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Investigation on Key Removal Characteristics of Fixed Abrasive Diamond Pellets Elasticity Tool

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Keywords： removal characteristics; fixed abrasive diamond pellets; elasticity; polishing; hard and brittle materials

ABSTRACT

To further explore the practicality of the fixed abrasive diamond pellets (FADPs) elasticity polishing tool (ET) developed by our group in machining of hard and brittle materials, series of experiments were designed and conducted in this study to investigate the stability and the key technologies related to the whole surface polishing of the proposed ET. The experimental results indicate that the stability of the proposed ET is good after long time polishing, with tiny weight lost, sharp abrasives and stable tool removal function. Moreover, due to the composite characteristic of flexibility and stiffness of the ET, by controlling the exceeding distance of ET over workpiece, the warping edge after polishing can be significantly reduced, thus the edge effect in polishing process can be obviously suppressed. In addition to above, along with the increase of the spacing of tool path, the roughness of workpiece surface after polishing increases, while both the total time of a polishing cycle and the removal depth of workpiece decreases. All of the above results prove the practicability of the proposed ET with FADPs. Consequently, in practical polishing, comprehensive optimal polishing quality can be achieved by taking above three factors into account using the proposed ET.

INTRODUCTION

Wang *et al.* (2013, 2014) had shown that Optical elements made by hard and brittle materials (HBMs) have been widely used in the industrial fields because of many obvious advantages, such as high modulus of elasticity, low coefficient of thermal expansion, and moderate density. However, it is time-consuming and costly to machine optical elements made by HBMs such as sapphire, silicon carbide and BK7 with traditional precision fabrication methods, and it was analyzed in detail in studies of Dong *et al.* (2014) and Witzendorff *et al.* (2013). Consequently, novel polishing technology used for fabrication of HBMs with large removal rate, less surface defects and subsurface damages are urgently needed.

Inasaki *et al.* (1987) and Wang *et al.* (2014) have shown that several technologies with the above merits have been proposed in recent years. For example, bonnet polishing technology was introduced in 2002 and has been widely applied to fabricate the optical components. The results have shown that this technology has high polishing efficiency and precision, introduced by Ke *et al.* (2016) and Wang *et al.* (2014). Lv *et al.* (2015) and Gagliardi *et al.* (2012) proposed a semi-rigid bonnet polishing tool for HBMs with high efficiency and certainty. However, it is found that along with the enhance of the polishing efficiency by increasing of the z-offset of machine tool, the shape of tool removal function of the proposed tool changes to be irregular, which limits the efficiency of the bonnet tool. In order to address this problem, elasticity polishing tool (ET) with fixed abrasive diamond pellets (FADPs) was designed and developed as shown in Fig. 1.After the development of the ET, the removal function of ET was also studied and presented in our previous study, as Tam *et al.* (2007) written. In terms of the above study, it is found that there are two advantages of the proposed ET that: (1) the FADPs are uniformly attached on the plate surface, which ensures the uniformity of the pressure distribution on the contact surface between tool and workpiece which can be shown from the article written by Luo *et al.* (2008, 2009), Cheng *et al.* (2014) and Yu *et al.* (2012) , for this reason, the removal function of ET has high stability. (2) the abrasive on the FADPs are fixed, therefore the polishing stress on the contact surface with ET is much larger than that of the conventional polishing technologies, which polishes workpiece with loose abrasive. Consequently, the material removal rate of ET is higher than the conventional polishing technologies, from the papers of Hee-Won *et al.* (2003,2004) and Tso *et al.* (2007). In addition to above, due to the application of the wave spring in the ET structure, the elasticity tool has fine surface adaptability, which is supposed to result in reduction of

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subsurface damages and surface defects.

Although the above merits of ET have been proved by the previous investigations, however, study on the application of ET in HBMs polishing is still far from complete. Most of our studies have been focused on the tool removal characteristics without feed motion, which did not take key technologies that related to the whole workpiece surface polishing with feed motion into account. Therefore, in order to further expand the application of ET, three key technical parameters are investigated in this paper, which include the stability of the removal function of ET, tool ability on suppression of the edge effect when using ET and optimization of path spacing based on whole polishing results. Stability of the removal function is essential requirement of implementing applications, then optimization of polishing parameters is the key to application.

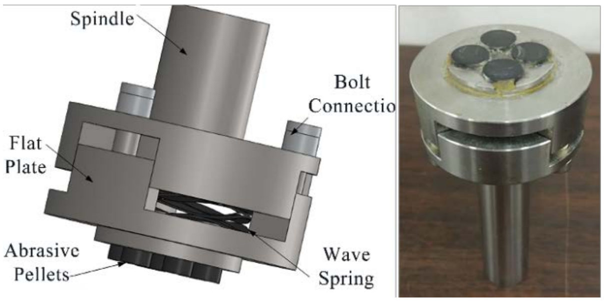


Fig. 1 Fixed abrasive diamond pellets elasticity tool

THE STABILITY OF THE REMOVAL FUNCTION OF ET

As presented in the previous studies, for most of the polishing technologies, the polishing tool declines with the increase of the utility time, which results in the variation of the removal stability of the polishing tool as well as the controllability of the polishing process. Since the developed ET is a deterministic material removal technology, the stability of the removal function of ET is intensively demanding.

Consequently, the removal stability of the proposed tool should be examined by experiment first. The examination process includes three parts, i.e.:

(1) the texture of the pellets on the polishing tool after a certain period of polishing

(2) the weight lost the pellets on the polishing tool after a certain period of polishing

(3) the tool removal characteristics of the polishing tool after a certain period of polishing.

ET was used in the experiments which consists of five parts. Cylindrical spindle is connected to CNC Machining Center, then the part of spindle and flat plate are bolted together that wave spring is placed in them, abrasive pellet is stuck in the bottom groove of the flat plate. Four concentric distribution FADPs elastic tool was employed due to denser and more disorganized polishing tracks compared to two or three concentric distribution FADPs. Contents of diamond pellet as shown in Table 1. As shown in Fig. 2, the radius of Pellet is r=5mm, e1 is the eccentric distance of ET from the geometric center of the common axis, the eccentric distance of pellets is e2 and the radius of the ET is e2+r. The ET polishes the workpiece with planetary motion. The specific experimental procedure includes:

(1) Before the experiment, the pellets were cleaned with dual-frequency ultrasonic cleaning device by 20min, to insure that there is no dust or loosing abrasives on the pellets surface. After that, the weight and texture of the pellets are measured by AB 104-Nmettler Toledo precision electronic balance and KEYENCE VHX-5000 microscope, respectively, as shown in Fig. 3.

(2) The polishing experiments are conducted using the conditions shown in Table 2, in which BK7 glasses are polished by the proposed ET.

(3) The texture, weight and the tool removal function of ET are measured in every 100 minutes polishing time with the approaches illustrated in step (1). Finally, after 600 minutes polishing, the measured results are recorded and revealed in Fig. 4.

Fig.4(a) shows that the polishing tool employed in the experiment worn with the increase of the polishing time. The weight of FADPs decreases from 1313.3mg to 1238.4mg after 600 minutes polishing, of which the reduction is only 5.703%. However, it is also shown in Fig. 4(b) that, although the weight lost increases with the polishing time, the raising rate is decreasing from 12.8mg per 100min to 12mg per 100min. It may be caused by the variation of the friction between the polishing tool and workpiece, i.e., both the surface roughness of workpiece and the pellets are rough at the initial polishing stage, therefore the friction force between the above is large which results in large worn weight. But both the surface roughness of the workpiece and the pellets will be decrease and tend to be stable with the increase of polishing time, therefore the friction force and the worn weight decrease until tends to be stable. Thus, the pellets is in a stable wear phase at 600 minutes and ET can meet the long-term polishing requirements.

On the other hand, according to the result shown in Fig. 5(a), along with the increase of the polishing time, the texture of the pellets does not show an obvious variation, moreover, by reference to the texture of the pellets after 600 minutes polishing as revealed in Fig. 5 (b), the particles on the pellets which cut the workpiece material remain sharp, which proves the stability of the proposed ET with FADPs.

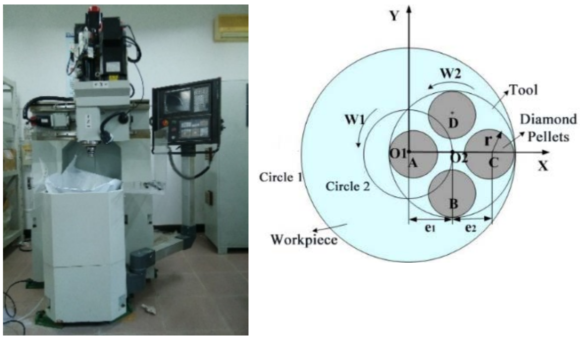
Although the stability of the polishing tool is partially demonstrated by the surface topography and weight lost of the above results, it is still not enough. Consequently, the removal characteristics of ET which include the shape and removal amount of tool removal function are also examined.

Table 1 The contents of diamond pellet

Manufacturers	Binding agent	Abrasive size (μm)	Abrasive density (g/cm^3)
EFFGEN	Special resin based binder	10	0.4

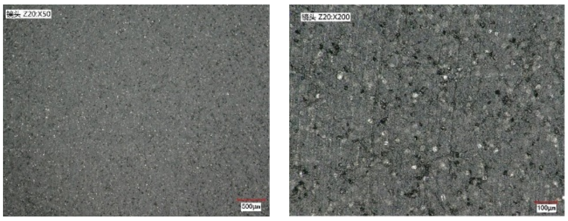
Table 2. The process parameters of experiment

Speed ratio	eccentricity	Pressure（N）	Spindle speed (rpm)	polishing time (min)
-3	0.7	100	600	100



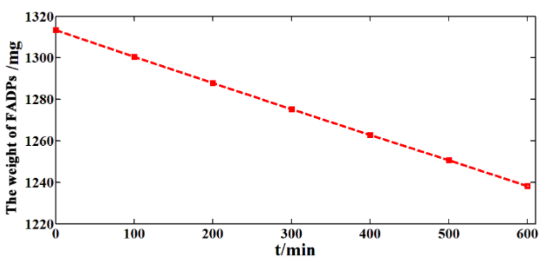
(a). CNC Machining Center (b). Diagram of polishing with ET

Fig. 2 Machining and polishing diagram

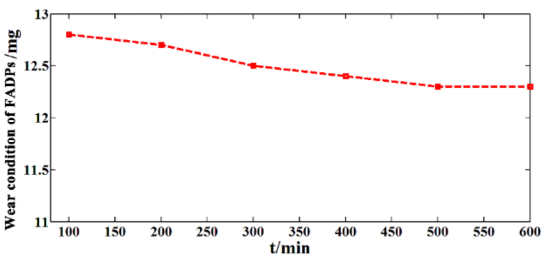


（a）50X micrograph （b）200X micrograph

Fig. 3 The cleaning surface of bonded abrasive sheet

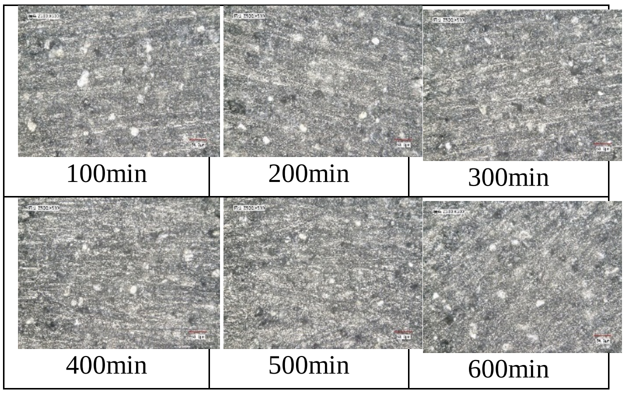


(a). The weight of bonded abrasive sheet

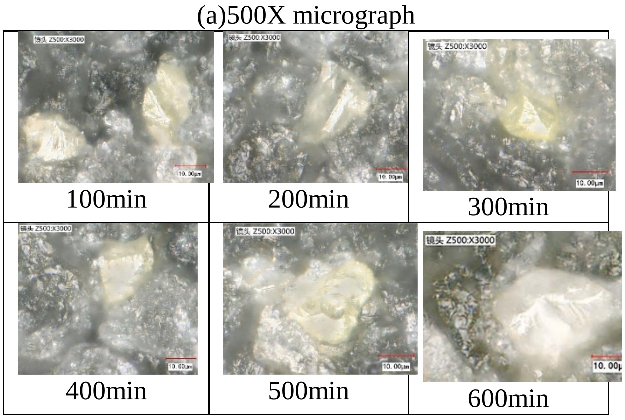


(b). The abrasion loss of bonded abrasive sheet per 100 min

Fig. 4 The abrasion loss result of bonded abrasive sheet



(a)500X micrograph



(b)3000X micrograph

Fig. 5 The micrograph of bonded abrasive sheet

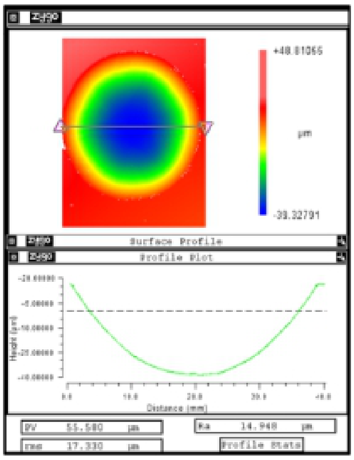
In order to study the stability of the remove function of ET with the increase of the polishing time, an additional experiment is design, of which the conditions are shown in Table 3. In order to keep the polishing removal function within the detection range of laser interferometer (Zygo.NV7300) after long processing, a smaller pressure of 20N and a spindle speed of 300rpm were selected, Meanwhile the residence time was extended to 40min in this experiment. The results of tool removal characteristics after polishing are shown in Fig. 6. After that, the removal functions of experiment 1 and experiment 2 are compared after normalized and de-tilted, and the comparison result is shown in Fig. 7.

The experimental results show that, the shape of the removal function of ET is stable, i.e., both of the shape of the removal functions is Gaussian shape, although the usage time of the polishing tool are widely different. It is also shown in Fig. 7 that, the maximum removal depth decreased form 60.818μm to 58.580μm in 640minutes polishing time, of which the reduction is less than 4%, which means the change of the remove function is small after long time polishing.

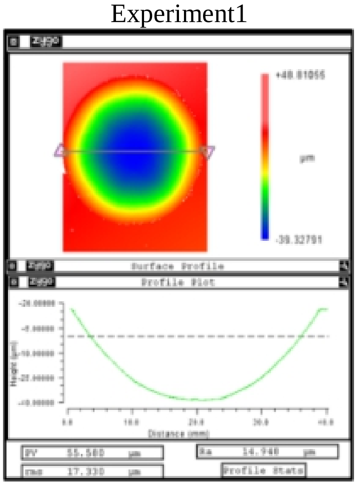
Based on the above analysis, it is can be demonstrated that the proposed fixed abrasive diamond pellets elasticity tool has good stability along with the increase of polishing time, therefore it can meet the requirements of deterministic polishing of HBMs.

Table 3 The process parameters of removal stability experiment

No	Speed ratio	eccentricity	Pressure (N)	Spindle speed (rpm)	polishing time (min)
1	-3	0.7	20	300	0-40
2	-3	0.7	20	300	600-640



Experiment1



Experiment2

Fig. 6 Study on the stability of removal function

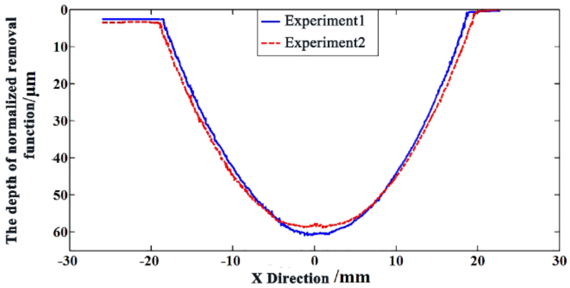


Fig. 7 Contrast of normalized removal function contour

KEY CAPACITIES OF ET ON HBMS POLISHING

Based on the above investigation, the stability of the removal characteristics of ET has been verified. However, in the practical polishing process, not only the removal characteristics of polishing tool should be concern, but also the key capacities of polishing tool that related to the machining quality of whole workpiece surface, such as the suppression of the edge effect and the optimization of polishing quality based on the selection of tool paths. For the above reason, the key capacities of ET are investigated in this section based on the polishing experiments of hard and brittle materials.

Suppression of edge effect using the proposed ET

Edge effect is a common phenomenon in the fabrication process of optical elements with hard and brittle materials. Edge effect is always formed for the reason that: when the edge of the workpiece is machining by the polishing tool, part of the tool exceeds the workpiece edge, which results in the non-uniform distribution of the pressure on the machining zone, therefore the material on the polished edge would either be overcut or undercut, thus the edge would be collapse or warped. The above situation has been taken into consider when the fixed abrasive diamond pellets elasticity tool was designed, hence the ET use rigid tool head and wave spring structure to guarantee the rigidity and flexibility at the same time. For the above reason, the ET has advantages to suppress edge effect when machining high precision optics glass lens. In order to verify the above opinion, polishing experiment related to suppression of edge effect is carried out, followed by the discussion.

Fig. 8 illustrates the principle of the polishing experiment. The workpiece is a BK7 plane glass, whose dimension is 100 mm × 100mm × 10mm. The other parameters used in the experiment are listed in Table 4. In addition to the above conditions, in order to find out the effect of the exceeding distance d of the ET over the sample edge on the polishing quality, 6 comparing groups experiments with various d are conducted, of which d =0,1,2,3,4,5 mm, as shown in Fig. 9. The experimental results are shown in Fig. 10 and Fig. 11.

Table 4 Experimental process parameters

Speed ratio	eccentricity	Pressure (N)	Spindle speed (rpm)	polishing time (min)
-3	0.7	125	600	2

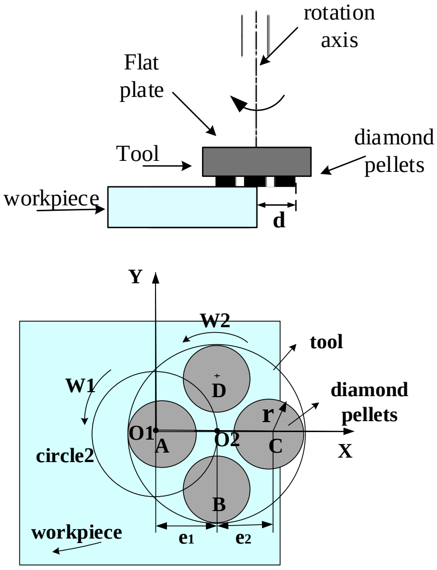


Fig. 8 Illustrator of edge polishing

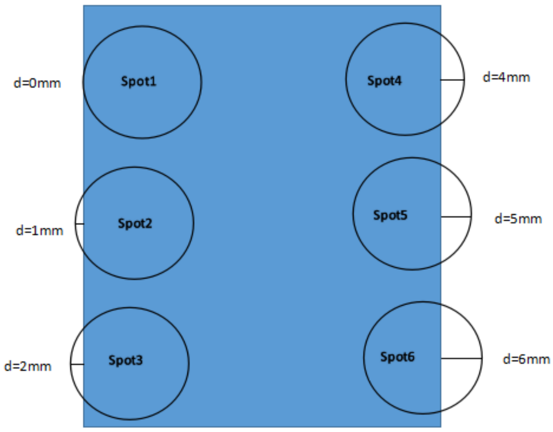
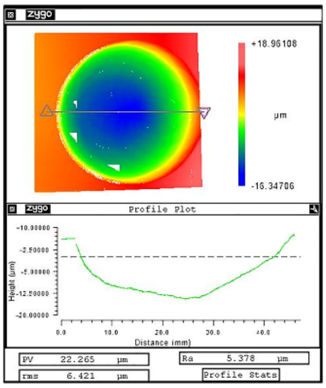
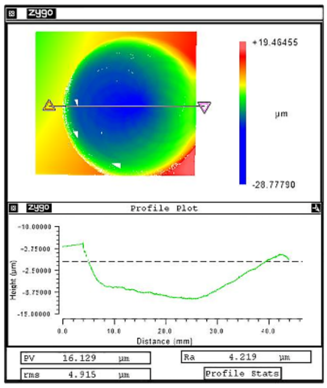


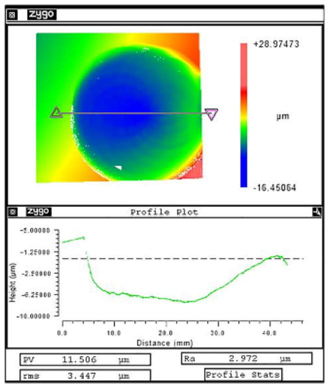
Fig. 9 Testing program (unit:mm)



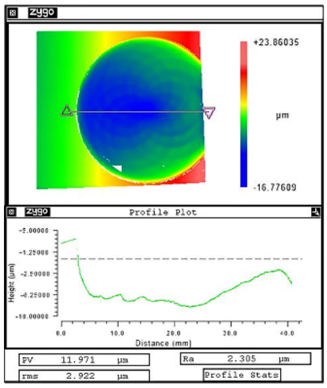
d=0mm



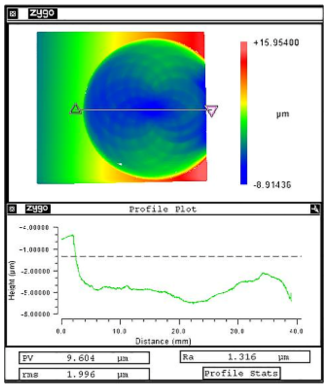
d=1mm



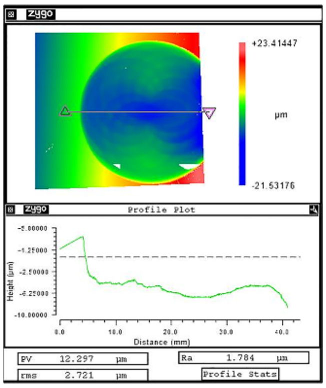
d=2mm



d=3mm



d=4mm



d=5mm

Fig. 10 Fringe effect with different overflow value

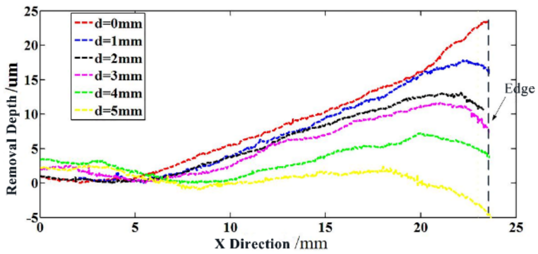


Fig. 11 Comparison of removal function with different overflow value

Fig. 10 reveals the edge spots obtained by the principle shown in Fig. 9 and the above experimental conditions. In order to quantitatively compare the width and the height of edge spots, the cross-sectional profiles in the X-axis direction of all polishing spot were extracted and compared as shown in Fig. 11.

According to Fig. 11, the edge effect exists in most of the experimental groups, and various with the change of the exceeding distance d. Specifically, when d = 0, the height of the Warped edge is about 24mm. Subsequently, along with the increase of the exceeding distance d, the height of the warped edge decreases. As soon as the exceeding distance d reaches 4mm, the height of the edge is almost the same as the center. However, along with the further increase of the exceeding distance d to 5mm, the edge collapses due to overcut.

Based on the above analysis, the edge effect in the polishing process can be suppressed by using the proposed polishing tool with an appropriate exceeding distance, i.e., when using the fixed abrasive elastic tool for pre-polishing, the edge effect can be reduced by increasing the exceeding distance d. Moreover, by using an appropriate exceeding distance, the warping edge can be significantly reduced, therefore the additional time spend on the subsequent correction cycle can be saved.

Surface polishing using ET

The removal amount of the material during the polishing process is always calculated by the convolution of the tool removal function and the dwell time along the tool path. Consequently, study on the tool path has attracted a lot of attentions. Raster tool path has been well known as a most commonly used tool path, of which the key parameter is the spacing between two adjacent paths. The spacing between two adjacent paths of the raster path has significant effect on both the polishing quality and efficiency. For this reason, optimization on the spacing of raster tool path is presented by experiments.

According to the previous literatures, when the spacing of raster tool path is large, the workpiece surface can be polished in a short time with poor polishing quality. In contract, when a small spacing is used, the workpiece surface can be polished precisely with a long period. Therefore, in order to obtain comprehensive optimized spacing of tool path, comparative experimental groups were conducted, followed by the discussion.

The principle of the comparative experiment is revealed in Fig. 12. The polishing tool traverses workpiece surface along the raster polishing path, by this approach, the material on workpiece surface is removed. The workpieces are BK7 glasses, whose dimension is $100\text{mm} \times 100\text{mm} \times 10\text{mm}$, the polished area is $50\text{mm} \times 50\text{mm}$ in the center of the workpiece. The key conditions used in this experimental group are shown in Table 5.

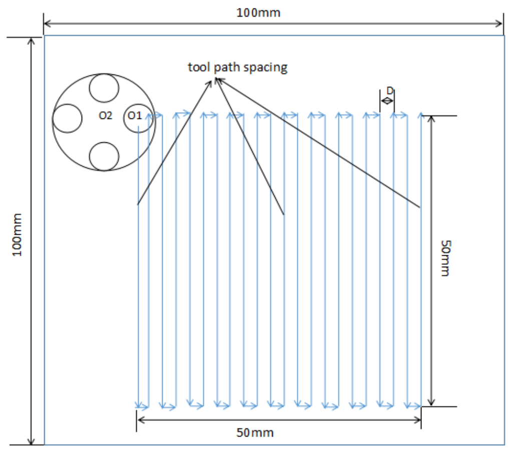


Fig. 12 Polishing path in whole polishing process

Table 5 Experimental process parameters

No	pressure (N)	Spindle speed (rpm)	feed rate rate (mm/min)	path space (mm)	machining region (mm)
1	100	600	200	0.5	50x50
2	100	600	200	1.0	50x50
3	100	600	200	1.5	50x50

4	100	600	200	2.0	50x50

After the above polishing experiments, the polishing quality includes surface shape and surface roughness and the total time of a polishing cycle obtained by using the above 4 different spacing types shown in Table 5 are compared, so that the preferred spacing of tool paths can be figured out. Note that, both the surface shape and surface roughness of workpiece are measured by Zygo.NV7300, the experimental results are shown in Fig. 13. For roughness measurement, the roughness of 5 measuring points is measured under the condition of 10 times and the average value is taken.

The total time T of a polishing cycle can be calculated through the parameters shown in Table 5 and Fig. 12, via the following steps: accumulate the number of reciprocating movement and multiply the number and the length of reciprocating movement (the length of reciprocating movement equals the length of the polished area). The number of reciprocating movement can be calculated through dividing the length of the polished area by spacing values. Finally, the total time of a polishing cycle can be got through dividing total length of the machining path by feed speed.

The comparing results of the total time of a polishing cycle and surface roughness obtained by various spacing of tool path are shown in Table 6. According to Table 6 and Fig. 14, the spacing of tool path has great effect on the surface roughness. Specifically, the surface roughness is proportional to the value of path space, i.e., along with the increase of tool path spacing from 0.5mm to 2mm, the surface roughness of workpiece after polishing increases from 20nm to 25.5nm, of which the increase rate is 27.5%. Based on the above result, it is inferred that smaller tool path spacing results in better surface roughness.

On the other hand, in terms of Table 6 and Fig. 15, the total time of a polishing cycle is inversely proportional to the tool path spacing. Specifically, along with the increase of tool path spacing from 0.5mm to 2mm, the total time of a polishing cycle decreases form 25.5min to 6.75min, of which the decaying rate is 70.75%. On the basis of the above result, smaller tool path spacing results in longer polishing time, which corresponding to lower efficiency.

In addition to above, regarding to the depth of the removed material which also related to polishing efficiency, by reference to Fig. 16, along with the increase of the tool path spacing, the depth of the removed material decreases form 38.814μm to 10.86μm, of which the declining rate is 72.02%.

Table 6 workpiece surface roughness, total time of a polishing cycle and removal depth with different path spacing

path space (mm)	T (min)	Ra (nm)	h (μm)
0.5	25.25	20	38.814
1.0	12.75	21.2	26.180
1.5	8.75	23.4	24.769
2.0	6.75	25.5	10.860

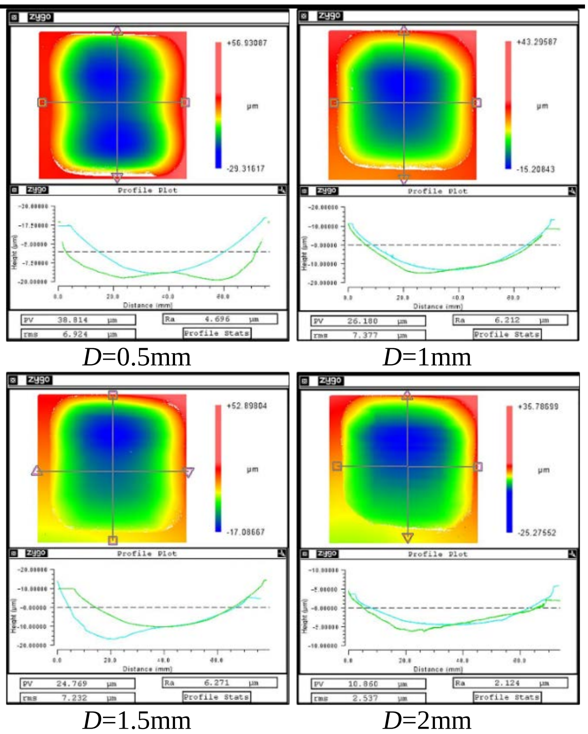


Fig. 13 The surface measurement result testing analysis with different path space

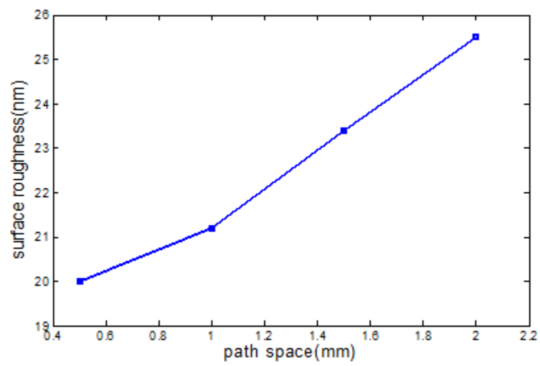


Fig. 14 Average surface roughness Ra with different path space

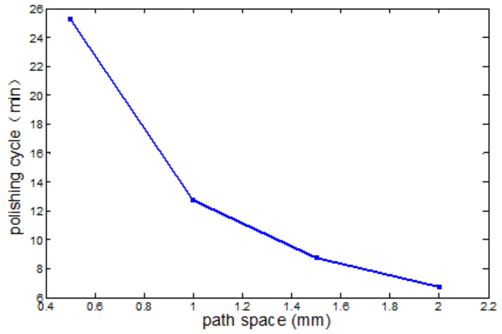


Fig. 15 Polishing cycle with different path space

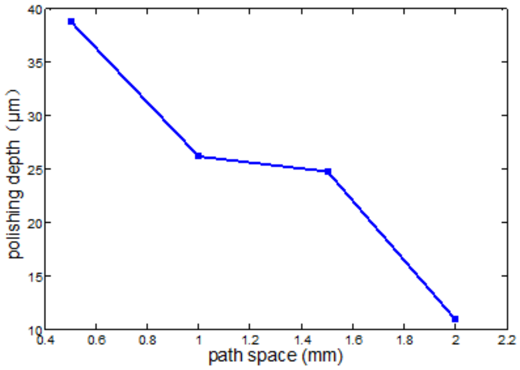


Fig. 16 Polishing depth with different path space

In practical polishing, in order to find out the optimal spacing of tool path in workpiece polishing using FADPs elasticity tool, all of the above factors should be considered, i.e., the accuracy and efficiency of polished surfaces with various spacing of tool path are compared from the above 3 aspects, the results are shown in Table 6. Therein, the minimal path space (D=0.5mm) was set as a standard, of which the value is 0. According to Table 7, comparing to the standard, when the spacing of tool path is 1mm, the total time of a polishing cycle reduces by half, meanwhile the surface roughness raises up by 6% and polishing depth decreases by 32.5%. When the spacing of tool path is set to be 1.5mm or 2mm, the total of a polishing cycle reduces further, while the increasing trend of surface roughness is more obvious, but the polishing depth decreases largely which maybe can't meet the requirements of polishing efficiency.

Table 7 Rate of change on workpiece surface roughness, polishing cycle and polishing depth with different path space

path space (mm)	Change rate of T	Change rate of Ra	Change rate of h
0.5	0	0	0
1.0	-49.5%	+6%	-32.55%
1.5	-65.324%	+17%	-36.6%
2.0	-73.26%	+27.5%	-72.02%

According to the above results, both the polishing quality (corresponding to surface roughness) and polishing efficiency (corresponding to total time of a polishing cycle and removal depth) are affected by the spacing of tool path. Consequently, comprehensive optimal polishing quality can be achieved by taking above three factors into account using the proposed ET. Specifically, different weighting factors for the above factors can be set to find the optimal spacing of tool path.

CONCLUSIONS

In order to further expand the application of the proposed ET with FADPs, investigation on the key removal characteristics of the ET was presented, and the following conclusions were achieved.

(1) The texture, weight lost and removal function of the ET before and after long time polishing are compared, it is found that although the polishing time increases a lot, the weight lost of the ET is tiny, while the texture of the abrasives which cuts the workpiece material remains sharp, moreover, both the shape and the efficiency of tool removal function are stable. All of the above results prove the stability of the proposed ET with the increase of the polishing time.

(2). By controlling the exceeding distance of the polishing tool over workpiece, the warping edge after polishing can be significantly reduced, thus the edge effect in the polishing process can be obviously suppressed, therefore the additional time spend on the subsequent correction cycle can be saved.

(3). Along with the increase of the spacing of tool path, the roughness of workpiece surface after polishing increases, while both the total time of a polishing cycle and the removal depth of workpiece decreases.

Consequently, in practical polishing, comprehensive optimal polishing quality can be achieved with the spot radius is 27mm, the exceeding distance d = 4mm and path space D=1mm by using the proposed ET.

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NOMENCLATURE

ET elasticity polishing tool

FADPs fixed abrasive diamond pellets

HBMs hard and brittle materials

r the radius of Pellet

e1 the eccentric distance of ET from the geometric center of the common axis

e2 the eccentric distance of pellets from the center of ET

d the exceeding distance of the ET over the sample edge

D the spacing of tool path

固定磨料金剛石顆粒彈性刀具的關鍵切削特性研究

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摘要

爲了進一步探究金剛石固結磨料(FADPs)彈性拋光工具(ET)在硬脆性材料加工上的能力，本文設計進行了一系列的實驗來驗證其加工穩定性和整面拋光應用相關的關鍵技術。實驗結果表明：該彈性拋光工具在長時間的加工過程中固結磨料片的磨損量小、磨粒依然能夠保持鋒利並且工具的去除函數能保持良好的穩定性，這均驗證了該工具具有好的加工穩定性；此外，加工時可通過控制工具的溢邊量來抑制邊緣效應，以此降低拋光後工件的翹邊現象；同時，整面拋光時隨著路徑間距的增大，拋光周期和去除深度相應的減小，但是工件的表面粗糙度增大。本文對于自研的固結磨料彈性拋光工具的實際應用具有重要意義，在實際加工過程，綜合考慮以上三個因素能夠優化拋光後的表面質量。