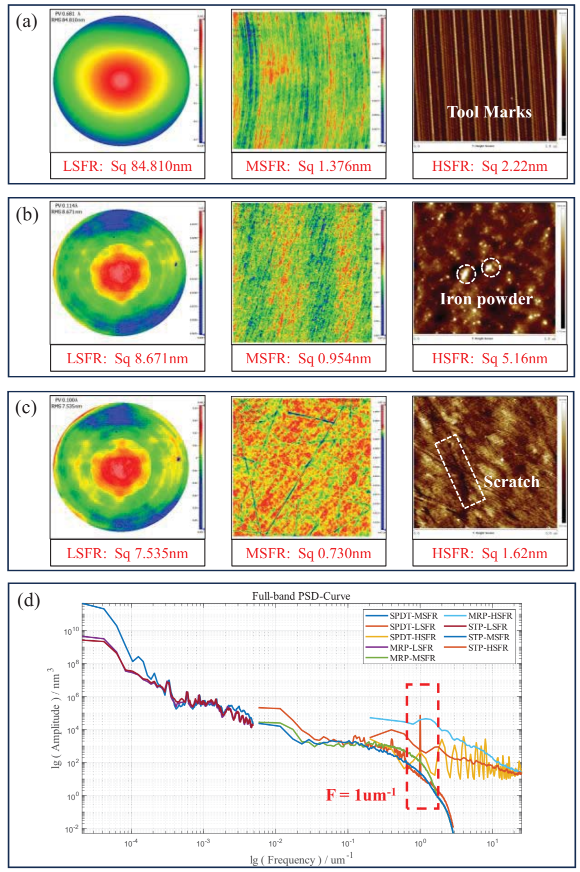


Fig.5 Results of combined polishing process (a) single point diamond turning results, (b) magnetorheological polishing results, (c) small tool polishing results, (d) PSD curve of combined polishing process

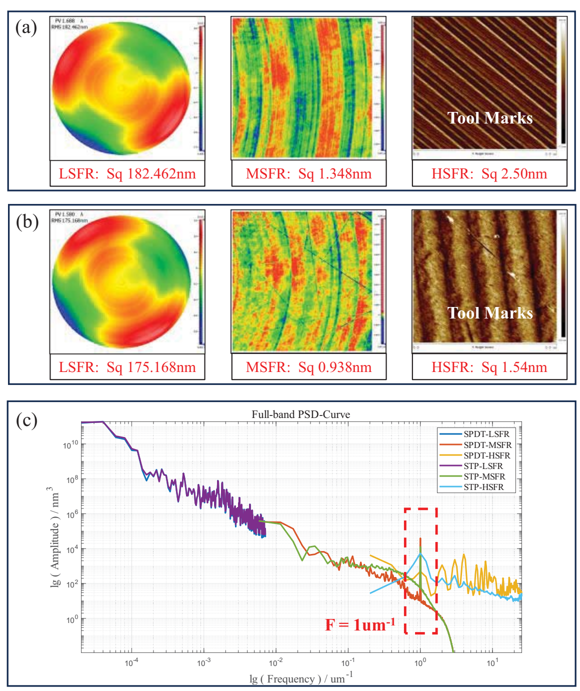


Fig.6 Results of single small tool polishing (a) single point diamond turning results, (b) small tool polishing results, (c) PSD curve of small tool polishing

4. Conclusions

In this paper, the combined polishing process of magnetorheological polishing and small tool polishing is used to polish the nickel-phosphorus alloy components. Through the comparison experiment of single polishing process and the combined polishing process of the nickel-phosphorus alloy plane mirrors, the following conclusions are drawn:

(1) Only by single point diamond turning, medium frequency roughness of less than Sq 1.5nm and high frequency roughness of less than Sq 2.5nm can be obtained on nickel-phosphorus alloy surface.

(2) Magnetorheological polishing can improve the low frequency and medium frequency roughness of the surface of nickel-phosphorus alloy, and quickly remove the turning tool marks left by SPDT.

(3) Small tool polishing can improve the medium frequency and high frequency roughness of the workpiece surface without deteriorating the low frequency surface accuracy, and at the same time remove the residual iron powder on the workpiece surface left by magnetorheological polishing.

(4) Through the combined polishing process of magnetorheological polishing and small tool polishing, the convergence of the full-band error of the nickel-phosphorus alloy surface can be realized, and the surface shape accuracy of 0.012λ, the medium frequency roughness of Sq 0.730nm, and the high frequency roughness of Sq 1.62nm can be obtained.

ACKNOWLEDGEMENT

This work was supported by the National Key R&D Program of China under Grant 2022YFB3403301, the National Natural Science Foundation of China under Grants U22A20207, 52475477 and 52335010.

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