Removal of single point diamond-turning marks by abrasive jet polishing

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Single point diamond turning (SPDT) is highly controllable and versatile in producing axially symmetric forms, non-axially-symmetric forms, microstructured surfaces, and free forms. However, the fine SPDT marks left in the surface limit its performance, and they are difficult to reduce or eliminate. It is unpractical for traditional methods to remove the fine marks without destroying their forms, especially for the aspheres and free forms. This paper introduces abrasive jet polishing (AJP) for the posttreatment of diamond-turned surfaces to remove the periodic microstructures. Samples of diamond-turned electroless nickel plated plano mirror were used in the experiments. One sample with an original surface roughness of more than 400 nm decreased to 4 nm after two iterations abrasive jet polishing; the surface roughness of another sample went from 3.7 nm to 1.4 nm after polishing. The periodic signatures on both of the samples were removed entirely after polishing. Contrastive experimental research was carried out on electroless nickel mirror with magnetorheological finishing, computer controlled optical surfacing, and AJP. The experimental results indicate that AJP is more appropriate in removing the periodic SPDT marks. Also, a figure maintaining experiment was carried out with the AJP process; the uniform polishing process shows that the AJP process can remove the periodic turning marks without destroying the original form. © 2011 Optical Society of America

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1. Introduction

Single point diamond turning (SPDT), which is categorized in ultraprecision micromachining technologies, possesses nanometric edge sharpness, form reproducibility, and wear resistance. With the rapidly growing demand for precision components such as optoelectronics products, Walter-type x-ray mandrels, and nonferrous metal mirrors, SPDT has become increasingly important for the manufacture of quality optical components with micrometer to submicrometer form accuracy and surface roughness in the nanometer range [1]. The main limitation has been the resulting microstructure, which is called SPDT marks and which produces a diffraction effect and stray light. For this reason, many components, including x-ray mandrels in particular, are hand postpolished to achieve both the form and texture required [2]. But hand postpolishing is extremely difficult on aspheres and free forms, which leads to an inevitable trade-off between quality of the surface texture achieved and destruction of the surface figure. Consequently, a method to eliminate the diamond-turning marks without destroying the form could be a required process going forward.

Many presently widely used polishing techniques, such as ion beam figuring (IBF), magnetorheological finishing (MRF), and computer controlled optical surfacing (CCOS), are not very fit for SPDT mark removal. Ion beam figuring has a strong selectivity in the polished materials, although it can produce a superfine surface [3]. The commonly used SPDT materials, such as nonferrous metals (including

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electroless nickel) and plastics, are not suitable for IBF. The same problems also exist with MRF and CCOS, for they can induce some nicks on the polished surfaces and destroy the forms, although they can remove the periodic signatures [4,5].

Abrasive jet polishing (AJP), as a novel deterministic precision optical manufacturing technique, was first presented by O. W. Fähnle at Delft University of Technology in 1998 [6]. In the AJP process, the homogeneously premixed polishing slurry is pumped by a low-pressured pump and sprayed onto the workpiece through a special nozzle to achieve polishing. The performance of the AJP process can be controlled by the components, concentration, and jet pressure of the slurry and also by the relative position and angle between the nozzle and workpiece [7]. Compared with traditional polishing methods, the AJP process has many advantages [8,9]. First, the slender jet will be less restricted by the shape or space of the workpiece, and it will be suitable for polishing various complex surfaces, especially for steep cavities. Second, the recycled polishing fluid will maintain the constant temperature of the workpiece, and it will weed out the machining debris automatically. Third, the slender jet will produce a very small machining spot and, consequently, has little edge effect, which is beneficial for polishing micro-optics. Finally, the tiny material removed can be controlled by an appropriate abrasive and particle size with the right flow velocity, which can produce highly precise surface forms.

In the work reported in this paper, the AJP process has been adopted to eliminate SPDT marks on different electroless nickel coated samples. The experimental results show that the AJP process can remove the periodic marks without destroying the forms. These applications will undoubtedly widen the use of single point diamond turned surfaces, as well as improving its performance in optical applications.

2. Experimental Setup

A. Seven-Axis Ultraprecision Freeform Polishing Machine

The AJP process investigation was conducted on a seven-axis ultraprecision computerized numerical control optical polishing machine produced by Zeeko Ltd. [10,11]. The machine contains three linear axes x, y, and z and four rotational axes A, B, C, and H. It can produce ultraprecise surfaces on a variety of optical materials and surface forms. Abrasive jet polishing does not have any direct contact with the workpiece. The slurry is ejected from the nozzle at a pressure no greater than 20 bars and attacks the surface of workpiece.

B. Experimental Procedures

In the present study, all the samples are electroless nickel coated on aluminum alloy substrates. Some of the samples will be roughly turned by SPDT with a roughness of hundreds of nanometers, while others will be finely turned with a roughness of less than 5 nm. After diamond turning, there will be SPDT marks appearing on the surfaces, and also a diffraction effect. Then the samples will be uniformly polished by the AJP process to remove the periodic marks left by the previous process. The marks on the samples will also be polished with MRF and CCOS to contrast the results with the AJP process. Finally, a figure maintaining experiment with a uniform AJP process will be carried out to validate its figure maintaining capability.

3. Machining Process

A. Single Point Diamond Turning

In SPDT, nonferrous metals and plastics are widely used, among which electroless nickel of an amorphous structure is one excellent material. In addition, electroless nickel has also been widely used in industrial and optical applications [12,13]. In our experiments we prepared electroless nickel plated on the plano aluminum alloy, A6061. Nickel plating was done for eight hours, and the thickness of the electroless nickel was approximately 100 μm. It contains about 10% phosphorus, which is widely used in the electroless nickel area and also in the optical application area, with an appropriate hardness for machining (the Vickers-hardness value equals about 550). The SPDT parameters for rough samples and fine samples are given in Table 1.

B. Abrasive Jet Polishing

In the AJP process, the polishing liquid containing 6 wt.% abrasive grains of alumina (Al_2O_3) and other additives was used in the experiments. The diameter of the nozzle was 1 mm. In our experiments a raster polishing path was chosen as the scanning mode, and the scanning step size was 0.2 mm. Some of the parameters used in the experiments are given in Table 2.

Table 1. SPDT Parameters for Different Samples

	Rough Samples	Fine Samples
Spindle speed (rpm)	1000	1000
Feed rate (mm/ min)	10	5
Depth of cut (μm)	5	1
Radius of tool edge (mm)	0.54	0.54

Table 2. AJP Parameters for Different Samples

	Rough Sample		
	First Polishing	Second Polishing	Fine Sample
Incidence angle (degrees)	60	60	60
Jet pressure (bars)	10	5	3
Particle size (μm)	1.5	1.5	1
Incidence distance (mm)	10	10	10
Removal depth (μm)	0.8	0.2	0.2

4. Results and Discussion

A. AJP Process

Figures 1(a)–1(c) show the views of microstructures of one rough sample at different steps of the use of AJP, which were obtained by a ZYGO NewView 200. Before the AJP process, the SPDT marks of the sample can be clearly seen in Fig. 1(a). The initial surface roughness, Ra, is more than 400 nm. After the first polishing process, almost all the SPDT marks are cleared away, and the surface roughness, Ra, decreases to about 8.6 nm, which is much smaller compared to the previous polishing process. From Fig. 1(b), we can find plenty of pits appearing in the polished surface. They are likely attributed to the collisions of the abrasive particles. After the second polishing process, the sample surface gets much smoother, with a roughness of Ra = 4 nm [see Fig. 1(c)]. Fewer pits appear in the polished surface compared to the first polishing process. It can be predicted that the surface can be improved further by optimizing the experimental parameters and/or controlling the material removal amount if required [14].

To estimate the surface quality and validate the focusing capability of the sample before and after the AJP process, we introduced power spectrum density (PSD) analysis to visualize the complex spatial frequencies, which is shown in Fig. 2. Because of the existing of periodic SPDT marks, there are some peaks on the original PSD curve. After polishing, the peaks disappear and the PSD curves decrease. From the PSD curves we can conclude that after two iterations of the AJP process, the SPDT marks have been eliminated thoroughly and the surface has been greatly improved.

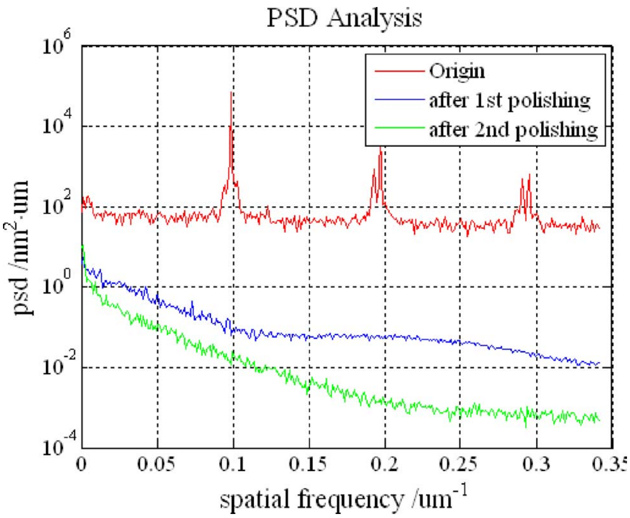


Fig. 2. (Color online) Analysis of PSD before and after polishing processes.

B. Comparison of Three Different Polishing Methods

We accomplished polishing processes with AJP, MRF, and CCOS on finely turned electroless nickel mirrors (see Figs. 3(a)–3(d)). The initial roughness of the samples is about 3.7 nm, with SPDT marks clearly showing in Fig. 3(a). After the AJP process, the SPDT marks are eliminated, and the surface roughness Ra = 1.4 nm, which is much less than the initial value. The high spatial frequencies are eliminated from the surface, substituted by a randomized microstructure as shown in Fig. 3(b). Figures 3(c) and 3(d) are respectively polished by MRF and CCOS. In the MRF process, the MR fluid containing cerium oxide (CeO_2) with a mean diameter of 80 nm and carbonyl iron was selected. The feed rate was 100 mm/ min, and the scanning step was 0.5 mm. The gap between the polishing wheel and the workpiece was 0.7 mm, and the removal depth in this process was about 0.15 μm. In the CCOS process, a select grade of pitch used exclusively for optical fabrication was used, and the polishing abrasives were diamond microabrasions with a mean diameter of 50 nm. No additional pressure was given except for the weight of the workpiece itself. The spindle speed of the polishing pitch was 60 rpm. The polishing time was 10 min and the removal depth was about 0.2 μm. Because electroless nickel is categorized with the soft nonferrous metals, it is easy to generate nicks on its surface when polishing by MRF and CCOS, as shown in the figures. Also, the surface roughness increases much more than in the original. Figure 4 shows the PSD analysis curves obtained when using different machining methods. Although all three polishing methods can remove the periodic marks, the MRF and CCOS processes make the PSD curves increase, which is unwanted in optical fabrication.

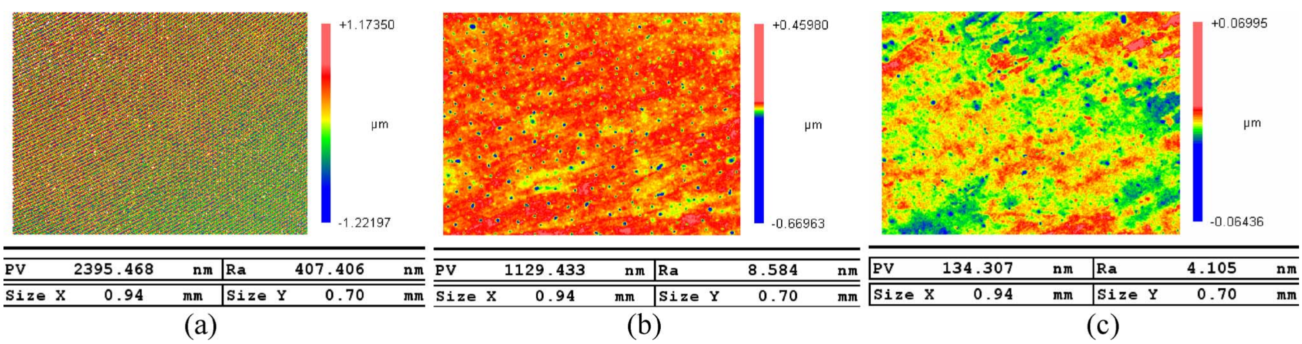


Fig. 1. (Color online) Surfaces of the rough sample (a) before polishing, (b) after first polishing, and (c) after second polishing.

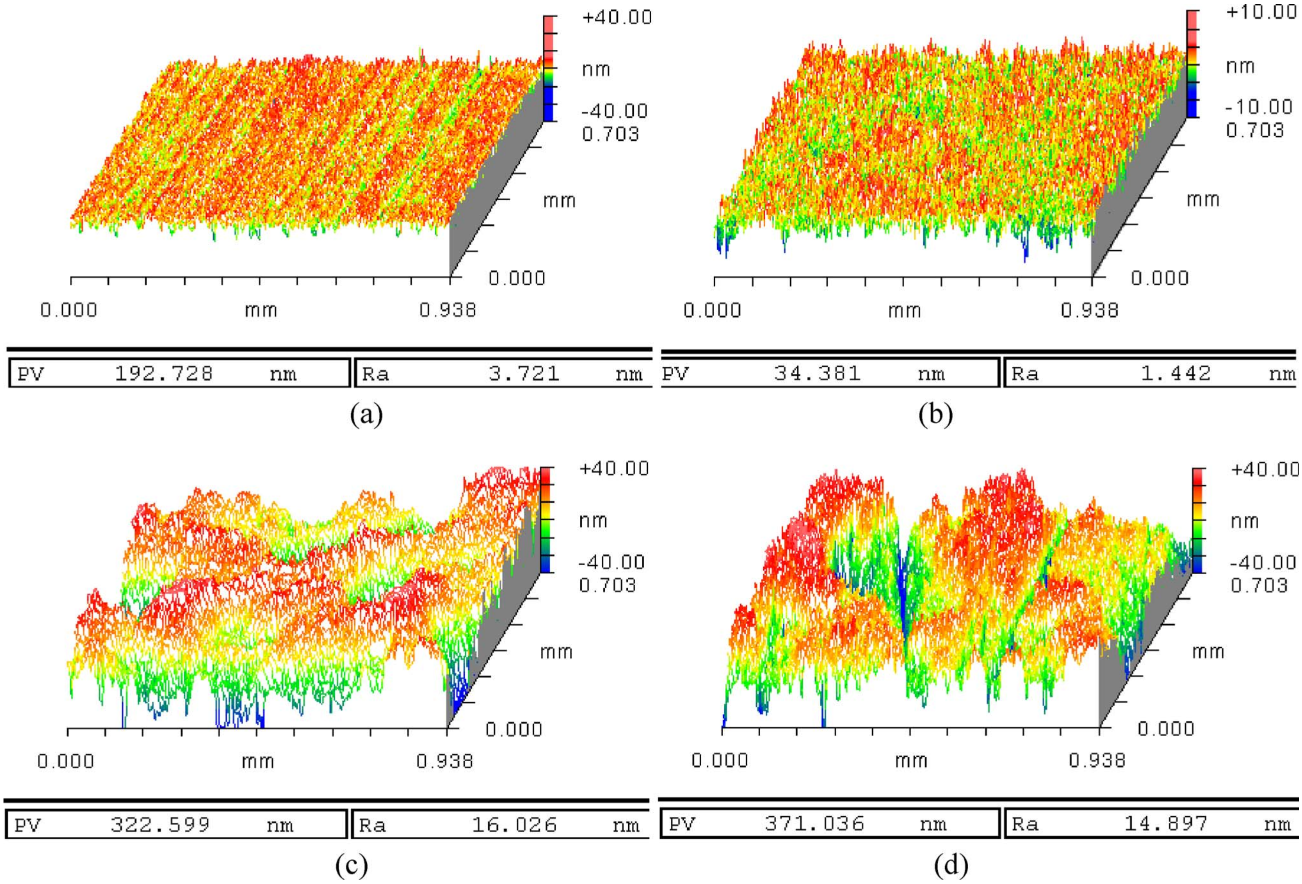


Fig. 3. (Color online) Surfaces of fine samples (a) before polishing, (b) after AJP, (c) after MRF, and (d) after CCOS.

Also, contrastive experiments of convergence rate using these three different polishing methods are investigated. The experiments were carried out on roughly turned electroless nickel plano round mirrors with diameters of 20 mm. The parameters of these three polishing methods were the same as described before. The experimental results are shown in Fig. 5. They indicates that both the MRF and CCOS processes have a high convergence rate compared to the AJP process. This is mainly due to the high material removal rate of these two polishing methods. Though the convergence rate of the AJP process is low due to its relatively low material removal rate, it can obtain a much finer surface

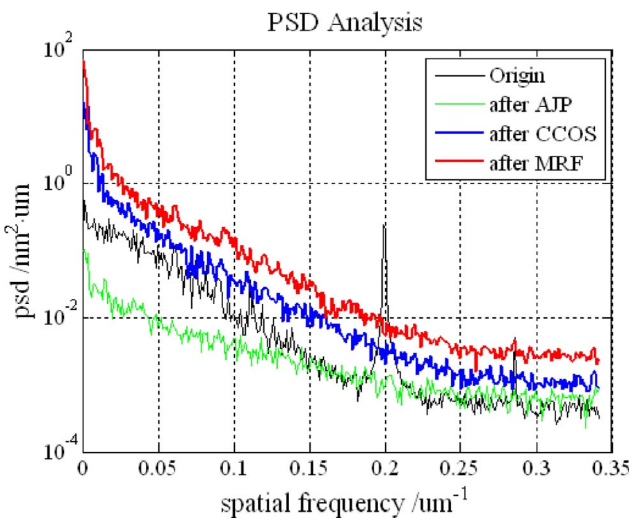


Fig. 4. (Color online) Analysis of PSD curves obtained by different machining methods.

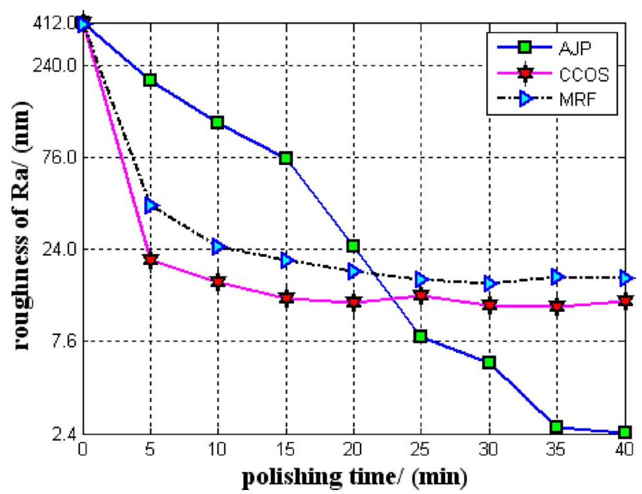
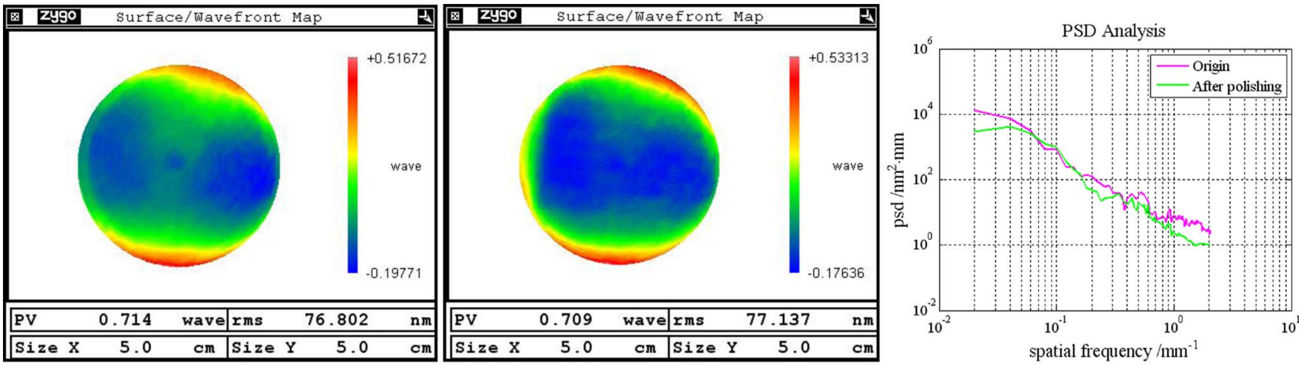


Fig. 5. (Color online) Comparison of convergence rates using different polishing methods.



(a) (b) (c)

Fig. 6. (Color online) Surface figure maintaining in uniform AJP process (a) before polishing, (b) after polishing; (c) PSD analysis before and after polishing.

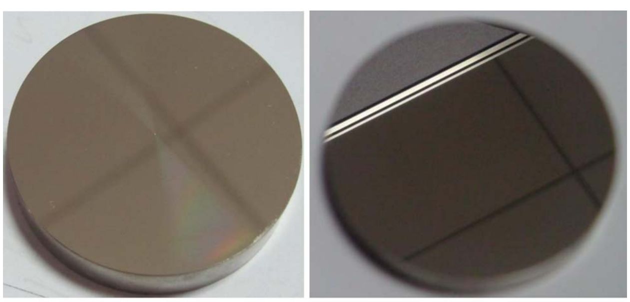
compared to the other two methods, just as shown in Fig. 5. So when polishing roughly turned electroless nickel, we can first use the MRF or CCOS process to remove the marks and reduce the roughness of the surface quickly, then we can use the AJP process to obtain a smoother surface, which could be used in optical areas.

C. Figure Maintaining in the AJP Process

We also researched figure maintaining in the AJP process with a finely turned electroless nickel mirror. The diameter of the mirror is 50 mm, and Fig. 6(a) shows the original surface figure of the mirror. After 150 min of uniform AJP process, the material removal depth is about 0.2 μm, and the polished figure surface is shown in Fig. 6(b). The PSD curves before and after polishing are given in Fig. 6(c). From the contrastive figures we can determine that the surface figure is well maintained during the uniform polishing process. Figures 7(a) and 7(b) show the photos of finely turned electroless nickel mirror before and after the uniform polishing process.

D. Discussion

Both the marks on rough and fine electroless nickel surfaces can be eliminated completely by the AJP process, while the roughness of the electroless nickel surface can be improved for both rough and fine turned mirrors. The contrastive experiments above reveal that the AJP process can obtain a smoother surface than MRF and CCOS processes when polishing the electroless nickel used in this paper, though it has a lower convergence rate. But we must emphasize that MRF and CCOS can also obtain a much smoother surface when polishing glass and ceramics, and even some metals that are not the same as those used here (see [15,16]). The experiments reported here also indicate that the AJP process can maintain figure when uniformly removing the periodic marks. Also, the experiments show that the AJP parameters significantly affect the surface quality, and optimized process parameters must be a required step going forward.



(a) (b)

Fig. 7. (Color online) Photos of the electroless nickel mirror (a) before polishing and (b) after uniformly polishing.

5. Conclusions

The applications of SPDT surfaces in optoelectronics products, Walter-type x-ray mandrels, and nonferrous metal mirrors are described in this paper. The periodic SPDT marks induce a diffraction effect and stray light, which limit the optical components' performance, and they are very difficult to remove by many widely used polishing techniques. Nowadays, the main method for this is hand postpolishing, which can easily cause degradation of the form of the SPDT surface, especially for the aspheres and free forms. On account of this, we have introduced AJP to remove the periodic marks from diamond-turned electroless nickel mirrors. In our experiments electroless nickel mirrors machined after SPDT were polished with the AJP process. Rough samples' surface roughness decreased from more than 400 nm to 4 nm, and fine samples went from 3.7 nm to 1.4 nm. All the diamond-turning marks on the mirrors have been eliminated thoroughly in the polishing process, with diffraction effect and stray light eliminated. Contrastive experiments were also carried out on fine samples, which indicate that the AJP process can produce a smoother surface than the MRF and CCOS processes while removing the periodic turning marks on the electroless nickel mirrors we used, though it has a lower convergence rate. Also, figure maintaining experiments in the AJP process were carried out, and the results show that the AJP process can maintain the original figures while uniformly polishing the mirrors.

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