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Ultra-precision optical surface fabricated by hydrodynamic effect polishing combined with magnetorheological finishing

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ABSTRACT

In the traditional machining method, the surface quality will get worse during the surface figuring process while the surface figure will be destroyed after ultra-smooth polishing process. To obtain an ultra-precision optical surface, these two processes are conducted iteratively which is time-consuming and unstable. A new fabrication method combined with the magnetorheological finishing (MRF) and hydrodynamic effect polishing (HEP) technology was presented. The surface figure error can be quickly depressed by MRF due to its high deterministic figuring ability, while the surface quality will get worse due to the introduction of MRF polishing marks. The material removal of HEP depends on the chemical interaction between the nanoparticles and workpiece in elastic mode, and an ultrasmooth surface with sub-nanometer level can been easily achieved with the surface figure well maintained. The experiment results show that the MRF polishing marks are removed clearly and the surface figure is well maintained after HEP process. Combined with MRF, a quartz glass with initial figure accuracy of 0.415 λ RMS (λ = 632.8 nm), mid-spatial frequency and high spatial frequency roughness of 0.407 nm RMS and 0.525 nm RMS has been improved to figure accuracy of 0.05 λ RMS, mid-spatial frequency and high spatial frequency roughness of 0.268 nm RMS and 0.163 nm RMS. Power spectral density (PSD) analysis indicated that the surface spatial frequency error has all been greatly depressed. It demonstrates HEP is an effective ultra-smooth polishing method with good ability to maintain the initial surface figure.

1. Introduction

Ultra-precision optical surface, which calls for not only the extremely low surface figure error but also the high requirement of surface/subsurface quality, has wide application in modern optical system. The errors in different frequency bands have different influences on the performance of the optical components [1,2]. Extreme ultraviolet lithography (EUVL) is considered as the next most promising lithography technology. The EUVL-mirrors call for extremely high requirements in different frequency bands representing for the highest optical manufacture process level [3]. According to the spatial resolution, surface error of the optical component can been divided into low-spatial frequency roughness (LSFR), mid-spatial frequency roughness (MSFR) and high-spatial frequency roughness (HSFR). LSFR, referred as surface figure accuracy, will

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cause abreactions leading to transfiguration of the image surface. MSFR related to the surface waviness will lead to near-angle scattering decreasing the contrast of the optical system, while HSFR related to the surface roughness will generate wide-angle scattering resulting in optical loss [4]. In EUVL system, LSFR is the surface errors in the frequency smaller than $1\,mm^{-1}$, while MSFR and HSFR are the errors with the frequency $1\,mm^{-1} \sim 1\,\mu m^{-1}$ and $>1\,\mu m^{-1}$, respectively [5,6]. To obtain the surface accuracy in different frequency bands, different polishing methods have been employed. Deterministic optical figuring techniques were developed to improve the LSFR, such as computer-controlled optical surfacing (CCOS) [7], fluid jet polishing (FJP) [8], ion beam figuring (IBF) [5] and magnetorheological finishing (MRF) [9]. Different ultra-smooth polishing techniques were developed to control of MSFR and HSFR, such as micro-jet polishing [4], chemical-mechanical polishing (CMP) [10] and float polishing [11]. To the best of the author's knowledge, the surface quality will get worse during the surface figuring process while the surface figure will be destroyed after ultra-smooth polishing. To obtain an ultra-precision optical surface, the figuring and smooth processes are conducted iteratively which is time-consuming and unstable. Wang [4] has fabricated the ultra-precision optical surface by the iteration of ion beam figuring (IBF) and micro-jet polishing (MJP) technology. In the process, the surface is processed by IBF to correct surface figure (LSFR), while the MJP is introduced to reduce MSFR and HSFR. These two processes were conducted iteratively to achieve high surface accuracy in different frequency bands.

Therefore, how to find an effective way to fabricate the ultrasmooth surface without destroying the surface figure becomes very meaningful. Hydrodynamic effect polishing (HEP), a non-contact machining process, can realize the processed surface roughness as smaller as atomic level [12]. The MSFR and HSFR can be greatly improved when the surface was polished by HEP. HEP possesses the advantage of the stable material removal, high smooth ability and fabrication of defect-free surface. All these advantages distinguish HEP as the final procedure for ultra-precision optical components fabrication. With uniform-polishing process the LSFR maintenance ability was investigated in this paper. It is known to all of us that MRF has the strong deterministic figuring ability. However the MRF polishing marks on the processed surface will greatly increase the MSFR and HSFR. In our previous research, we have found that the MRF marks can be removed by the nanoparticle jet polishing method with the similar material removal mechanism to HEP [13]. However the polishing marks cannot be removed clearly and the improvement of the surface quality is not so obviously.

In this paper, an ultra-precision optical surface fabricated by HEP combined with MRF technology was investigated experimentally. The surface figure error was firstly corrected by MRF, and then successively smoothed by HEP. The LSFR, MSFR and HSFR of the processed surface were analyzed respectively.

2. Principle of the combined technology

2.1. MRF deterministic figuring technology

MRF is an ultra-precision deterministic polishing method developed to overcome the fundamental limitations of traditional polishing techniques. The material is removed in plastic flow by shear stress under a magnetic field. Based on the theory of the computer-controlled optical surface, MRF has the advantages of stable material removal, high convergence efficiency and high adaptability to all kinds of complex surface. When the physical parameters determined the removal function $r(x, y)$ are hold stably, the material removal $h(x, y)$ depends on the removal function and the dwell time $t(x, y)$ on a certain part of the surface. Then the deterministic figuring process can be represented by the following the two dimensional convolution [14]:

$$h(x, y) = r(x, y) * *t(x, y) \tag{1}$$

In practical optical fabrication, the removal function was obtained by the fix-point polishing method under a certain dwell time. The initial surface figure error will be measured first and then the material removal can be evaluated. According to Eq. (1), the dwell time can be solved from the inverse convolution. When the tool moves along the target path with different velocity, the surface figure error can be corrected. MRF, as a novel and fast deterministic figuring method, has been widely used for the manufacture of high-precision optics. In MRF, the material is removed in the form of plastic flow by high shear stress under a magnetic field. However, the main limitation has been the wavy microstructure caused by plastic flow which are called MRF marks and which produce diffraction effects and stray light. The MRF marks have great influence on the improvement of the surface quality. How to remove it without destroying the surface figure becomes very essential.

2.2. HEP ultrasmooth technology

In HEP ultrasmooth technology, the wheel is made up of a metallic core and a wearable polymer shell with certain elasticity. Nanoparticles with high adsorption are employed as the polishing medium. The wheel and workpiece are all submerged into the polishing slurry during the polishing process. A lubricated film will be established to separate the wheel from the workpiece when the wheel rotated at a certain speed, as shown in Fig. 1. A fluid dynamic pressure and shear stress zone will be established on the workpiece surface. The wheel-workpiece distance is about micrometers or tens of micrometers which is much larger than the average diameter of the nanoparticle. Nanoparticles are very small, and their general velocity is very slow. The kinetic energy of nanoparticles is not large enough to cause plastic deformation, so we can