A study of surface morphology evolution in fluid jet polishing

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ABSTRACT

Fluid jet polishing (FJP) has been extensively utilized in the ultra-precision manufacturing of optical components and molds. The polishing time is of great importance for the surface quality after polishing under different polishing parameters. When the polishing time is long, the nonuniform abrasive impact results in large erosion pits, increasing the surface roughness. On the other hand, short-time polishing is insufficient for improving surface quality due to less material removal. As a result, it is essential to determine the polishing time by investigating the surface morphology evolution process in FJP. This paper focuses on a study of the effect of different parameters on the surface morphology evolution process and hence identifies the presence and cause of the large erosion pits in FJP. The impact position distribution of abrasives and material removal amount by a single abrasive were considered in the model. The result of the study can be utilized to optimize the polishing time in FJP under different polishing conditions.

INTRODUCTION

With the ever-increasing need for ultra-precision components, the requirements for surface quality and form accuracy of optical components are becoming higher and higher so as to achieve a high performance of equipment [1]. Fluid jet polishing (FJP) does not result in tool wear and has superior applicability to the manufacturing of complicated freeform surfaces with a high efficiency [2], which has been extensively utilized in the final finishing of optical components and precision molds [3-6].

In FJP, the polishing slurry is prepared by mixing the abrasives and water. The abrasives are accelerated by the high pressurized water in the nozzle [7]. One problem is that the abrasives impact the workpiece surface unevenly due to the turbulence and pressure gradient change of fluid. As a result, unlike contact mechanical polishing, the material removal in different positions is nonuniform in FJP. Large erosion pits appear on the workpiece surface in FJP, especially under a long polishing time. To achieve a good surface quality, large erosion pits should be avoided. Some prior research has been conducted to investigate the effect of different parameters on the surface quality after polishing. Tsai et al. [8] optimized the machining parameters using Taguchi experiments, and the surface roughness of steel mold was significantly reduced by only qualitatively analyzing the relationship between surface roughness and polishing parameters. It was found that the surface roughness increased after a long blasting time. However, the detailed reason was not elucidated.

To reveal the real physical process in FJP, theoretical models were also built. Wang et al. [9, 10] simulated the material removal in the macro scale by computational dynamic fluid (CFD) software and the results agreed well with the experimental results. Che et al. [11] established a mathematical model of surface roughness for polishing super hard materials by solving the maximum indentation depth. Wang et al. [12, 13] modeled the surface morphologies after abrasive air jet polishing. Nevertheless, in this model, the polishing time was short and it was not possible to generate large erosion pits as in FJP. As a result, the model cannot be applied in the optimization of polishing parameters in FJP.

Despite the efforts placed on the parameter optimizations and theoretical models of FJP, most of these methods are built without considering the generation of large erosion pits, which exerts a tremendous influence on the final finishing surface quality. Hence, it is still hard to determine the appropriate polishing time to avoid the large erosion pits on the workpiece surface after polishing.

In this paper, the surface morphology evolution process in FJP was investigated. The effects of different parameters including abrasive size, jet pressure, polishing time, and jet impinging angle on the generation of large erosion pits were considered. The results provide the basis for the optimization of polishing time according to the surface morphology evolution process.

EXPERIMENTAL WORK

The experiments were conducted on a ZEEKO IRP200 ultra-precision freeform polishing machine as shown in Figure 1. The workpiece used in the experiments is NiCu alloy. To avoid the effect of initial surface morphology on the material removal, the workpiece was machined by single point diamond turning first and the surface roughness was 5 nm. The workpiece was polished under different conditions using the slurry containing aluminum oxide. The average diameters of abrasives were 2 μm, 5 μm, and 10 μm, respectively. The abrasive morphologies measured by scanning electron microscope are shown in Figure. 2. The surface morphology evolution under different polishing parameters was measured by ZYGO optical profiler. The polishing time was controlled by the feed rate of the nozzle in FJP. The surface roughness was evaluated by arithmetical mean height Sa. The detailed design of polishing experiments were shown in Table 1.

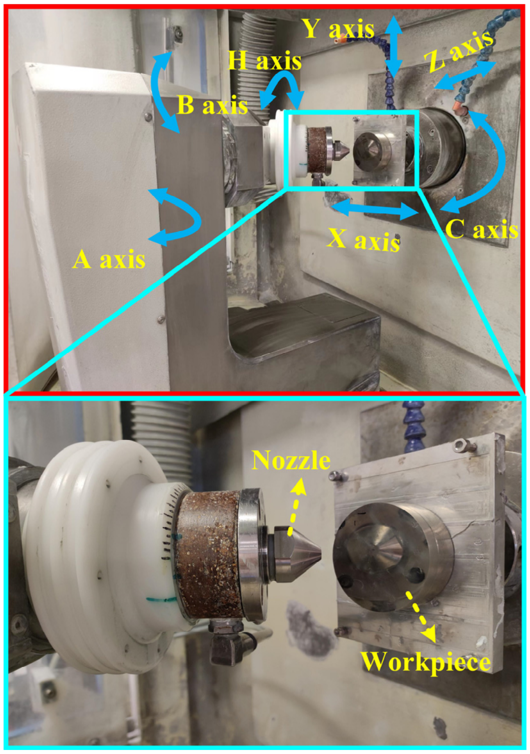

FIGURE 1. Polishing machine utilized in the experiments

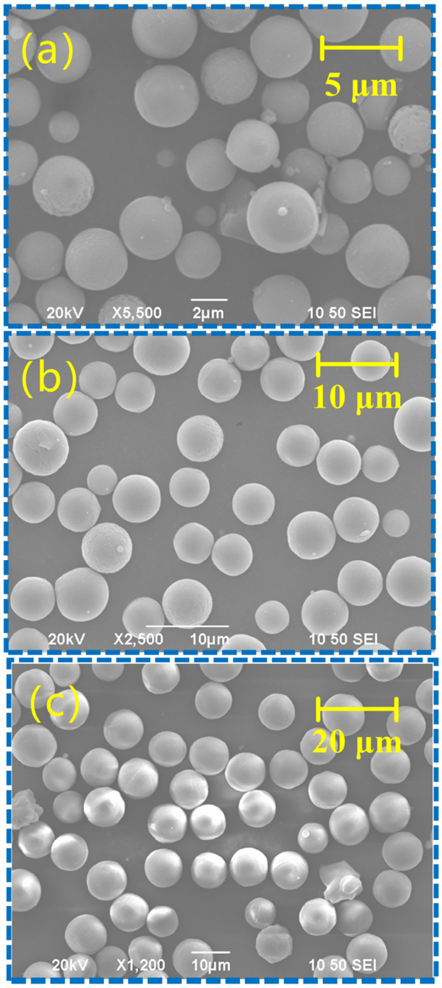

FIGURE 2. Abrasives with different sizes used in the experiments (a) 2 μm, (b) 5μm, and (c) 10μm

TABLE 1. Experimental design

Parameters	Group 1	Group 2	Group 3
Pressure (bar)	4, 6, 8, 10	8	8
Feed rate (mm/min)	20	20,40,100,500	20
Abrasive size (μm)	10	10	2, 5, 10
toolpath	Raster path with 0.2 mm scan interval		
Jet angle (degree)	90		
Polishing area	5 mm*5 mm		

EROSION PIT MEASUREMENT IN FJP

In FJP, a highly smooth surface with low surface roughness is preferred. The large erosion pits are harmful to the improvement of surface quality. To investigate the reason for the generation of a large erosion pit in FJP, the surface morphologies after polishing with 10 µm abrasives were measured as shown in Figure 3. The jet pressure was 8 bar, and the feed rate was 100 mm/min. Inside the large erosion pits, there were a lot of small erosion pits resulting from the single abrasive impacts. In the center of a large erosion pit, there were more small abrasive erosions. However, fewer single abrasive erosion pits were found on the edge of the large erosion pits. Hence, the results demonstrated that the impact frequency in different positions of the workpiece surface was different, which was unlike contact polishing such as bonnet polishing [14], and mechanical abrasive polishing [15]. The nonuniform abrasive impacts led to the appearance of large erosion pits. The large erosion pit appeared owing to a larger amount of material removal resulting from higher frequency impacts in some positions as compared with the adjacent zone.

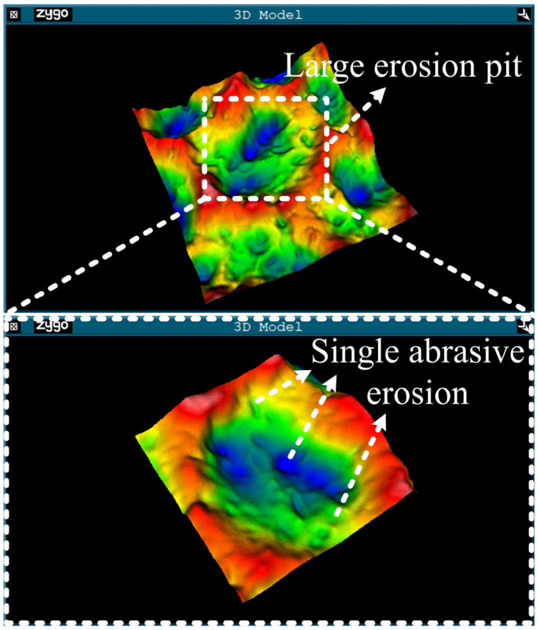

FIGURE 3. The surface morphologies after FJP

Figure 4 shows the surface morphologies after FJP using different sizes of abrasives. When the abrasive size was small such as 2 *µm*, the size of the erosion pit was very small as well and high surface quality with a surface roughness of about 7 nm was obtained. However, when the abrasive size increased to 10 µm, several large erosion pits can be found due to the large size. Meanwhile, it can be found that the height of peak to valley increased sharply when the abrasive size was 10 µm, which indicated that the depth of the large erosion pits increased. Under the effect of increasing size and depth of large erosion pits, the surface roughness increased from 7 nm to 42 nm. Hence, polishing with large abrasives is not beneficial to the improvement of surface quality as a result of the generated large erosion pits with a large size and depth.

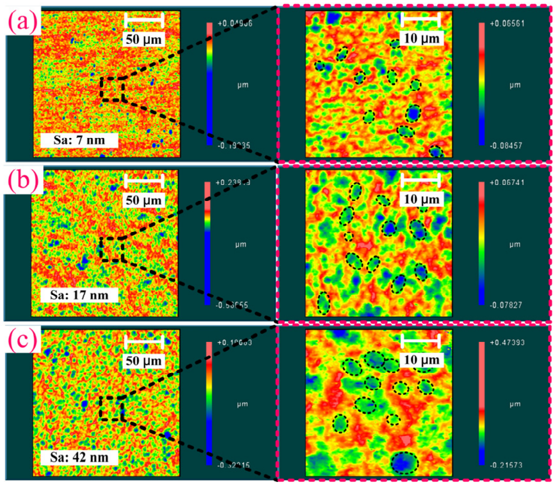

FIGURE 4. The surface morphologies after polishing with different sizes of abrasives (a) 2 µm (b) 5 µm (c) 10 µm

Figure 5 shows the surface morphologies after polishing under different jet pressures. It can be found that the size of the large erosion pits increased with the increase of jet pressure. It was because high pressure led to more abrasive impacts and a larger single abrasive erosion pit, which aggravated the nonuniform material removal. As a result, the surface roughness arithmetical mean height Sa was larger when polishing using higher pressure.

Figure. 6 shows the surface morphologies after polishing under different jet impinging angles. It is interesting to note that the jet impinging angle had a minimal effect on the size of the large erosion pits. However, the surface roughness increased from 31 nm to 42 nm with the increase in jet impinging angles. Hence, a small jet impinging angle was beneficial to the improvement of surface roughness. It was because the abrasives impact the workpiece surface at a shallower angle when polishing using a smaller jet impinging angle [16]. Consequently, the cutting action was enhanced under a small jet impinging angle, which can remove the peak on the workpiece surface better and reduce the depth of the large erosion pit. Besides, under a shallow impact angle, the abrasives were more likely to impact the peaks rather than the bottom surface of large erosion pits. The detailed process is shown in Figure 7. As a result of the enhanced cutting action and abrasive impact position differences, lower surface roughness was obtained under a small jet impinging angle.

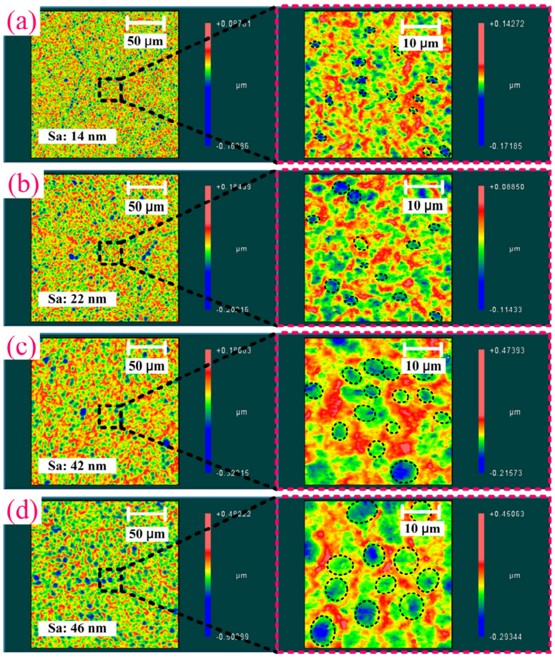

FIGURE 5. The surface morphologies after polishing with different pressures (a) 4 bar (b) 6 bar (c) 8 bar (d) 10 bar

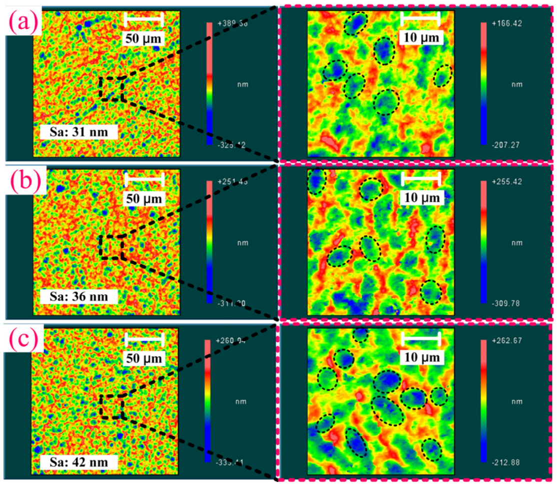

FIGURE 6. The surface morphologies after polishing with different jet impinging angles (a) 60 degrees (b) 75 degrees (c) 90 degrees

To investigate the surface evolution process, the workpiece was polished under different feed rates. The feed rates were 500mm/min, 100 mm/min, 40 mm/min, and 20 mm/min, respectively. The polishing time was inversely proportional to the value of feed rates. Figure 8 shows the surface morphologies after polishing. The initial turning tool marks on the workpiece surface can not be removed when the feedrate was 500 mm/min owing to the low material removal amount. With the decrease in feed rate, the polishing time increased and more material removal was achieved. However, the largest erosion pits appeared when the feedrate was 20 mm/min, leading to a large surface roughness of 42 nm. The reason was that, when an erosion pit appeared, the surface had a slope angle between the edge and center of the erosion pit. The slope angle changed the material removal direction from the vertical direction on a plan surface to the horizontal direction. The abrasives were more likely to impact the slopped surface rather than the peak on the edge of the erosion pits. As a result, with the increase in material removal amount, the size of the large erosion pit increased as well. It is possible to optimize the feed rate and obtain a better surface quality by removing the tool marks completely as well as avoiding the appearance of large erosion pits.

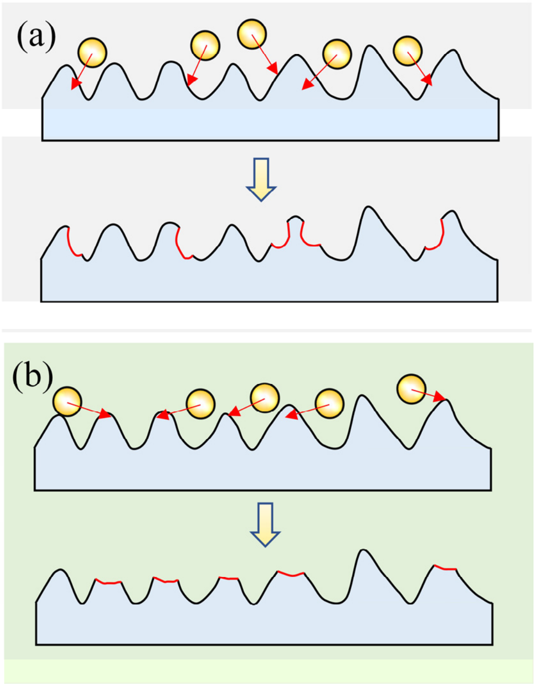

FIGURE. 7 The material removal process under different jet impinging angles (a) high impinging angle (b) low impinging angle

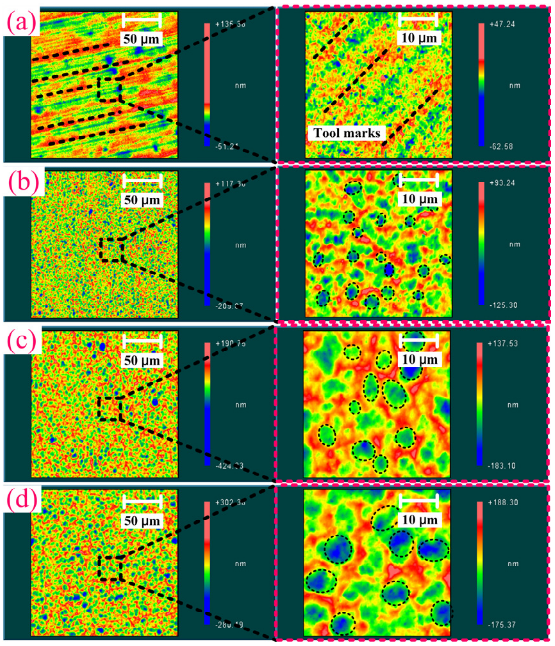

FIGURE 8. The surface morphologies after polishing with different feed rates (a) 500 mm/min (b) 100 mm/min (c)40 mm/min (d)20 mm/min

SUMMARY

This paper revealed the generation of large erosion pits in FJP. The experimental results demonstrated the large erosion pits resulted from the nonuniform impact of abrasives in different positions. Large abrasive size, high jet pressure, high jet impinging angle, and long-time polishing were more likely to lead to the generation of large erosion pits in FJP. The generation of the large erosion pits deteriorates the surface roughness of the workpiece surface, which should be restrained. On the other hand, to achieve a high surface quality in FJP, the polishing time under different manufacturing parameters should be optimized to improve the initial surface quality as well as to avoid the generation of large erosion pits.

FUTURE WORK

This work explained the generation of large erosion pits in FJP. In future work, the detailed material removal process will be considered and modeled to predict the surface morphologies under different polishing parameters, providing some guidelines for the restraining of large erosion pits and improving the surface quality after polishing.

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