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ORIGINAL ARTICLE

The effect of tool wear on the removal characteristics in high-efficiency bonnet polishing

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Abstract In order to figure out the effect of tool wear on the material removal process in bonnet polishing, an experimental study based on the comparison of removal characteristics of bonnet tools with various wear conditions is presented. Before the experiments, the tool surfaces were measured using a digital microscope, and it revealed that not only the surface contour but also the surface topography were changed by tool wear. For this reason, a preprocessing, i.e., a uniformity controlling method for the spot size, was proposed and validated to keep the spot size constant using static stress sensor. Subsequently, the comparative experiments were conducted, and it was indicated that along with the increase of the wear degree of the bonnet tool, the removal shape changed and the peak removal depth, peak removal in unit time, and removal volume reduced significantly, but the roughness of the polished surface becomes better. Based on the results and the analysis, we deduced that the probably causation for the above phenomenon is the variation of the friction between the workpiece and bonnet tool, because of the alteration of the tool surface topography brought by tool wear. Consequently, the forces in the polishing process were measured using a 3-component dynamometer, and the friction coefficient was calculated. The results showed that the variation trend of the friction coefficient is similar to that of the removal volume, i.e., the removal volume and the friction coefficient of the mild wear tool are basically the same to the new tool, but apparently larger than the severe wear tool, which demonstrates that the reduction of the friction coefficient by tool wear is one of the most important reasons for the decrease of the removal efficiency.

Keywords Bonnet polishing · Tool wear · Precision polishing · High precision optics

1 Introduction

Due to the superior optical performance, high precise optics have been more and more widely used in the fields of military, aerospace, and civil, which contribute to its high strategic position and tremendous demand. For the above reasons, manufacturing technology for high precise optics has become a research hotspot in recent years, and consequently, great progress has been made by the researchers [1–3]. To date, not only various technologies such as ultra-precision grinding, computer-controlled optical surfacing, ion beam finishing, and bonnet polishing have been introduced and developed but also the processing strategy, i.e., "high efficiency grinding-precision polishing-low defect production" were proposed and demonstrated [4–7].

In the processing strategy, precision polishing is supposed to be the most important procedure, which determines the

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machining period and cost, because it takes charge of the surface error as well as improving the surface roughness. However, precision polishing is still a time-consuming work so far because of the ubiquitous instability and uncertainty in the material removal process. And this is the main reason that restricts the development of mass processing of high precision optics [5, 8].

In most of the existing material removal theories, the removal characteristics of the polishing tool keeps stable in the polishing process is a basic assumption [9, 10]. However, some researchers pointed out that the removal characteristics of the polishing tool would be affected when the tool is worn.

For example, Su et al. [11] found via experiments that both the surface texture and radius of curvature of the polishing tool change when the tool is worn, which varies with the removal characteristics. Park et al. [12] investigated the influence of pad wear on the removal characteristics of CMP process, by measuring the surface topography and its corresponding removal characteristic, respectively. The results revealed that the worn of polishing tool has significant impact on the removal stability and uniformity, and the mechanism was also explained. Belkhir et al. [13] examined the surface grooves and topographies of the same polishing pad in different periods via SEM, and proposed that the pad is worn by the abrasives and chips of workpiece. Moreover, the worn of pad reduces the polishing efficiency and the accuracy of polished surface of workpiece. Yann et al. [14] indicated that the worn of the polishing tool is one of the most important reasons which results in the removal instability and uncertainty of the polishing tool in the machining process, on the basis of their experimental studies.

As an emerging technology, bonnet polishing is firstly introduced by Walker et al. [15], attracts wide concerns, and has been used in various kinds of applications for its two apparent merits [16–19], i.e., high efficiency and controllability.

Currently, most of the existing literatures pay attention to the controlling and processing technology. Although there is few report on the effect of tool wear on removal characteristics in bonnet polishing, it is almost certainly that the high removal efficiency would rapidly lead to the worn of bonnet tool, then affects the removal stability and certainty in polishing process. Consequently, in order to improve the machining process of high precision optics, it is important to investigate the effect on the removal characteristics by the worn of the bonnet tool in this paper. Based on this work, the prediction and compensation can be conducted to make sure the removal stability and certainty of bonnet tool remains stable in the future work.

2 Experimental design and setup

With the aim to investigate the impact of tool wear on the removal characteristics, comparative experiments are carried out in this section. Indeed, in order to save time, three bonnets with different initial conditions are tested to polish the specimens with identical parameters, and the removal characteristics are compared and discussed. The machine tool used in the experiments is a self-developed equipment, which has been introduced in the previous studies [10, 20].

2.1 Measurement of the surface texture

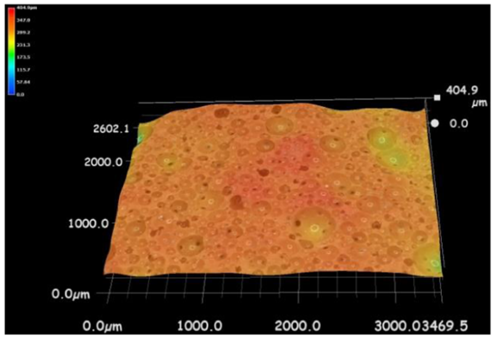
Before the experiments, the surface texture of the three tools is measured by digital microscope (NewView 7200, made by Zygo), the results of which are presented in Fig. 1. It is interesting to find from the axis scales on the top right corner (404.9 μm for new pad, 868.5 μm for mild wear pad, and 1175.6 μm for severe wear pad) of Fig. 1 that the new pad (shown in Fig. 1a) is flatter than the other pads in overall; nevertheless, it seems more rough due to the dense pores on the surface. Figure 1b, c reveals the surface texture of the mild wear tool and severe wear tool, respectively. It is clear that after a period of processing, there are many pits on the pad surface due to wear of abrasives and workpiece; moreover, most of the pores have been change to glazing area.

Based on the measured results of the three tools in Fig. 1, it is evident that the tool wear can alter the surface shape and texture. According to our previous studies, the variation of the surface shape and texture would lead to the change of the actual compression of the polishing tool, thus influencing the shape and size of polishing spot. However, the uniformity of spot shape and size is premise to compare the removal characteristics of bonnet tools with the three wear conditions. Thus, before the comparative experiments, the processing parameters and, indeed, the compression of the bonnet tool should be controlled to keep the spot shape and size constant.

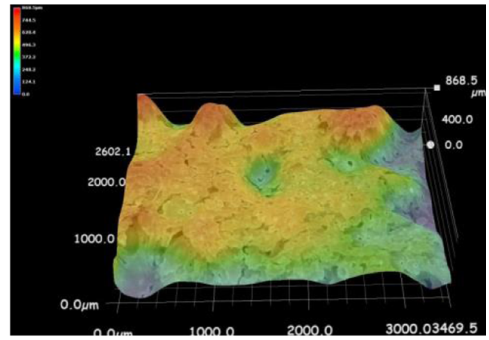
2.2 Uniformity controlling of spot size

As stated in the above paragraph, the control of spot size uniformity is presented before the comparative experiments using a static stress sensor (as shown in Fig. 2, I-Scan, made by Tekscan), which is used for measuring the stress distribution of the polishing spot. Referring to Fig. 2b, the details of the controlling process are as follows: push down the bonnet tool slowly, until there is a force between the tool and workpiece, and set the position of tool as the original point. After that, the bonnet tool is kept on pushing down until the compression is 1 mm with a descent velocity of 2 mm/min. During

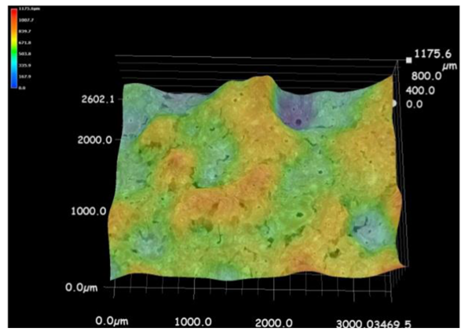
Fig. 1 Surface texture of bonnet tools with the three wear conditions



(a) new



(b) mild wear



(c) severe wear

this period, the variation of the area and stress distribution on the contact zone are recorded and plotted in Fig. 3.

Figure 3 shows that the spot size of all the tools varies along with the change of the compression (corresponding to the variation of the time) and the wear condition. As stated before, the purpose of the measurement of static stress distribution on the polishing spot is to obtain the appropriate compression for each tool, which ensures that the spot sizes of tools with the three wear conditions are the same. In our experiments, the spot area of 310 mm^2 is selected to be the controlling objective, which is a most frequently used parameter in actual polishing. Referring to Fig. 3, the required compressions of the three tools are 0.89, 0.93, and 0.65 (the corresponding times are 26.8 s for the new pad, 27.9 s for the mild wear tool and 19.6 s for the severe wear tool). The spot size and the stress shape after controlling are shown in Fig. 4.

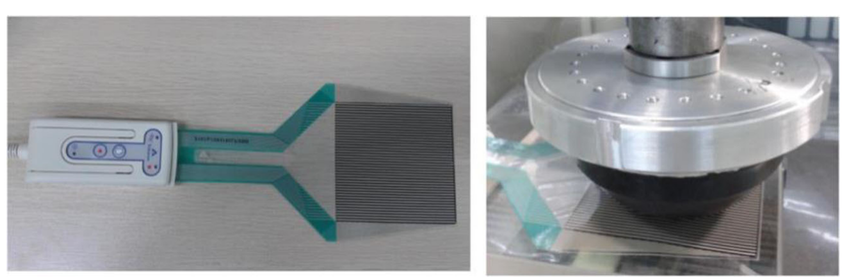
According to Fig. 4, it is apparent that the spot size of the three wear condition tools becomes the same after the control strategy, also as the stress distribution on the polishing spot. These results prove the validity of the proposed controlling method.

Consequently, after the preprocessing (i.e., the measurement of the surface texture of tool, uniformity controlling of spot size) stated in the above paragraphs, the polishing experiments are conducted by tools with the three wear conditions.

2.3 Experimental conditions

Figure 5 illustrates the specifications of the comparative experiments. As can be seen, the removal process is conducted on a 100 × 100-mm BK7 glass, the peak value (PV) of which is pre-polished to ~1 μm, and the reserved edges of both directions are 5 mm. Besides, for each condition of bonnet tool, three spots are obtained to make sure the correctness of the results. Other experimental conditions are listed in Table 1. After that, the removal characteristics including removal efficiency and polishing quality are compared, followed by the discussion.

Fig. 2 The measurement of the stress distribution by static stress sensor



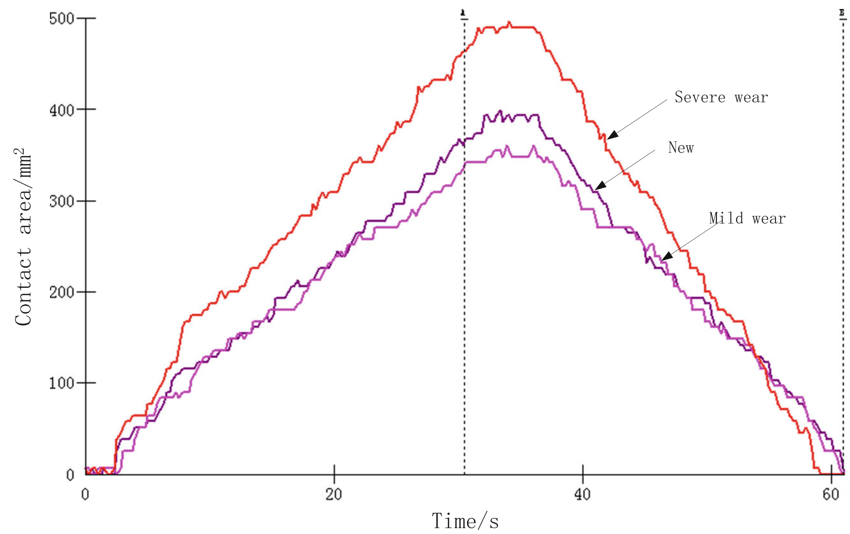


Fig. 3 The variation of spot area during the compression of the bonnet tool with the three wear conditions

3 Results and discussion

3.1 Removal characteristics

Figure 6 reveals polishing spots by different tools with the three wear conditions. Indeed, every three spots in the same line are polished by the same tool, to make sure the repeatable of the experiment. Moreover, the spots are generated by the new, mild wear, and severe wear tools respectively from top to down. The results in Fig. 6a illustrate that the stability of the tools are not affected by the wear condition, since the spots in every line are uniform and consistent. Figure 6b exhibits the removal contour of various spots polished by different wear condition tools. It is found that, under the condition of the uniformity of the spot size, the removal depth of bonnet tool decreases with the increase of the wear degree of bonnet tool. The details of the polishing spots in Fig. 6a are shown in Table 2, which includes the size, shape, and peak removal depth of the spots, and Fig. 7 shows the corresponding comparison results.

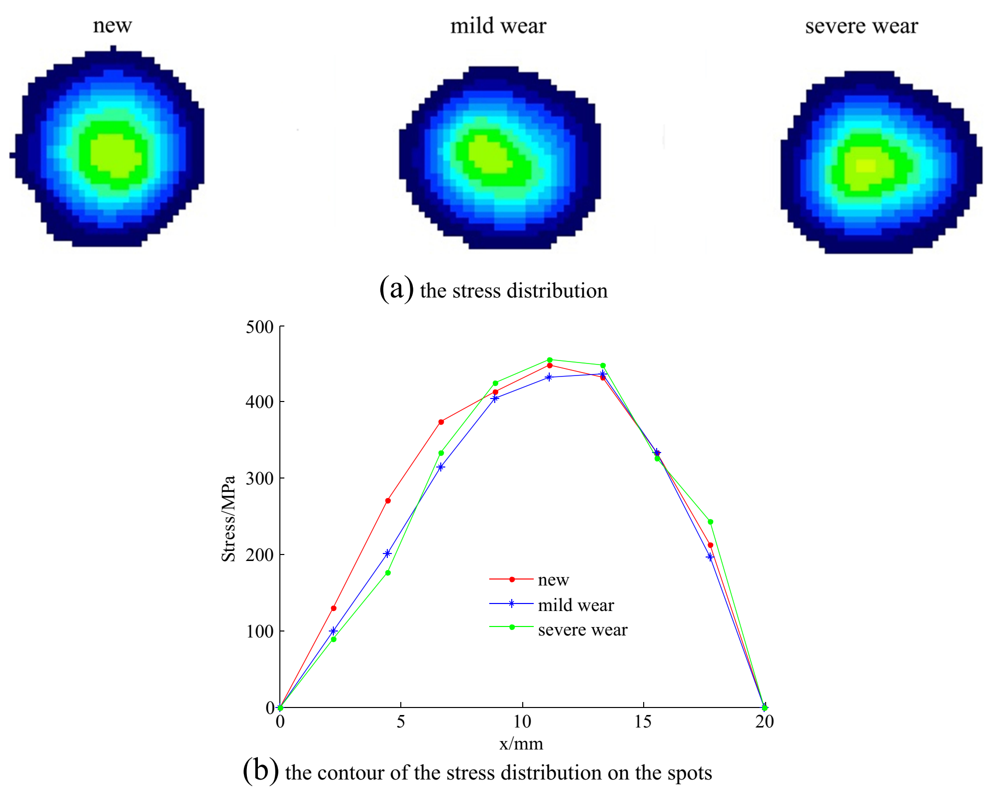


Fig. 4 Comparison of the stress distribution on the spots using different tools with the three wear conditions

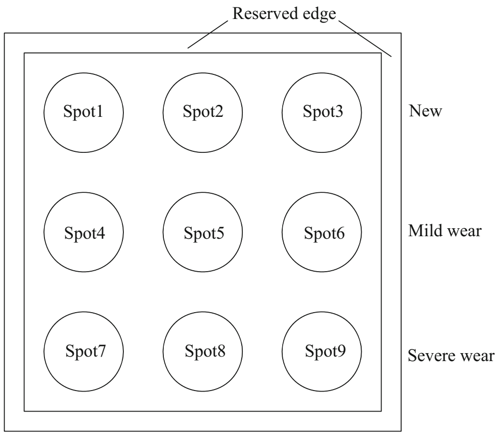


Fig. 5 Experimental specifications

On the basis of the experimental results, discussion of the effects on removal characteristics brought by tool wear is presented from two aspects as follows:

(1) Spot size and spot shape

According to the results in Table 2, the sizes of the spots basically remain unchanged (~19.8 mm) by the assistance of the static pressure transducer. On the other hand, speaking to the shape of the spots, it can be seen from Fig. 7a that the average full widths at half maximum (FWHM) of the three tools are 8.32, 10.8, and 10.08 mm, respectively. This demonstrates that the spot shape changes slightly with the increase of the wear degree of the polishing tool, because the widths of the spots are the same, but not the height.

(2) Removal efficiency

The removal efficiency of polishing tool includes peak removal depth, peak removal efficiency, and removal volume. By referring to Table 2 and Fig. 7b, c, it is found that the average peak removal depth of the new, mild wear, and severe wear tools is 2.33, 1.94, and 1.05 λ, respectively, which exhibits a significant reduction, whose maximum percentage is 54.94%. On the other hand, the average peak removals in unit time of the three kinds of tools are 0.292, 0.243, and 0.131 λ/s, respectively, which also presents an apparent reduction, whose maximum percentage is 55.14%. Regarding the removal volume, according to Fig. 7d, the average removal volume of the new tool is 0.87 mm^3/min and increases about 5% when the mild wear tool is used. However, when the bonnet tool is seriously worn, the removal volume decreases significantly, the value of which is about 0.46 mm^3/min, only approximately half of that of the former two situations. On the basis of the aforementioned results, it is evident that the worn of the bonnet tool directly affects the removal efficiency.

3.2 Roughness

After the comparison of removal efficiency, the polishing quality of tools with the three wear conditions is also compared. In order to ensure the correctness of the result, each experiment is repeated for five times. The specimens applied in this experiment are round, flat, and pre-polished BK7 optics, whose radius and initial roughness are 50 mm and ~1 nm, respectively. The other experimental conditions are the same as the previous experiments. Table 3 shows the roughness of the specimens before and after polishing of various worn condition, and Fig. 8 are the corresponding results of Table 3.

According to Table 3 and Fig. 8, the average roughness of the specimens before polishing is 1.096, 1.014, and 1.19 nm, respectively. However, after polishing, the corresponding average roughness is 2.122, 1.71, and 1.642 nm, respectively. It is interesting to find that all the average roughness values are increasing, no matter what kind of the bonnet tools with different degrees of wear is used. That is because the specimens are polished by the polyurethane pad in this experiment, which is harder than the pitch polishing tool used in the previous process. Therefore, the accuracy of the polished surfaces is reduced. In addition to the above phenomenon, it is also evident that the worn conditions of the bonnet tool influence the accuracy of the polished surface. Indeed, it is found that the quality of the polished surface becomes better with the increase of the wear of bonnet tool.

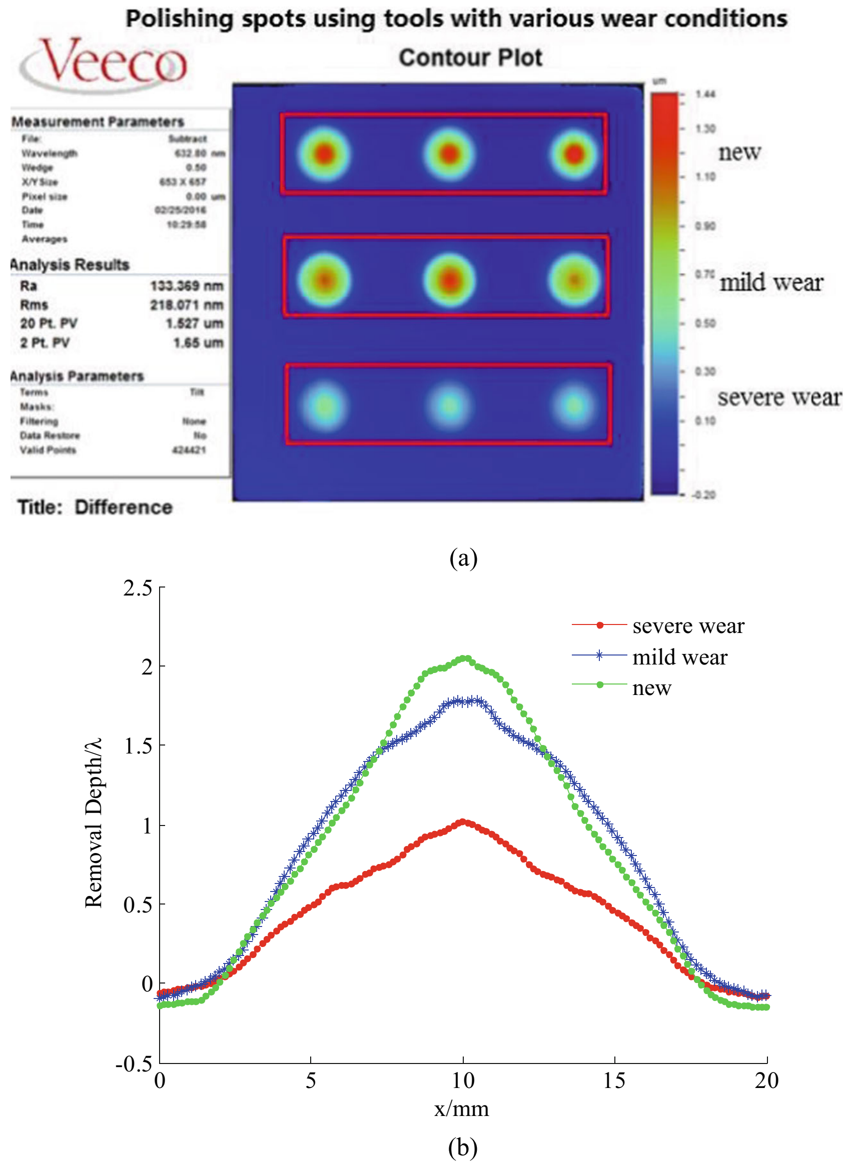
The combination of the experimental results of removal efficiency and polishing quality reveals that the worn condition of the bonnet tool not only greatly affects its removal efficiency but also significantly influences its polishing quality.

It is well known that the Preston law, i.e., $R = k \times p \times v$, is the most frequently used theory to explain the material removal mechanism of polishing process. In which, R represents the removal amount of the material, k is the Preston coefficient, and p and v are the pressure and velocity of the polishing spot. According to Fig. 4, since the spot size in the experiment remains stable, the shape and the value of the pressure on the polishing spot is also basically unchanged. This result

Table 1 Experimental conditions

Bonnet radius (mm)	Spot size (mm)	Bonnet rotational speed (rpm)	Bonnet pressure (MPa)	Precession angle (°)
80	20	1000	0.15	23

Fig. 6 Spots polished by tools with the three wear conditions



makes clear that pressure is not the reason which causes the apparent removal reduction as shown in Fig. 7b. More than that, the velocity distributions of the three bonnets with the three wear conditions is basically the same, because of the constant of the main parameters, i.e., the bonnet revs per minute and the precession angle. It makes clear that velocity is not

Table 2 Removal characteristics of bonnets with the three wear conditions

	Spot size (mm)	Full width at half maximum (mm)	Peak removal depth (λ)	Peak removal efficiency (λ/s)	Removal volume (mm^3/min)
New	19.84	8.84	2.23	0.279	0.897
		8.53	2.27	0.284	0.882
		7.6	2.5	0.313	0.831
Mild wear		11.25	1.85	0.232	0.945
		10.30	2.16	0.271	0.953
		10.85	1.80	0.225	0.868
Severe wear		9.8	1.12	0.14	0.478
		10.3	0.99	0.124	0.450
		10.15	1.04	0.13	0.477

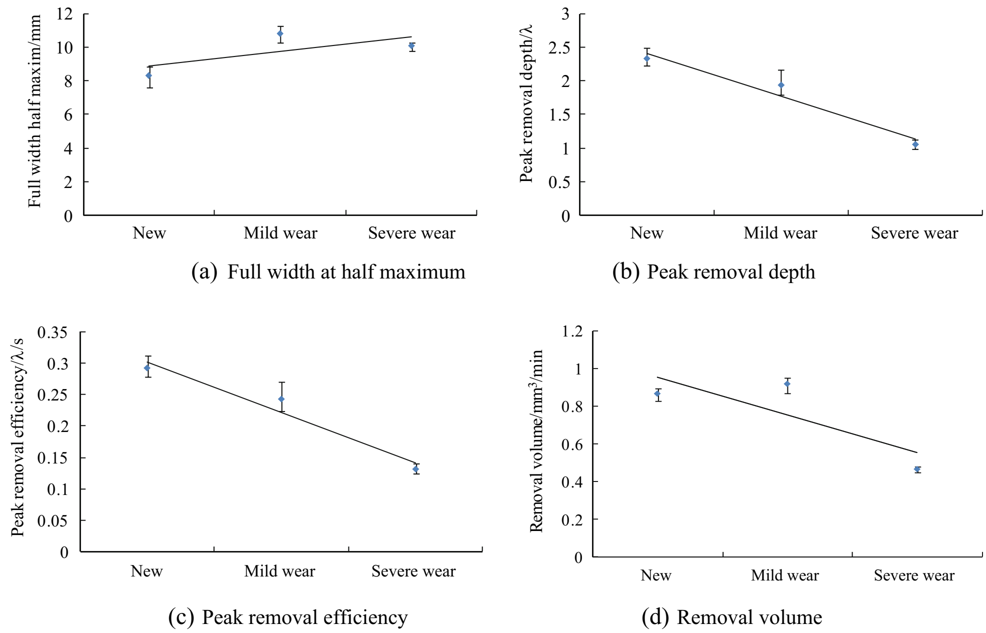


Fig. 7 The effect of tool wear on the removal efficiency

the reason for the apparent reduction of removal efficiency. Consequently, the differences of the removal characteristics of various worn bonnet tools is caused by the Preston coefficient *k*, which affected by the material of the specimen, concentration of the polishing liquid, friction coefficient, abrasive size and hardness, and so on.

On the basis of the above experimental results and the analysis of Preston' s law, we summarized the probably causation of the reduction of removal efficiency as well as the increase of the polishing quality along with the wear of bonnet tool—the pores on the surface are changed to the glazing zone by the wear (see the comparison in Fig. 1) along with the polishing process. This on the one hand smoothes the tool surface and therefore reduces the frictional force between the workpiece and bonnet tool, which is an important part to removal the material. On the other hand, part of the two-body abrasion has been change to three-body abrasion in the polishing process, since most of the pores which support the abrasives are disappeared.

In order to verify the deduction, the forces between the bonnet tool and workpiece in the polishing process using various worn tools are measured and compared. For this purpose, a 3-component dynamometer (model-9255C, made by Kistler) is mounted below the fixture of workpiece as shown in Fig. 9. The specimens are polished under the conditions shown in Table 1, and the forces in the polishing process are measure and indicated in Fig. 10.

Figure 10a indicates the measured normal force in the polishing process using different worn tools. It is clear that the normal force in all processes is stable and periodic, of which the average value are all about 80 N. The difference

Table 3 The roughness of the specimens before and after polishing by tools with the three wear conditions

	Before (nm)	Average(nm)	After (nm)	Average (nm)
New	1.15	1.096	1.9	2.122
	0.99		2.25	
	1.16		2.59	
	1.02		2.26	
	1.16		1.61	
Mild wear	1.01	1.014	1.71	1.71
	1.02		1.43	
	1		1.19	
	1.08		2.48	
	0.96		1.74	
Severe wear	1.34	1.19	1.3	1.642
	1.18		1.7	
	1.19		1.65	
	1.13		1.39	
	1.11		2.17	

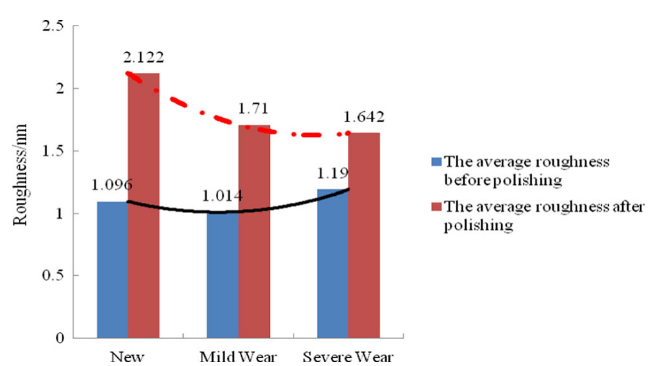


Fig. 8 The quality of the surfaces after polishing by tools with the three wear conditions

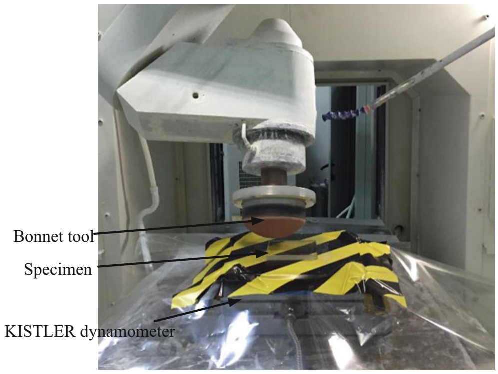


Fig. 9 Measurement of the forces in the polishing process by 3-component dynamometer

is that the amplitudes of the variation period of the later two are larger than that of the new one, because the roundness of the bonnet tool is conditioned before polishing in the new pad, but not the other two.

Figure 10b shows the measured tangential force in the polishing process using different worn tools. According to the result, the biggest difference between the new tool and the other tools is that the variation trend of the tangential force using the new pad goes up straightly at the first, then falls down, and becomes stable at the end, as shown in the red circle. Since the other experimental conditions are keeping constant, the reason of this phenomena is that, comparing to the used tools, the surface of the new pad is harder and more rough at first, which leads to a larger initial tangential force (caused by frictional force). Subsequently, since the surface becomes smoother along with the polishing process, the tangential force falls down gradually until to a fixed value. This is similar to the results reported in the published literatures by Park [21] and Belkhir [22].

Figure 10c reveals the measured *y*-directional force in the polishing process using different worn tools. All the *y*-directional forces are close to 0, because the motion of bonnet tool in this experiment is inclined polishing.

Figure 10d illustrates the friction coefficient (i.e., the ratio of tangential force and normal force [22, 23]) in the polishing process using different worn tools. As can be seen, the values of friction coefficient in polishing processes using the new and mild wear tools are 0.315 and 0.326, respectively. However,

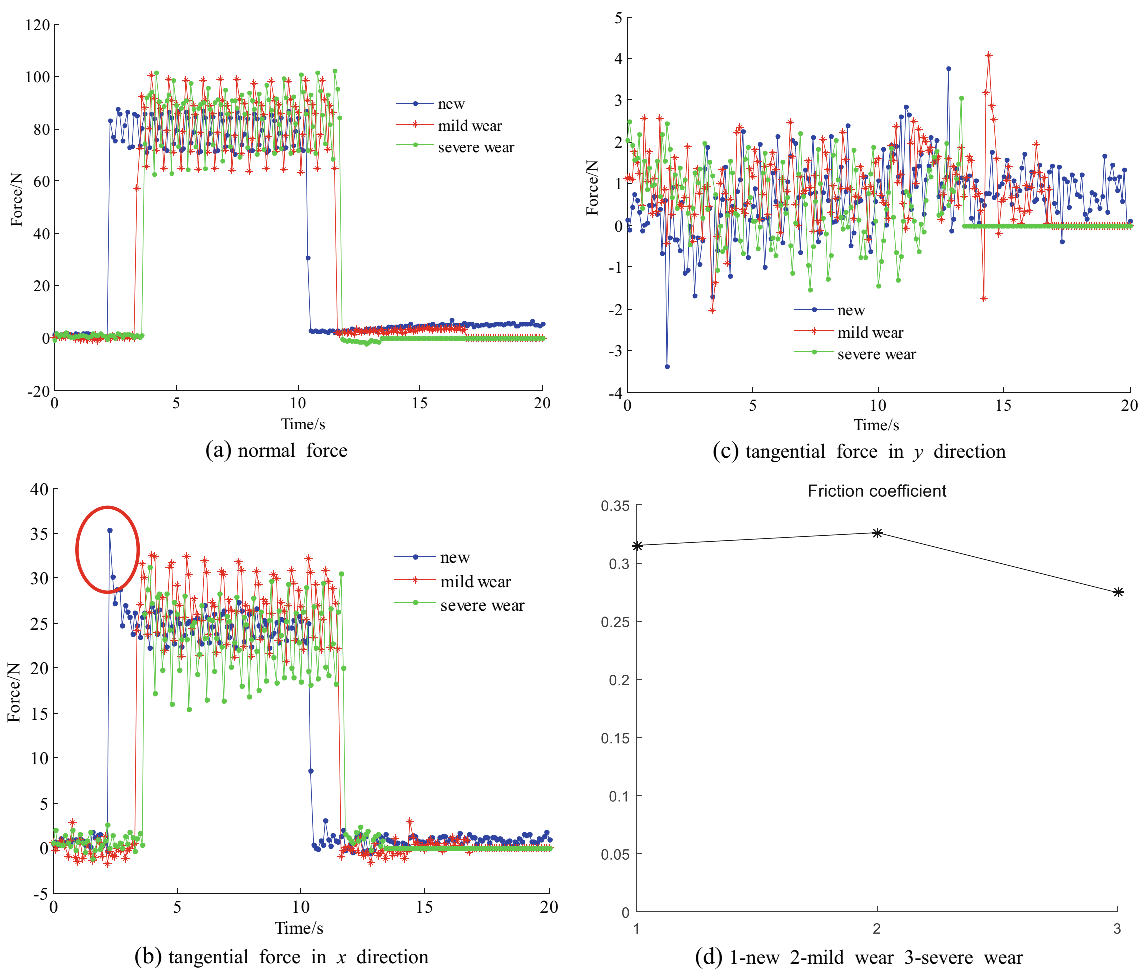


Fig. 10 Measurement results of the forces in the polishing process: normal force (**a**), tangential force in *x* direction (**b**), tangential force in *y* direction (**c**), and friction coefficient (**d**)

when the bonnet tool is seriously worn, the friction coefficient falls down significantly to 0.275. The results demonstrate that an apparent sign of tool wear in bonnet polishing is the reduction of the surface roughness of bonnet tool (refer to Fig. 2, the glazing zones increase when the tool is worn), which leads to the decrease of the tangential force and therefore the drop of the removal efficiency.

4 Conclusions

With the aim to investigate the effect of tool wear on the removal characteristics in bonnet polishing process, experimental studies on the comparison of removal characteristics of bonnet tools with various wear conditions were carried out, and the following conclusions are obtained:

(1) The surface of bonnet tools with the various wear conditions were measured firstly by the digital microscope, and the results revealed that not only the surface contour but also the surface topography were greatly changed by tool wear. For this reason, a uniformity controlling method for the spot size is presented and validated to keep the spot size constant using static stress sensor.

(2) It was indicated in the comparative experiments using bonnet tools with the various wear conditions that the wear degree of the bonnet tool influences the removal characteristics under the same experimental conditions. Indeed, along with the increase of the wear degree of the bonnet tool, (1) the FWHM are 8.32, 10.8, and 10.08 mm, respectively. This means the contours of the removal function changes slightly. (2) Both the peak removal depth and the peak removal in unit time of the polishing spots fall down straightly, of which the percentage are 54.94 and 55.14%, respectively. (3) The removal volume of the new and mild wear tools is basically equal. However, when the tool is severely worn, the removal volume decreases for about 50% comparing to that of the former two conditions. (4) The roughness of the polished surface decreases, i.e., the quality of the polished surface becomes better with the increase of the wear of bonnet tool.

On the basis of the above results and the Preston's law, we summarized the probably causation—the pores on the surface are changed to the glazing zone by the wear (see the comparison in Fig. 1) along with the polishing process. This on the one hand smoothes the tool surface and therefore reduces the frictional force between the workpiece and bonnet tool, which is an important part in the material removal process. On the other hand, part of the two-body abrasion has been change to three-body abrasion in the polishing process, since most of the pores which support the abrasives are disappeared.

(3) Aim to validate the reduction of the removal efficiency is partially caused by the decrease of the frictional force between the workpiece and the bonnet tool. The forces in the polishing process are measured using a 3-component dynamometer, and the friction coefficient is also calculated. The results shows that the variation trend of the friction coefficient is similar to that of the removal volume, i.e., the removal volume and the friction coefficient of the mild wear tool are basically the same in the new tool, but apparently larger than those in the severe wear tool, which demonstrates the reduction of the friction coefficient by tool wear is one of the most important reasons for the decrease of the removal efficiency.

Based on the achievement of this study, the prediction and compensation can be conducted to make sure the removal stability and certainty of bonnet tool remain stable in the future work.

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