AN INVESTIGATION OF MULTI-JET POLISHING OF PRECISION SURFACES

C.F. Cheung *, C.J. Wang, L.T. Ho, and W.B. Lee
Partner State Key Laboratory of Ultra-precision Machining Technology
Department of Industrial and Systems Engineering
The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

INTRODUCTIONS

Fluid jet polishing (FJP) [1,2] is one of the promising polishing methods as compared to other polishing methods. This is particularly true for its unique advantages, such as high machining accuracy, suitable for polishing various complex surfaces (especially for steep, concave aspheric surfaces), no tool wear, no temperature increase of the workpiece during polishing, and can be used on many kinds of materials including optical glass, ceramics, semiconductor materials, crystal materials, hard alloys, etc. [3-6]. However, there still exist limitations of FJP. Low polishing efficiency is one of the main limitations, which affects its application in polishing medium-large size components. Besides, it also takes a relatively long time to polish a small size component as compared to other polishing methods.

According to the reported literatures [7,8], the material removal rate can be increased by increasing the fluid pressure and slurry concentration. However, high fluid pressure would lead to bad surface finish, while high slurry concentration would not only make it difficult to control its stability, but also lead to the congestion of the slurry supply system. Moreover, the enhancement is limited by only a single jet. Beyond that, researchers also attempted to add the pressured gas into the fluid jet to enhance the polishing efficiency [9]. Although it can increase the material removal rate, the polished surface has deeper surface defects and poorer surface finish than the traditional FJP. Recently, Beaucamp et al. [10] proposed a novel ultrasonic cavitation assisted fluid jet polishing to enhance the polishing efficiency. However, the enhancement of the efficiency is less than 4 times of the normal fluid jet polishing according to the reported results. Hence, an effective way to largely enhance the polishing efficiency (i.e. tens or hundreds of times) of FJP is still much needed. With this in view, multi-jet polishing (MJP) process was developed to address this problem [11]. In the MJP process, many orifices are designed and fabricated in a larger size nozzle. In MJP, the input fluid with relatively high energy can be distributed to each individual fluid jet which owns the energy similar to the single jet polishing (SJP) process. Hence, the polishing efficiency is largely increased depending on the number of the orifices. In this paper, an investigation and discussions of MJP were carried out.

MULTI-JET POLISHING PROCESS

In MJP process, pressurized polishing fluid mixed with water and abrasive particles is delivered by a pump to a purposely designed converging nozzle. The jet impinges the workpiece and thus generating material removal. The configuration of the orifices on the MJP nozzle can be customized with linear, circular, or square array topologies as shown in Fig. 1. It can be used to polish various kinds of surfaces, including flat and freeform surfaces. Specifically, the linear distributed MJP nozzle can be used to undertake the polishing work on circular or cylindrical surfaces as shown in Fig. 1(e) and Fig. 1(f).

MATERIAL REMOVAL CHARACTERISTICS

<u>Material removal rate</u>

Comparison experiments for studying material removal rate were firstly conducted, and the experiments were undertaken on ZEEKO IRP200 seven axes computer controlled ultraprecision polishing machining system as shown in Fig. 2. Several types of MJP nozzles were purposely designed for conducting the experiments as shown in Fig. 3(a). The diameter of each orifice is 300μm.

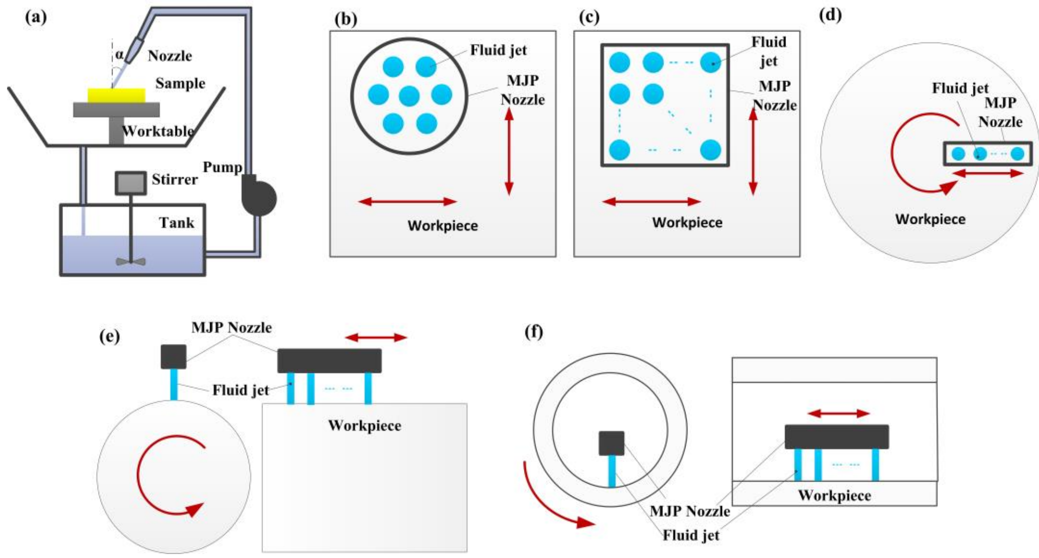


FIGURE 1. Schematic diagram of Multi-Jet Polishing (MJP) process and several typical polishing situations: (a) MJP process system, (b) polishing using a circular distributed MJP nozzle, (c) polishing using a square array type distributed MJP nozzle, (d) linear distributed MJP nozzle polishing circular samples, (e) linear distributed MJP nozzle polishing cylindrical surface and (f) linear distributed MJP nozzle polishing internal surface.

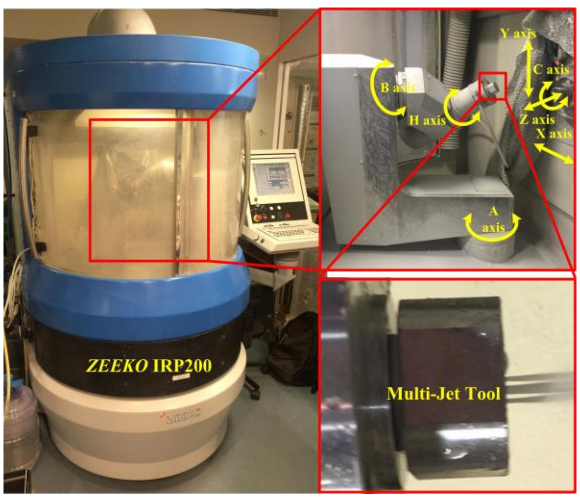


FIGURE 2. Photographs of experimental setup.

Experiments for studying the tool influence function generation were conducted on nickel copper (NiCu) alloy and BK7 optical glass under the same polishing conditions as summarized in TABLE 1. The polishing slurry for polishing NiCu is wt.10% 4000# silicon carbide, whose average particle size is about 3.2 µm. The polishing slurry for BK7 is 10 wt. % Cerox SUPER 1663 CeO_2, with the average size of 1.5 µm. Fig. 3(b) demonstrates the generated TIF contour of these three nozzles on NiCu.

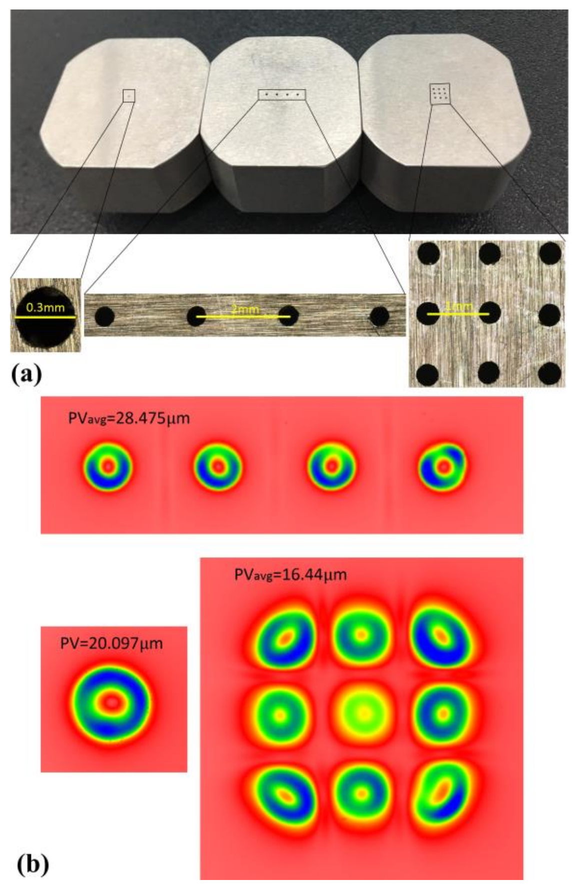


FIGURE 3. Photographs of the purposely designed SJP and MJP nozzles for the experiments and corresponding TIFs on Nickel copper alloy surfaces: (a) nozzles, (b) TIFs.

TABLE 1. Polishing conditions for the TIF generation experiments

Fluid pressure	6 bars
Stand-off distance	3 mm
Impinging angle	90 degree
Dwell time	3 minutes

Figure 4 shows the comparison results of material removal rate adopting different nozzles both on NiCu and BK7. The results indicate that the material removal rate of MJP is much higher than that for SJP, and the enhancement of the removal rate is almost proportional to the number of orifices integrated in the MJP nozzle.

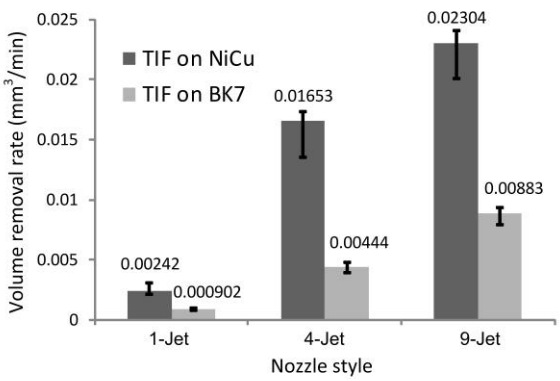


FIGURE 4. Comparison of the material volume removal rate of these three kinds of nozzles on nickel copper alloy and BK7 optical glass.

Effects of polishing parameters to the surface roughness

The effect of two main polishing factors to the surface roughness was investigated, which are fluid pressure and stand-off distance. As shown in Fig. 3(a), a 9-jet MJP nozzle was used in this experiment. Moreover, a total of 8 groups of experiments were conducted on BK7 optical glass and single crystal silicon (100) as shown in Table 2. Those surfaces have been pre-polished to mirror surface to reduce the effect of the original surface.

Figure 5 shows the analysis results of the effects of these two factors to the polished surface roughness, which is the average arithmetic roughness (Ra) value of three measured results. The results indicate that the fluid pressure has great influence on the surface roughness, and the larger fluid pressure leads to an increase of surface roughness. The effect of the stand-off distance is very small to the surface roughness, and no obvious relationship was observed between the stand-off distance and the surface roughness. Moreover, it is interesting to note that when the fluid pressure is 3 bars and the stand-off distance is 4 mm, the surface roughness is the smallest among them.

TABLE 2. Experimental design of the effect of polishing factors

No.	Fluid pressure (bars)	Stand-off distance (mm)	Slurry	Sample material
A1	3	2, 4, 6	10 wt.% CeO_2	BK7 optical glass
A2	4	2, 4, 6		
A3	5	2, 4, 6		
A4	6	2, 4, 6		
B1	3	2, 4, 6	5 wt.% SiC	Single crystal silicon
B2	4	2, 4, 6		
B3	5	2, 4, 6		
B4	6	2, 4, 6		

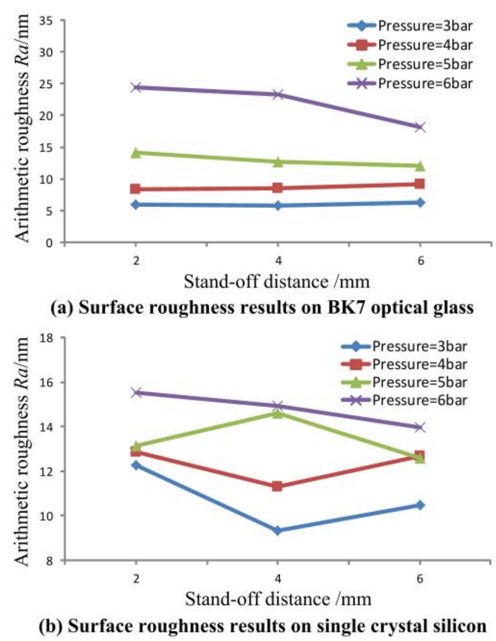


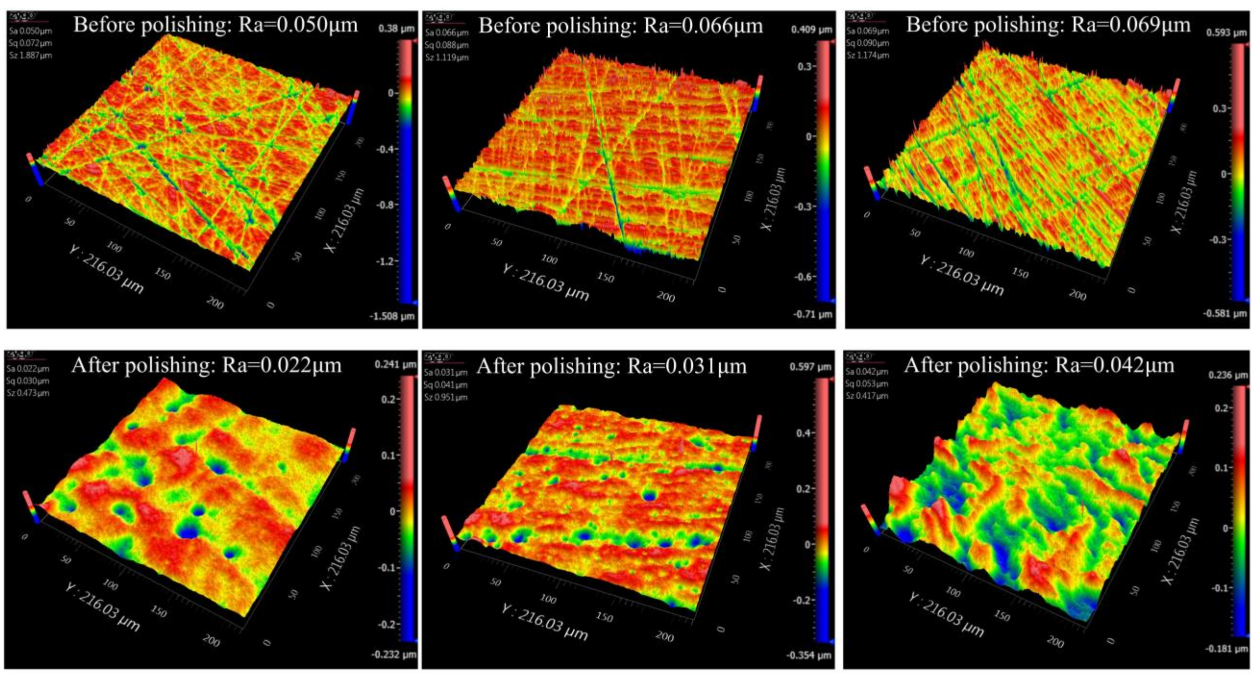
FIGURE 5. Analysis of effects of fluid pressure and stand-off distance to the surface arithmetic roughness on BK7 optical glass and single crystal silicon surface (The roughness value is the average arithmetic roughness value of 3 measured surface roughness value)

Surface texture after polishing on different materials

To compare the surface texture after polishing by MJP on different materials, polishing experiments were conducted on BK7, single crystal silicon (110) and stainless steel under the same polishing conditions as tabulated in Table 3. The surface of these samples before polishing are rough surfaces as shown in the top part of Fig. 6, which was measured by *Zygo Newview* 3D profilometer. And the polished surface textures of them have also been shown in the bottom part of Fig. 6. The arithmetic roughness (Ra) of the polished surface of BK7, single crystal silicon and stainless steel are 22 nm, 31 nm, and 42 nm, respectively. It suggests that the surface roughness on the hard-brittle materials such as BK7 glass and single crystal silicon is lower than that on ductile metal surface such as stainless steel under the same polishing conditions. It is also observed from the results on BK7 and NiCu as we reported in Ref. [11]. It can be explained that the indentation depth for the ductile surface is deeper than that for the hard-brittle surface under the same particle impact energy. And these surface results were polished after only one cycle under the polishing conditions as shown in Table 3. Their surface roughness can be further improved through subsequently polishing process. Figure 7 shows the photo of several regions on single crystal silicon surface before and after polishing in this experiment. Mirror-like surface can be achieved on single crystal surface after MJP.

TABLE 3. Polishing conditions comparison of surface textures

Fluid pressure	3 bars
Stand-off distance	4 mm
Impinging angle	90 degree
Polishing path	Raster path
Path pitch	0.1 mm
Path region	2 mm ×2 mm
Feed rate	6 mm per minute
Polishing time	~7 min



(a) BK7 (b) Single crystal silicon (c) Stainless steel

FIGURE 6. Comparison of surface topography of different materials polished by MJP

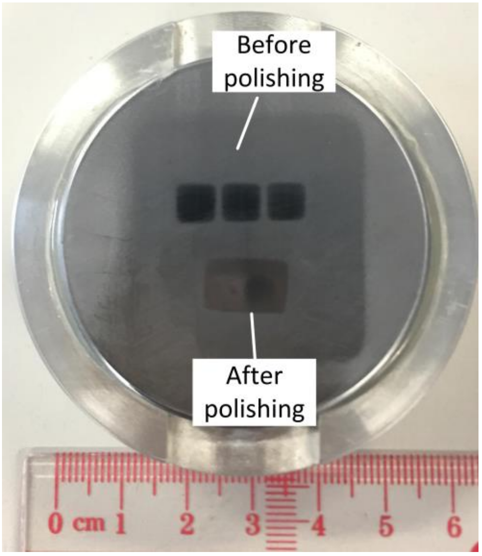


FIGURE 7. Snapshots of single crystal silicon surfaces before and after polishing

DISCCUSIONS

Material removal rate comparison

Limited by the maximum fluid pressure of our experimental device, only a few orifices were integrated in one nozzle in the present study. However, the results have proven the feasibility of this process. Through increasing the size and number of the orifice in the designed nozzle with a higher fluid pressure, it can be used to polish medium-large surfaces. The volume removal rate (VRR) of single jet polishing on BK7 using 0.3mm diameter nozzle is only 9 x 10 mm^3/min. Normally, VRR of single fluid jet polishing varies from 1 x 10^{-4} mm^3/min to 0.01 mm^3/min when the nozzle diameter is ~1 mm, and the peak removal rate (PRR) varies from 0.1 μm/min to 10 μm/min. The removal rate could be influenced by many factors, such as slurry concentration, fluid pressure, stand-off distance, particle type, workpiece material, etc. Assuming that 100 Ø1mm orifices are integrated in one MJP nozzle, then the VRR could be up to ~1mm^3/min. This material removal rate is comparable or even larger to the VRR of magnetorheological finishing (MRF) on BK7 as reported in literature [12], which is smaller than 0.9mm^3/min. Moreover, the number of the orifice could be much more than 100 in the MJP nozzle, which would further enhance its VRR.

Applications

Classical single jet polishing can only be used to polish small size surfaces and edge of large surfaces. With the successful development of the MJP process, the application of fluid jet polishing technology can be further extended to the polishing of medium-large size freeform surfaces, such as mirrors used in high-power laser system, large scale functional surfaces, etc. Moreover, the MJP nozzle can be purposely designed for polishing of various kinds of surfaces, such as cylindrical surfaces, internal surface, etc., as shown in Fig. 1.

Beaucamp et al. [6] successfully combined the single fluid jet polishing and bonnet polishing process for the fabrication of hard X-ray molding dies. Identically, MJP could also be combined with bonnet polishing for the optimization of process chain for high efficiency manufacturing of industrial products. This will be studied in the future work.

CONCLUSIONS

A novel Multi-Jet Polishing (MJP) process is presented in this paper. The experimental results show that it not only possesses a much higher polishing efficiency than that of single jet polishing (SJP), but also reaches the surface accuracy at the equivalent level to the single jet polishing. The experimental investigations of MJP also indicate that the fluid pressure has great influence on the surface roughness, and the larger fluid pressure leads to larger surface roughness. The effect of the stand-off distance is very small to the surface roughness, and no obvious relationship was observed between the stand-off distance and the surface roughness. In addition, the polishing results on different materials also infer that the surface roughness after MJP for ductile metal materials is larger than that for hard-brittle materials. The development of the MJP polishing process will help to extend the application of fluid jet polishing to medium-large size surfaces.

ACKNOWLEDGEMENTS

The work described in this paper was mainly supported by the grants from the Innovation and Technology Commission (ITC) (Project no. GHP/031/13SZ) of the Government of the Hong

Kong Special Administrative Region (HKSAR), China.

REFERENCES

[1] Faehnle OW, Brug HV, Frankena HJ. Fluid jet polishing of optical surfaces. Appl. Opt. 1998; 37:6771–6773.

[2] Booij SM. Fluid Jet Polishing-possibilities and Limitations of a New Fabrication Technique (Ph.D. thesis), Delft University, 2003.

[3] Fang H, Guo PJ,Yu JC, Surface roughness and material removal in fluid jet polishing. Appl. Opt.2006; 45: 4012-4019.

[4] Tsai FC., Yan BH, Kuan CY, Huang FY. A Taguchi and experimental investigation into the optimal processing conditions for the abrasive jet polishing of SKD61 mold steel. Int. J. Mach. Tools Manuf. 2008; 48: 932-945.

[5] Beaucamp A, Namba Y, Freeman R. Dynamic multiphase modeling and optimization of fluid jet polishing process. CIRP Ann. – Manuf. Technol. 2012; 61: 315–318.

[6] Beaucamp A, Namba Y. Super-smooth finishing of diamond turned hard X-ray molding dies by combined fluid jet and bonnet polishing. CIRP Ann.-Manuf. Technol. 2013; 62: 315-318.

[7] Chen FJ, Miao XL, Tang Y, Yin SH. A review on recent advances in machining methods based on abrasive jet polishing (AJP). Int. J. Adv. Manuf. Technol. 2017; 90: 785-799.

[8] Zhu HT, Huang CZ, Wang J, Li QL, Che CL. Experimental study on abrasive waterjet polishing for hard–brittle materials. Int. J. Mach. Tools Manuf. 2009;49: 569-578.

[9] Messelink WACM, Waeger R, Wons T, Meeder M, Heiniger KC, Faehnle OW. Prepolishing and finishing of optical surfaces using fluid jet polishing. Proc. SPIE 2005;5869:586908.

[10] Beaucamp A, Tomoya K, Zensaku K. A novel ultrasonic cavitation assisted fluid jet polishing system. CIRP Ann.-Manuf. Technol.2017.

[11] Wang CJ, Cheung CF, Ho LT, Liu MY, Lee WB. A novel multi-jet polishing process and tool for high-efficiency polishing. Int. J. Mach. Tools Manuf. 2017;115:60-73.

[12] Donald G, Jacobs SD, Kordonski WI, Dumas P. Precision optics fabrication using magnetorheological finishing. In Critical Review Collection, pp. 102890H-102890H. International Society for Optics and Photonics, 2017.