euspen's 22nd International Conference &
Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

An investigation of maskless fluid jet polishing of three dimensional structured surfaces

Chunjin Wang[1,*], Zili Zhang[1], Chi Fai Cheung[1], Lai Ting Ho[1]

[1] *State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*

Corresponding Author: chunjin.wang@polyu.edu.hk

Abstract

Various kinds of functional three dimensional (3D) structured surfaces have been widely used in different fields, such as imaging and illumination. However, the machining process of these kinds of structured surfaces usually leaves tool marks, burs, debris and defects on the structured surface. Currently, it is still a challenging problem to remove those defects so as to further improve the surface quality effectively for better functional performance. In this paper, a maskless fluid jet polishing (MFJP) method is presented which attempts to address this challenge. In MFJP, low pressure micro abrasive water jet slurry is impinged on the structured surface to achieve tiny material removal without using a mask. A series of experiments were conducted on the polishing of different kinds of 3D structured surfaces that are pre-shaped by different machining processes. The surface quality in terms of surface roughness, form maintainability, and surface smoothness of lens array surface and cylindrical array surface were analysed. The results indicate that the MFJP can significantly improve the surface quality of these kinds of 3D structured surfaces, while possessing high form maintainability under certain conditions. It has the potential to become a competitive method for the precision polishing of 3D structured surfaces. This study also sheds some light on the application of MFJP for polishing other kinds of surfaces with small or micrometre scale cavities or channels, such as microfluidic chips, high end mould inserts with complicated cavities, etc.

Keywords: Fluid jet polishing, finishing, structured surface, mould, ultra-precision machining

1. Introduction

Various kinds of three dimensional (3D) structured surfaces have been widely used in different fields, such as imaging and illumination [1,2]. However, the machining process of 3D structured surface usually leaves tool marks, burs, debris and defects on the surface. Subsequent polishing on the machined 3D structured surface are usually required to further improve its surface quality.

Induced by the tool interference, it is difficult to use the traditional mechanical polishing method to polish 3D structued surfaces. Different kinds of polishing methods have been purposely developed for the polishing them， such as copying tool polishing [3-5], magnetic field assisted polihsing [6,7], vibration-assisted polishing [8], etc. Brinksmeier et al. [9] proposed the wheel-shaped and pen-shaped tools to polish the structured array on the mold steel and electroless nickel-plated steel. The surface roughness after polishing reached 4.5 nm. Zhao et al. [10] added vibration assistance on the basis of chemical mechanical polishing to obtain a better surface quality than non-vibration assisted polishing. Yamaguchi et al. [7] and Riveros et al. [11] proposed a novel magnetic field assisted polishing method for the polishing of micropore structures on the X-ray focusing mirrors using the magnetorheological fluid, and the final polished surface roughness can reach RMS 0.18 nm, which is well within the roughness requirement for the next generation X-ray telescope application. However, there still exists certain problems for the current polihsing methods. As for copying tool, one tool can only be purposely used for the polishing of one kind of structured surface with specific size. It is difficult for other polishing methods to maintain the surface form accuracy after polishing. Hence, a generic polishing method is still needed for the polishing of 3D structured surfaces. The authors recently proposed a novel maskless fluid jet polihsing (MFJP) method for the polishing of 3D structured surfaces [12]. The maskless is a relative definition as compared to the abrasive water jet polishing method using a mask proposed by Matsumura et al. [13]. The feasibility of this method has been validated on electrical discharge machined sinusoidal structured surface and ground V-groove surface.

In this paper, the polishing performance of MFJP on diamond lens array surface and micro-milled channel array surface are presented, aiming to further eliminate the tool marks and improve the surface roughness.

2. Working principle of maskless fluid jet polishing

Fluid jet polishing (FJP) method proposed by Fähnle et al. [14] has been widely used in the polishing of optical lenses and molds, especially for aspherical or freeform surfaces. During FJP, the polishing slurry containing micro/nano meter scale abrasive is pumped out of the nozzle, impinging the target surface to implement material removal through the erosion process, as shown in Fig. 1. The fluid jet is highly flexible, which can easily adapt to the surface with complicated geometry. It also can be used for the polishing of wide range of materials such as ceramic, metal, and glass, etc [15,16]. This is the main reason why this method is used for the polishing of 3D structured surfaces. Moreover, low fluid pressure, i.e. normally lower than 15 bar), is adopted in MFJP, which is beneficial to maintain the surface form accuracy, and the mask is not needed.

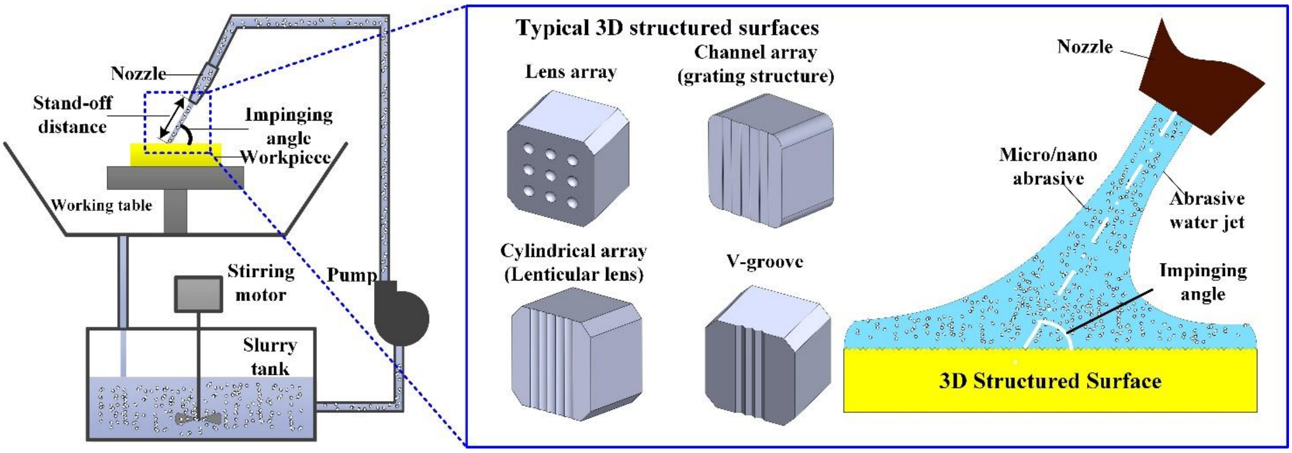


Figure 1. Schematic disgram of maskless fluid jet polishing of 3D structured surfaces

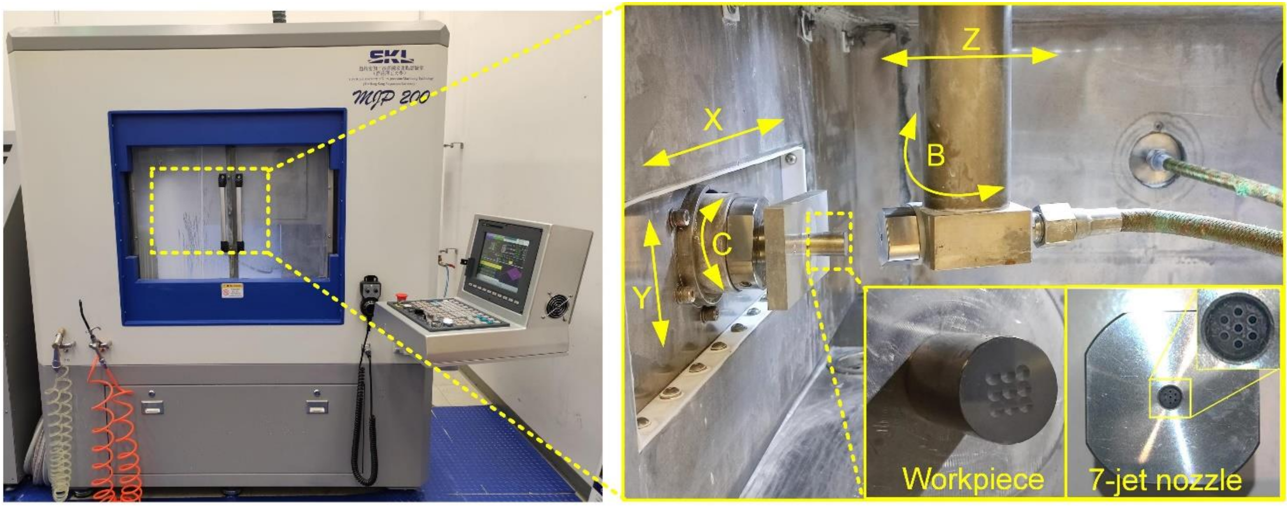


Figure 2. Experimental set-up

3. Experiments

In this study, both single jet polishing and multi-jet polishing were conducted for the polishing of 3D structured surfaces. The multi-jet polishing can largely boost the polishing efficiency while maintaining good surface quality, which has been demonstrated in our previous research [17,18]. The experiments were conducted on a purpose-built multi-jet polishing machine *MJP-200* developed by the authors as shown in Fig. 2. Both single jet and multi-jet polishing experiments on 3D structured surfaces were conducted. Two kinds of 3D structured surfaces were tested in this study, which are diamond turned lens array mold made of nickel copper alloy and micro-milled cylindrical array surface made of 304 stainless steel. The drawings of them have been demonstrated in Fig. 3. These two kinds of materials are commonly used as the mold material. The diameter of the single jet nozzle is 1 mm, whose orifice material is sapphire. 7-jet multi-jet nozzle was used in this study, whose diameter is 0.5 mm, as shown in Fig. 2. Table 1 summarizes the polishing conditions of the experiments. In this study, *Cerox* 1663 cerium oxide slurry was used for the polishing of lens array surface and cylindrical surface.

The surface roughness was measured on *ZYGO NEXVIEW* white light interferometer. The magnification of the object lens is 40 and the measurement area is 213.78 µm × 213.78 µm. The arithmetic mean height (Sa) and root mean square height (Sq) of the measured area were used to evaluate the surface roughness, which are defined according to *ISO25178* standard. The surface roughness was analyzed using the software MX. Nine order polynomial filter was used, and other settings are default setting of the software. The surface form was also measured by *ZYGO NEXVIEW* white light interferometer. Sectional profile was extracted from the 3D measurement results, and the comparison of the profile was analyzed by MATLAB program. The surface topography before and after polishing were characterized by Hitachi Electron Microscope TM3000 with different magnifications.

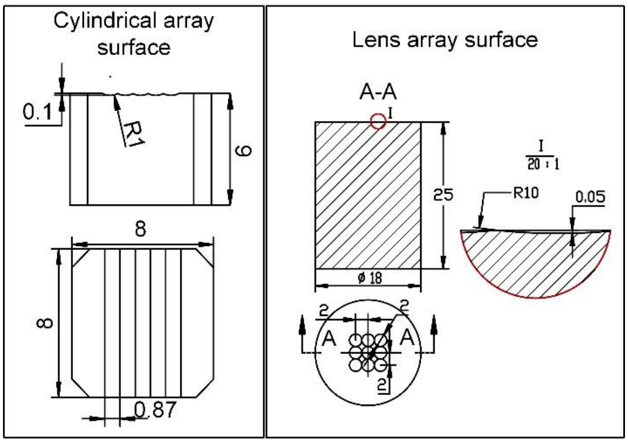


Figure 3. Drawings of the workpieces

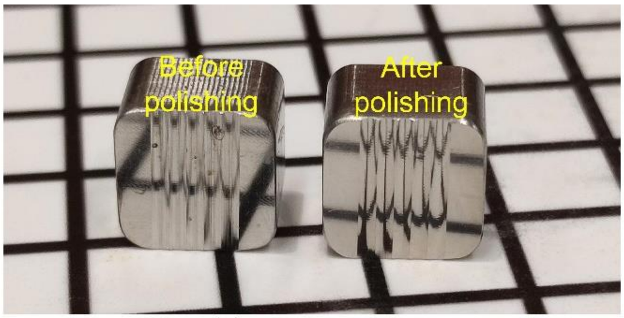
Table 1 Experimental design

Workpiece type	Cylindrical structure array	Lens array
Nozzle	1-jet nozzle, 1mm diameter	7-jet nozzle, 0.5mm diameter
Machine	MJP200	
Slurry	Wt.5% cerium oxide, size of ~1.5um in average.	
Fluid pressure	8bar	
Stand-off distance	4mm	
Tool path	raster	
Impinging angle	90 deg	
Path interval	0.2mm	0.1mm
Feedrate	20mm/min	100mm/min
Polishing cycle	6 cycles	1 cycle

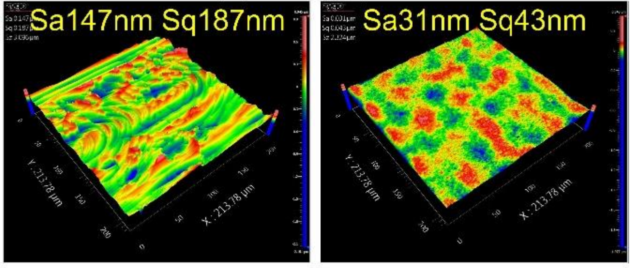
4. Results and discussions

4.1. Polishing performance on micro milled cylindrical structure array surface

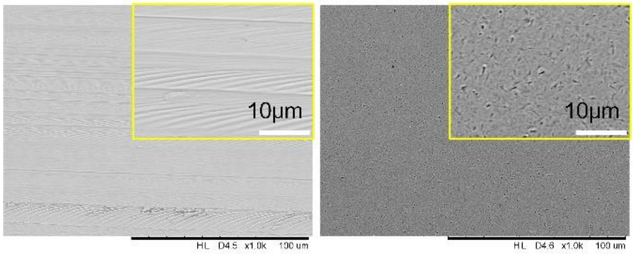
Fig. 4 shows the polishing results on the cylindrical array structured surface. The surface quality has been highly improved to obtain a mirror-like surface as shown in Fig. 4(a). The surface roughness was reduced from Sa 147nm to Sa 31nm as shown in Fig. 4(b), which is attributed to the removal of the milling tool mark as shown in Fig. 4(c). Only some erosion marks were left on the polished surface, including some erosion grooves and pits. The surface forms before and after polishing were also compared as shown in Fig. 5. It is interesting to note that good form maintainability can be observed.



(a) Photographs



(b) 3D surface roughness contour



(c) SEM photographs

Figure 4. Polishing performance on cylindrical array surface

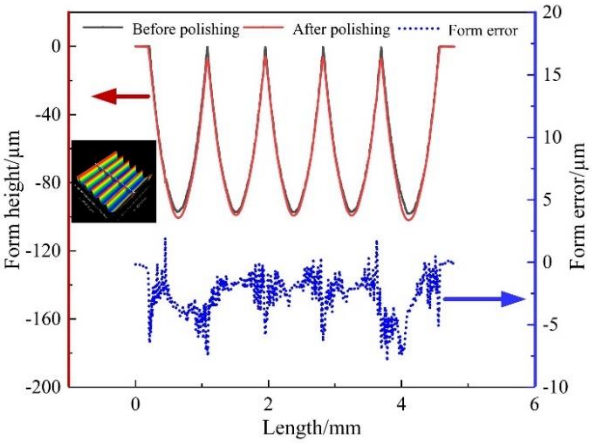
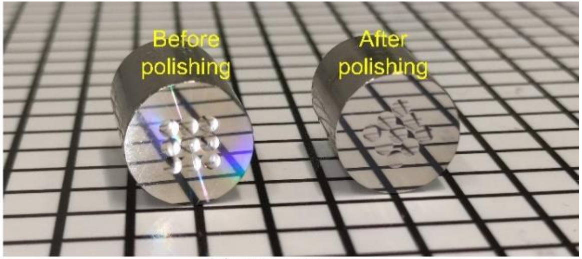


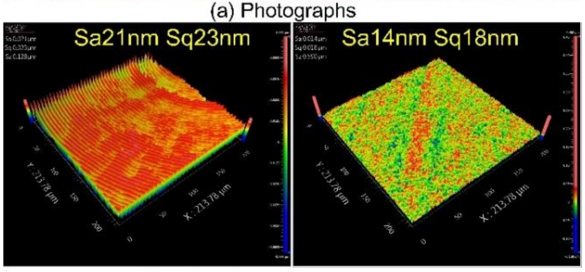
Figure 5. Surface form before and after polishing analysis of cylindrical array surface

4.2. Polishing performance on diamond turned lens array surface

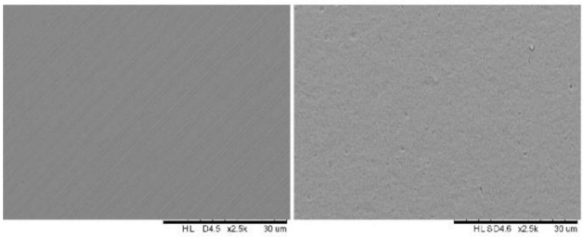
Fig. 6 shows the polishing results on the diamond turned lens array surface. It is found that the surface after diamond turning is already a mirror like surface. However, there is a rainbow pattern induced by the diamond turning tool marks, which is a main problem limiting the application of diamond turned surface in visible and ultraviolet wavelengths. However, the elimination of the diamond turning marks is still a challenge, especially on 3D structured surfaces. As shown in Fig. 6(a), the rainbow pattern has been successfully eliminated after polishing. The surface roughness was reduced from Sa 21nm to Sa 14nm after one pass of polishing showed in Fig. 6(b), which is attributed to the removal of the diamond turned tool mark as shown in Fig. 6(c). Only some erosion marks were left on the polished surface, including some erosion grooves and pits. The surface forms before and after polishing was also compared as shown in Fig. 7. The form deviation is less than 1 μm in peak-to-valley (PV) value in this experiment which reveals good form maintainability of MFJP.



(a) Photographs



(b) 3D surface roughness contour



(c) SEM photographs

Figure 6. Polishing performance on lens array surface

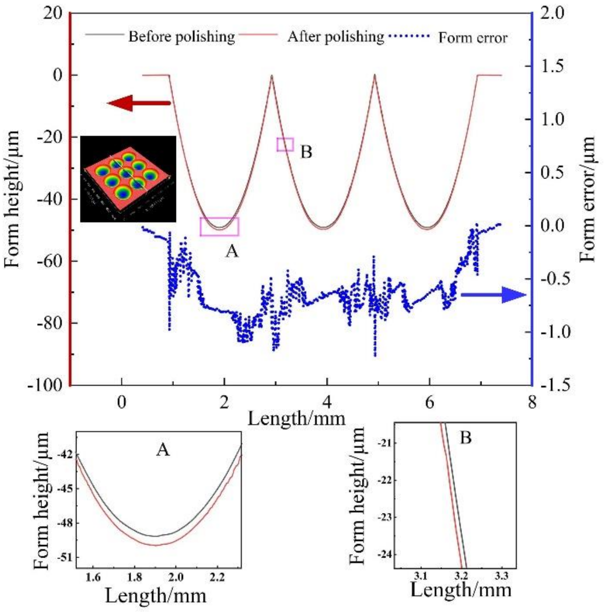


Figure 7. Surface form before and after polishing analysis of lens array surface

4. Summary

A pilot study of maskless fuild jet polishing (MFJP) on 3D structured surfaces were carried out in this paper. The experiments were conducted both using single fluid jet polishing and multi-jet polishing on a purpose-built multi-jet polishing machine *MJP200*. The results show that MFJP can be successfully used to remove the tool marks left by milling and turning on 3D structured surfaces, so as to reduce the surface roughness. At the meantime, the surface form of 3D structure can be maintained well after polishing.

However, research efforts are still needed to investigate the material removal and surface topography evolution mechanism, so as to obtain optimized polishing parameters to obtain lower surface roughness and higher form maintainability. Moreover, selection of the polishing abrasive including material and size are critical to this process, which should be further investigated and provide a decision strategy for the known initial surface quality. It is possible to obtain sub-nanometer scale surface roughness through using nanometer scale or colloidal abrasive, which will be investigated in the near future.

Acknowledgement

The work described in this paper was mainly supported by a grant from the Guangdong Natural Science Foundation Program 2019-2020 (Project No.: 2019A1515012015) and Research Grants Council of the Government of the Hong Kong Special Administrative Region, China (Project No. 15200119) and a grant from International Partnership Scheme of the Bureau of the International Scientific Cooperation of the Chinese Academy of Sciences (Project No.: 181722KYSB20180015). In addition, the authors would also like to express their sincere thanks to the funding support from the Research Office of The Hong Kong Polytechnic University for the research studentships (Project codes: RK3M).

References

[1]Zhang S, Zhou Y, Zhang H, Xiong Z, and To S, 2019 *International Journal of Machine Tools and Manufacture*, **142** 16-41.

[2] Yan G, Zhang Y, You K, Li, Z., Yuan, Y., and Fang, F., 2019 *Optics express*, **27** 10873-10889.

[3] Brinksmeier E, Riemer O, and Gessenharter A, 2006 *Precision Engineering*, **30** 325-336.

[4] Klocke F, Brinksmeier E, Riemer O, Klink A, Schulte H, and Sarikaya H, 2007 *Industrial Diamond Review* **67** 65-69.

[5]Zhao Q, Sun Z, and Guo B, 2016 *International Journal of Machine Tools and Manufacture*, **103** 28-39.

[6]Guo J, Liu K, Wang Z, and Tnay G L, 2017 *Tribology International*, **114**, 306-314.

[7]Yamaguchi H, Riveros R E, Mitsuishi I, Takagi U, Ezoe Y, Yamasaki N, Mitsuda K, and Hashimoto F, 2010 *CIRP annals*, **59** 351-354.

[8]Guo J, Feng, W, Jong H J H, Suzuki H, and Kang R, 2020 *Journal of Manufacturing Processes*, **49**, 204-213.

[9]Brinksmeier E, Riemer O, Gessenharter A, and Autschbach L, 2004 *CIRP Annals*, **53** 247-250.

[10]Zhao Q, Sun Z, and Guo B, 2016 *International Journal of Machine Tools and Manufacture*, **103** 28-39.

[11] Riveros R E, Yamaguchi H, Boggs T, Mitsuishi I, Mitsuda K, Takagi U, Ezoe Y, Ishizu K, and Moriyama T, 2012 J*ournal of manufacturing science and engineering*, **134**.

[12] Wang C, Zhang Z, Cheung C F, Luo W, Loh Y M, Lu Y, Kong L, Wang S, 2022 *Precision Engineering*. **73** 270-83.

[13] Matsumura T, Muramatsu T, & Fueki S, 2011 *CIRP annals*, **60** 355-358.

[14] Fähnle O W, Van Brug, H, and Frankena H J, 1998 *Applied optics*, **37**, 6771-6773.

[15] Beaucamp A, Namba Y, and Freeman R, 2012 *CIRP annals*, **61** 315-318.

[16] Wang C J, Cheung C F, Ho L T, Loh Y M, 2021 *Journal of Manufacturing Processes*. **61** 15-24.

[17]Wang C J, Cheung C F, Ho L T, Liu M Y, Lee W B, 2017 *International Journal of Machine Tools and Manufacture*. **115** 60-73.

[18] Cheung C F, Wang C, Ho L T, Chen J. Curvature-adaptive multi-jet polishing of freeform surfaces, 2018 *CIRP Annals*. **67** 357-60.