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ORIGINAL ARTICLE

Influencing mechanism of the key parameters during bonnet polishing process

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Abstract In order to better understand the material removal mechanism during bonnet polishing process, an experimental study on revealing how the key parameters affect the material removal of workpiece from the view of force and friction is presented. Firstly, we propose a setup for the measurement of the polishing forces and the calculation method for the friction coefficient. Subsequently, based on series of experiments, the correlation of key parameters, polishing forces/friction coefficient, and material removal of the workpiece is investigated. It indicates that the variation of the spot size rarely affects the friction coefficient but has evident effect on the normal force, which results in the change of the tangential force (i.e., frictional force) and the material removal. The increase of tool rotational speed slightly affects the normal force, but greatly reduces the friction coefficient due to the friction state, therefore decreases the tangential force, but the material removal still grows because the removal frequency of the polishing tool increases with a larger magnate. The tool inner pressure has little effect on the polishing forces, friction coefficient, and the material removal. The tool surface condition is demonstrated to have great impact on both the polishing forces and the friction coefficient, therefore affects the material removal. Moreover, it is found that conditioning of the tool surface is an effective way to improve the tool removal characteristic. Finally, based on the above results, some suggestions for the optimization of the polishing process are proposed. All the findings in this study are important bases to our future study.

Keywords Bonnet polishing · Friction · Key parameters · Material removal

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1 Introduction

Bonnet polishing has been introduced and demonstrated as a new optical manufacturing technology with high efficiency and accuracy. Although it has attracted more and more attentions in recent years due to its obvious merits, the material removal mechanism of workpiece during bonnet polishing process is still far from fully understood [1].

According to the previous literatures, knowing the correlation of the key parameters, acting forces (including the friction between polishing tool and workpiece), and the material removal of the workpiece is crucial to better understand the material removal during the machining process. For example, MIAO et al. [2] studied the effects of processing parameters on material removal for borosilicate glass based on the collected polishing forces. Ajay Sidpara et al. [3] experimentally investigated the effects of the process parameters on polishing forces and material removal and found the normal force is more dominant on material removal compared to other forces. Subsequently, a theoretical model of normal force and tangential force acting on the workpiece is also proposed and validated, which improved the understanding of the workpiece-abrasive particles interaction in the MR fluid based finishing process. Homma et al. [4] explored the effects of parameters on the characteristics of chemical mechanical polishing through measuring frictional force acting on a wafer. Based on the results, an experimental equation was proposed to describe the material removal by modifying Preston's empirical equation. Singh et al. [5] reported their experimental findings about the forces acting during magnetic abrasive finishing and provided correlation between the surface finish and the forces. By this way, the mechanism of material removal is understood. Berkhir et al. [6] measured the friction coefficient between tool and workpiece in CMP process using a computer-controlled electrical system and found that some polishing parameters such as velocity and polishing pad nature have important influences on the friction behavior, which is related to the material removal. Zeng and Blunt [7] presented a research on the influence of process parameters on the polishing forces, as well as the material removal in bonnet polishing. They indicated that normal force increases with the increase in the precession angle, head speed, and tool offset, but varies only slightly with the variation of the tool pressure. Tangential force increases with the increase in the precession angle and tool offset while it shows little variation with the change of the head speed and tool pressure. It is concluded that both normal force and tangential force can contribute to the material removal rate, but tangential force is found to be more correlated with the width of the influence function while normal force has a stronger correlation with the maximal height of the influence function.

Based on the above analysis, figuring out how the key parameters affect the material removal of workpiece from the view of the forces and friction is an effective way to better understand the material removal mechanism, which provides theoretical base for the precision control of the material removal. However, there is few study involved with bonnet polishing focuses on it [8–13]. Consequently, with the aim to better understand the material removal mechanism of workpiece during bonnet polishing process, the setup for the measurement of the polishing forces and the calculation method for the friction coefficient is proposed in Section 2. Subsequently, in Section 3, an experimental study on establishing the correlation among key parameters, polishing forces/the friction coefficient, and material removal is presented, and the influencing mechanism of the key parameters during the glass polishing process from the view of force and friction is discussed. After that, some suggestions for the polishing process are given, followed by the conclusions in Section 4.

2 The measurement of polishing forces and the calculation of the friction coefficient

Figure 1 depicts a typical glass polishing process using bonnet tool, the involved forces during the polishing process are as follows: F_n—normal force and F_t—the tangential force (i.e., the frictional force, which is the resultant force of the component forces F_{tx} and F_{ty}). Thus, according to the definition and the previous study [6], the friction coefficient μ between the bonnet tool and the workpiece is calculated by the following equation:

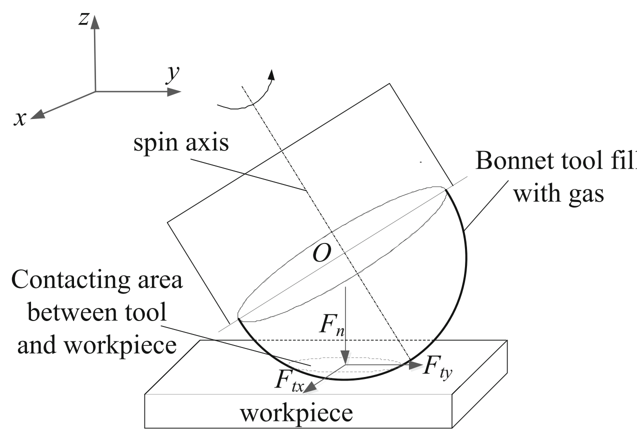


Fig. 1 Typical bonnet polishing process

$$\mu = F_t \big/ F_n \tag{1}$$

As long as the polishing forces are measured, the friction coefficient can be figured out.

Figure 2a schematically illustrates the measurement principle of the polishing forces proposed in this study. The polishing forces are collected by a 3-component dynamometer, which is mounted below the fixture of workpiece. The workpiece, dynamometer, and workpiece fixture are aligned along the z-axis of the machine tool, so that false reading of force measurement due to offset mounting of either workpiece or dynamometer is avoided. The collected data of the polishing forces are transmitted from the dynamometer to the computer, thus it can be analyzed and exported from the user interface of the software. Figure 2b shows the experimental setup established according to the measurement principle. The model of the dynamometer used in this study is 9257B, made by Kistler.

Through the abovementioned methods, the polishing forces and the friction coefficient during the polishing process can be achieved. Thus, the correlation of the key parameters, polishing forces/friction coefficient, and the material removal of workpiece can be established and investigated from the experiment.

3 Experimental study

3.1 Experimental design

In order to figure out the affecting mechanism of the key parameters on the polishing process, multi-group experiments are designed; within every group, the bonnet tool polishes the

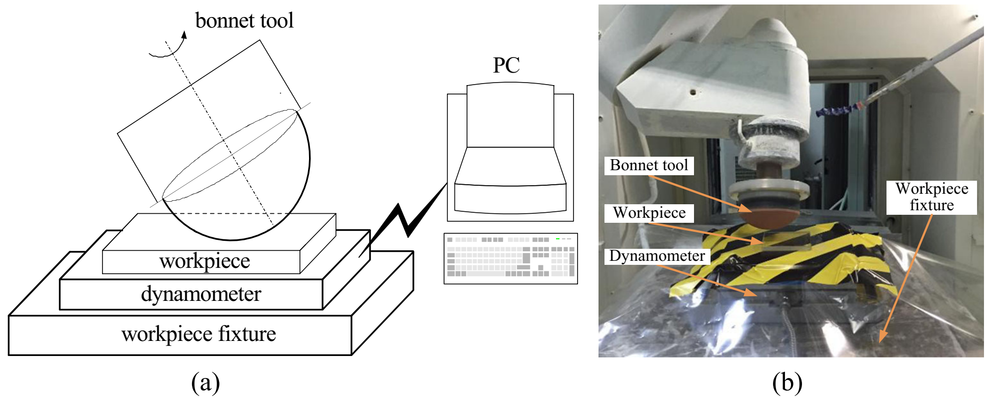


Fig. 2 The principle and the setup of the measurement of polishing forces

workpiece with fixed spot under given parameters. By reference to Fig. 1, the bonnet tool is initially a few centimeters above the workpiece, it moves down firstly to polish the workpiece, after several seconds polishing, it moves up and leaves the workpiece surface. During the polishing process, the polishing forces are collected by the setup shown in Fig. 2b, and the friction coefficient is calculated. Subsequently, the removed material of the workpiece is measured by sub-aperture interferometer (NewView 7200, Zygo made). Based on the above, the correlation among the involved parameters, the polishing forces, and material removal can be established.

According to Fig. 1, the key parameters include the area of the contacting zone (also known as spot size), inner pressure of the bonnet tool, tool rotational speed, and the inclined angle of the spindle. Therein, the inclined angle is excluded because it is hard to control precisely and a lot of factors would be affected if it is changed. Besides, the tool surface condition is found to have impact on the tool removal characteristic; therefore, it is also defined as a key parameter in this study.

The conditions of the designed experiments are listed in Table 1. Note that, for every experimental group, only one parameter changes while other parameters are keeping constant. The workpiece used in the experiment is square optical element, whose length, width, and height are 100, 100, and 10 mm, respectively. The powder of the polishing liquid is CeO_2, of which the size and concentration are ~ 3μm and ~ 2%, respectively. In order to ensure the correctness of the results, for each experimental group, three tests were repeated and the average values of the polishing forces and removed material are obtained. The detailed results and discussion are shown in the following section.

3.2 Experimental results

3.2.1 The influencing mechanism of the spot size on the polishing process

The results of the experimental group 1 of Table 1 are revealed in Figs. 3 and 4.

Figure 3 illustrates the collected polishing forces and the calculated friction coefficient during polishing process using various spot sizes. It is found that the tangential force in *y* direction rarely changes during the polishing process; it is

Table 1 Experimental conditions

Group	Specimen material	Polishing time(s)	Spot size(mm)	Tool rotational speed(rpm)	Inner pressure(MPa)	Tool surface condition
1	Fused silica	8	15	1000	0.15	New
			20			
			25			
2			20	500		
				1000		
				1500		
3				1000	0.05	
					0.1	
					0.15	
4		4			0.15	Severe worn
						After conditioning

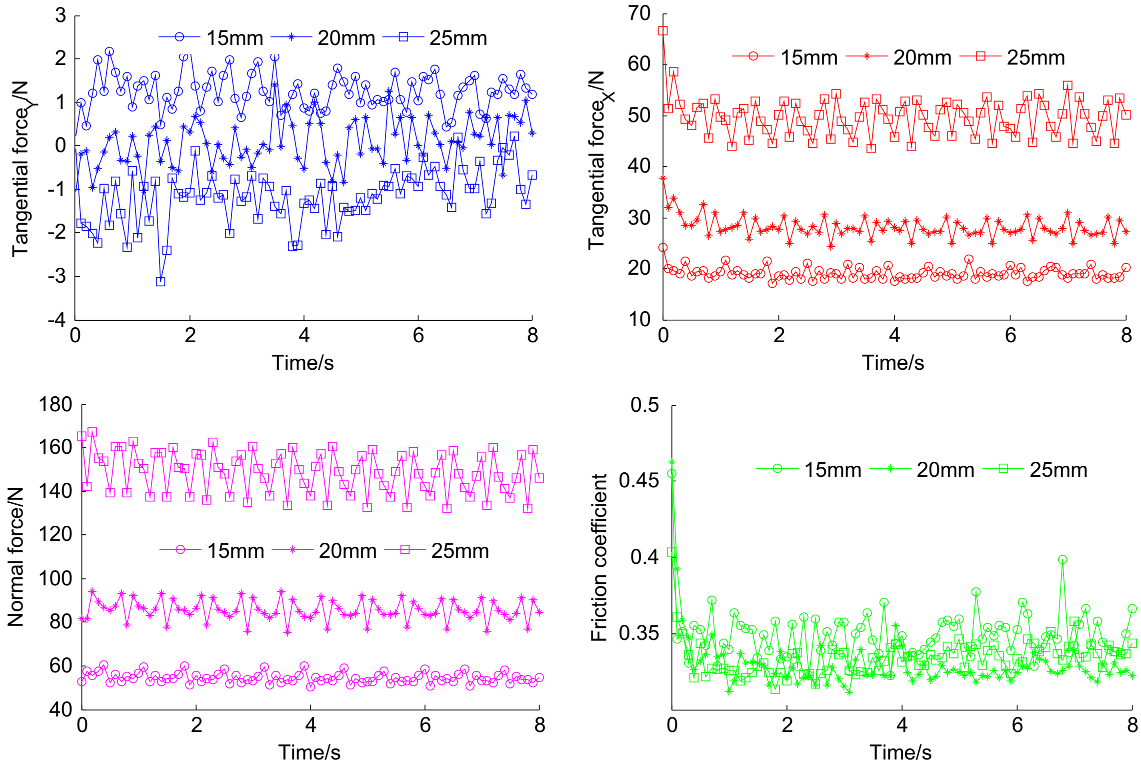


Fig. 3 The collected polishing forces and the calculated friction coefficient during polishing process using various spot sizes

negligible comparing to the normal force and the tangential forces in x direction. According to Fig. 1, that is because the tool polishes the workpiece with incline posture and single rotational direction. Therefore, in this study, the friction coefficient between the polishing tool and the workpiece is calculated by dividing the tangential force in x direction by the normal force.

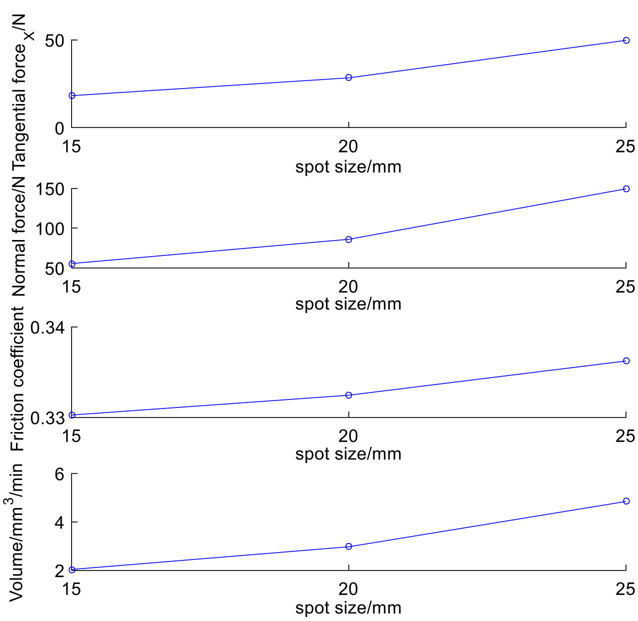


Fig. 4 Correlation of polishing forces, friction coefficient, workpiece material removal efficiency, and spot size

The normal force is found larger than the tangential force. Moreover, the normal forces of various spot sizes change stably and periodically, while the tangential forces decrease sharply in the first seconds and then tend to stabilized.

The friction coefficient between the polishing tool and the workpiece changes with the polishing time and exhibits a similar trend to the variation of the tangential force. From the view of friction [6], this can be explained as follows: in the first seconds, due to the friction between the rough sample surface and the tool surface, the friction coefficient is larger. Subsequently, as time goes, the roughness of the surface decreases and the sample surface takes the form of the tool; the friction coefficient decreases and becomes stable.

Based on the collected polishing forces and the measured data of workpiece material removed by polishing tool, the correlation of polishing forces, friction coefficient, the removal volume per minute, and spot size is established and revealed in Fig. 4. Note that, the data is achieved by the average of the three repeated tests.

According to Fig. 4, all the polishing forces, friction coefficient, and workpiece material removal efficiency are proportional to the increase of the spot size. Specifically, when the spot size increases from 15, 20 to 25 mm, the corresponding normal force F_n is 55.609, 86.060, and 149.432 N, respectively. Comparing to the initial value, the growing rate of the latter two are 54.76 and 168.72%, respectively. Implying that the normal force is very sensitive to the change of the spot size, because (1) with the increase of the spot size, the actual contacting area of workpiece and polishing tool grows, and also the numbers of the particles embed in the contacting area; therefore, the total normal force acting on the workpiece increases. (2) Larger spot size is corresponding to larger bonnet compression against the specimen, which results in a larger interaction force.

With the increase of spot size, the friction coefficient also increases from 0.330, 0.332 to 0.336. However, the differences are only 0.6 and 1.81%. In consideration of the roughness of various local polishing areas are different; we infer that the friction coefficient is basically unaffected by the spot size.

The tangential force increases from 18.238, 28.393 to 49.757 N, with the growth rate of 55.68 and 172.82%. This can be easily explained by Eq. (1).

Moreover, workpiece material removal efficiency is also found to increase with the spot size, i.e., increases by 60.33 and 176.70% from 1.283, 2.057 to 3.550 mm^3/min, showing a close variation range to that of the normal and tangential forces.

Based on the analysis above, the mechanism of how the spot size affects the material removal of workpiece during bonnet polishing process can be summarized as follows: although the increase of spot size has little effect on the friction coefficient between the bonnet tool and the specimen, but it results in the growth of the contacting area between workpiece and polishing tool, therefore rises the numbers of the particles embed in the contacting area and increase the interaction force, both of which greatly enhances the normal forces. Thus, according to Eq.(1), the tangential force increases as well. Since the forces are important cause of material removal; therefore, the material removal efficiency also increases.

3.2.2 The influencing mechanism of the tool rotational speed on the polishing process

The purpose of the experimental group 2 is investigating the effect of tool rotational speed on the material removal of workpiece during polishing process from the view of polishing forces, and the results are revealed in Figs. 5 and 6.

According to Fig. 5, it is found similar to Fig. 3 that the tangential force in y direction is negligible comparing to the other two forces. The normal force is larger than that of the tangential force in x direction. Moreover, there is also a “sharply decreases and then tends to be stable” trend in the collected tangential force in x direction and the calculated friction coefficient. On the other hand, in contrast to Fig. 3, the differences are as follows: the normal force does not change obviously, while the friction coefficient various significantly with the tool rotational speed, that is, the tool rotational speed has less effect on the normal force but more on the friction coefficient than that of the spot size.

Figure 6 depicts the correlation of polishing forces, friction coefficient, the removal volume per minute of the polishing tool, and tool rotational speed. Along with the increase of the tool rotational speed, the normal force varies slightly, i.e., increases firstly by 6.11% from 77.494 to 82.232 N, then falls down to 77.183 N by − 6.14%. The friction coefficient exhibits an inverse proportional relation to the tool rotational speed. Indeed, it decreases from 0.450, 0.335 to 0.310 with the differences of − 25.56 and − 31.11%. This trend is in agreement with the result of Kelm’s et al. [14]. From the view of tribology, this can be explained by the following:

firstly, the bonnet tool polishes the specimen with lower tool rotational speed; therefore, the friction state of the contacting face between them is close to dry friction, of which the friction coefficient is large. Subsequently, as the tool rotational speed raises, more polishing liquid absorbs on the tool surface. Thus, a lubrication film is formed and the face friction state is transformed to boundary friction, which decreases the friction coefficient. Finally, due to the continuous increases of the rotational speed, the face friction state transforms to liquid friction, consequently the friction coefficient reduces further. The tangential force also decreases by − 21.38 and − 32.08% from 34.697, 27.280 to 23.567 N. According to Eq. (1), since the normal force changes slightly while the friction coefficient decreases with a major range, the tangential force shows a significant downward trend. Nevertheless, workpiece material removal efficiency still increases with the tool rotational speed. Indeed, according to Fig. 6, the removal volume per minute of the polishing tool increases with the rotational speed by 21.51 and 25%, from 1.72, 2.09 to 2.15mm^3/min, as expected by the Preston law [15].

On the basis of the results of the above experimental groups, although both the increase of spot size and tool rotational speed enhance the tool removal efficiency, the influencing mechanism is different. Specifically, the increase of the spot size results in the enhancement of the polishing forces, therefore promotes the material removal efficiency. While on the other hand, the increase of the tool rotational speed either varies slightly or decreases the polishing forces, but owing to the increase of the removal frequency in unit time, the material removal efficiency is growing equally. Moreover, the increase of the tool rotational speed is first found to reduce the friction coefficient, which explains why the growth rate of the removal volume per minute is not linear to that of the tool rotational speed in our experiments.

3.2.3 The influencing mechanism of the tool inner pressure on the polishing process

The aim of the experimental group 3 is to investigate the effect of inner pressure of bonnet on the polishing process. Note that, different from the above experimental groups, since the variation of tool inner pressure affects the tool contour as well as

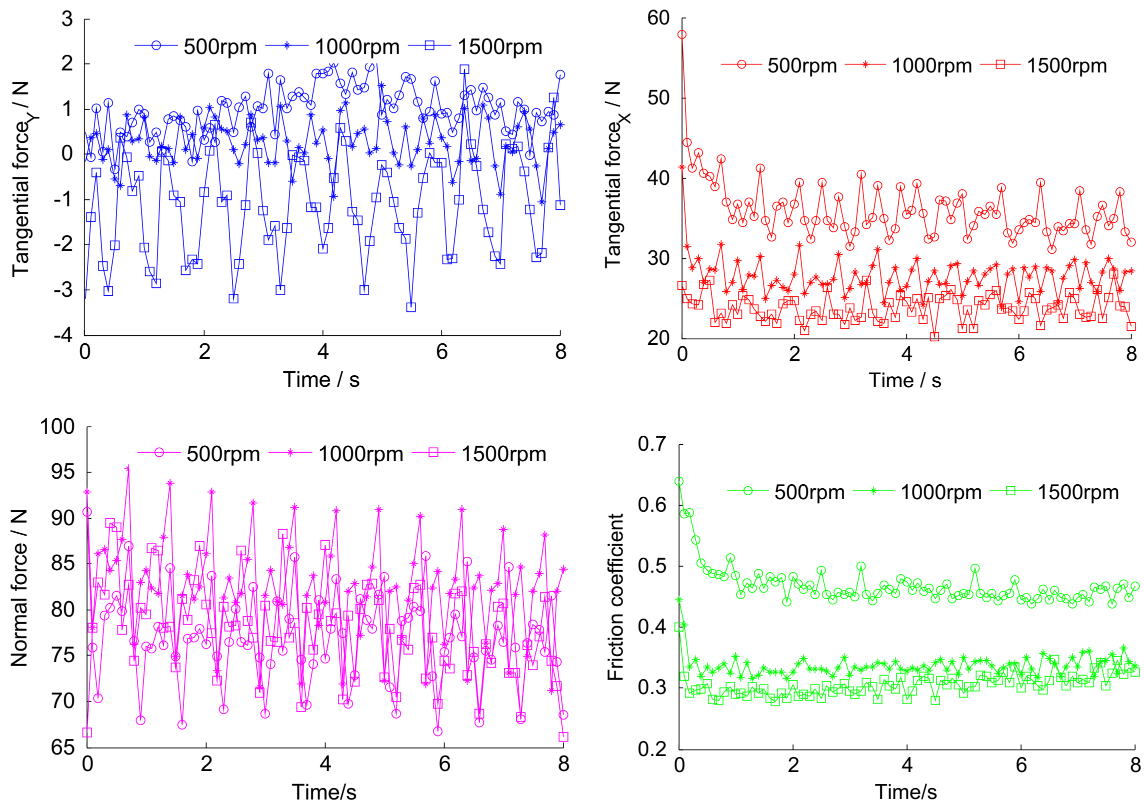


Fig. 5 The collected polishing forces and the calculated friction coefficient during polishing process using various tool rotational speeds

the contacting area between tool and specimen (i.e., spot size); therefore, in order to ensure the uniformity of the spot size, once the inner pressure is changed, the z-offset of the machine tool (corresponding to the bonnet compression) is adjusted too. The experimental results are shown in Figs. 7 and 8.

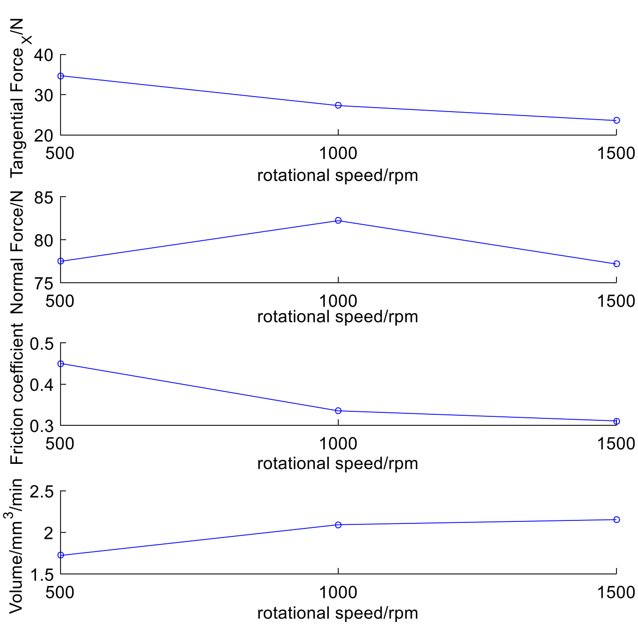


Fig. 6 Correlation of polishing forces, friction coefficient, workpiece material removal efficiency, and tool rotational speed

According to Fig. 7, neither the polishing forces nor the friction coefficient shows significant changes along with variation of the inner pressure of bonnet tool, which is distinct from the above two experimental groups. Specifically, refer to Fig. 8, all of the normal force, the tangential force, and the friction coefficient are inverse proportional to the tool inner pressure. Indeed, along with the increase of the tool inner pressure, the normal force falls down by 0.50 and 9.76% from 93.420, 92.951 to 84.298 N. The tangential force reduces from 30.051, 28.586 to 25.962 N by 4.87 and 13.61%. The friction coefficient decreases by 4.9 and 4.9% from 0.325, 0.309 to 0.309. On the other hand, the workpiece material removal efficiency does not show an apparent trend along with the increase of the tool inner pressure, in fact, it increases firstly by 3% from 2.082 to 2.145 mm^3/min, then falls down by 8.77% to 1.899 mm^3/min.

It should be pointed out that according to the related studies [16, 17], the normal force is supposed to increase with the tool inner pressure, which is opposite to the experimental result. By analyzing the polishing process, this is caused by the adjustments of the z-offset of machine tool. As stated before, in order to ensure the uniformity of the spot size, as long as the inner pressure is changed, the z-offset is adjusted. Therefore, with regard to the tool with higher inner pressure that causes more deformation of tool contour, the z-offset is less, which reduces the normal force (see Fig. 4, less z-offset is corresponding to smaller spot size).

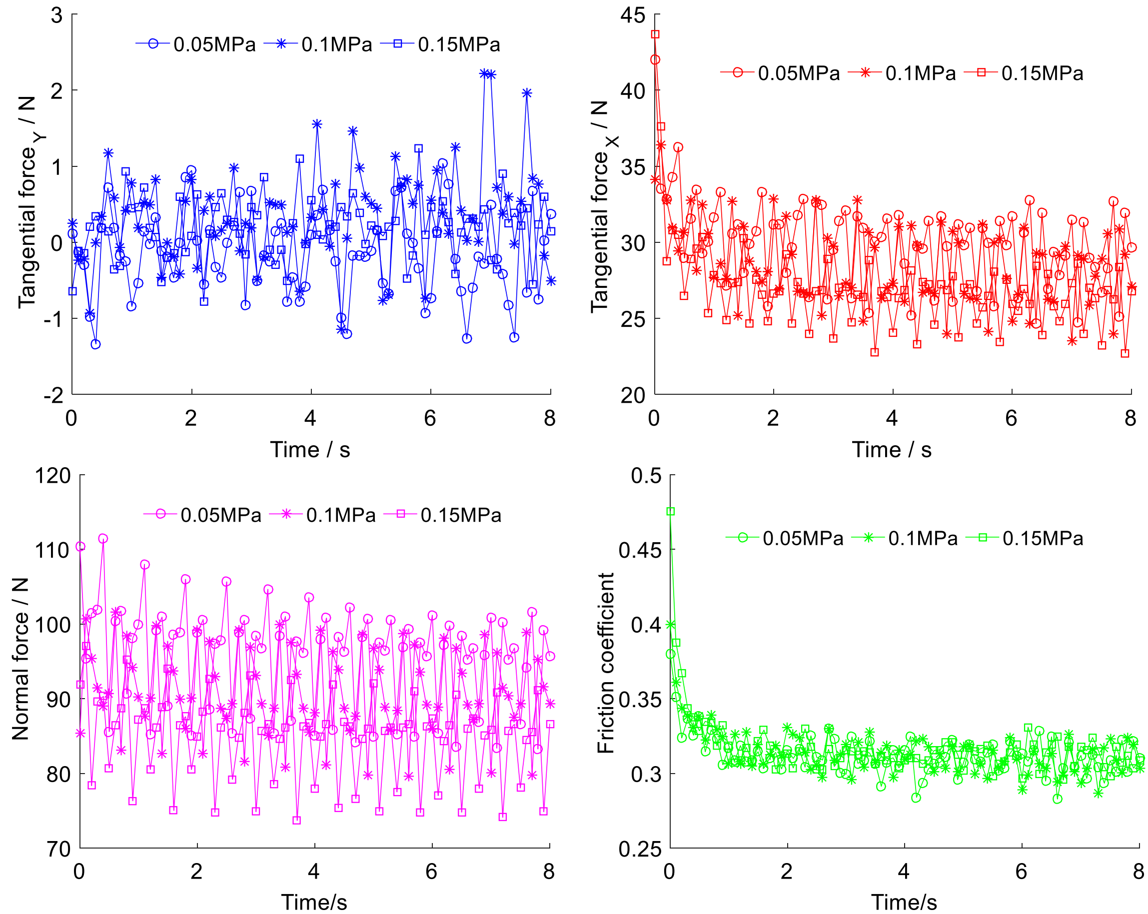


Fig. 7 The collected polishing forces and the calculated friction coefficient during polishing process using various inner pressures

With the purpose to demonstrate that the reduction of normal force is caused by the variation of z-offset, an additional experiment is carried out, of which the conditions are shown in Table 2. In this experiment, the z-offset is keeping constant. Figure 9 reveals the experimental result.

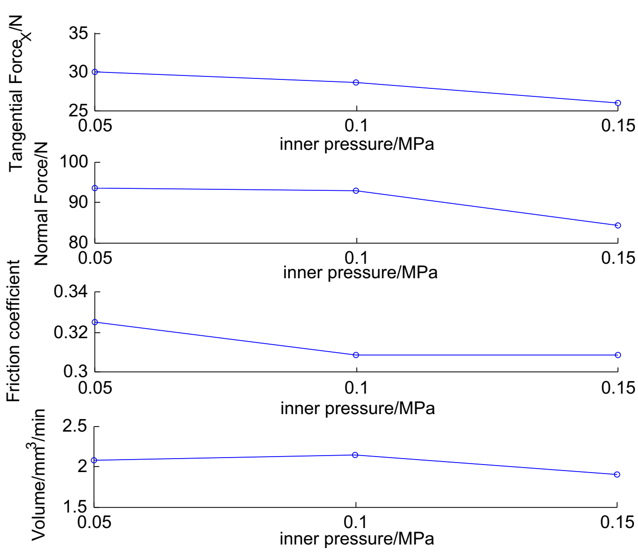


Fig. 8 Correlation of polishing forces, friction coefficient, workpiece material removal efficiency, and tool inner pressure

According to Fig. 9, on the premise that the z-offset is keeping constant, all of normal force, tangential force, and friction coefficient are proportional to the tool inner pressure, which exhibits an opposite trend to the initial experimental results shown in Fig. 8.

Combing the above experimental results, it is proved that the reduction of normal force in Fig. 8 is caused by the variation of z-offset because of the multi-adjustment, implying that tool inner pressure affects the polishing forces by changing the tool contour.

Table 2 Conditions of the additional experiment

Pressure (MPa)	Spot size (mm)	Tool rotational speed (rpm)	Pad condition	Workpiece material
0.05	20	1000	New	K9
0.1				
0.15				

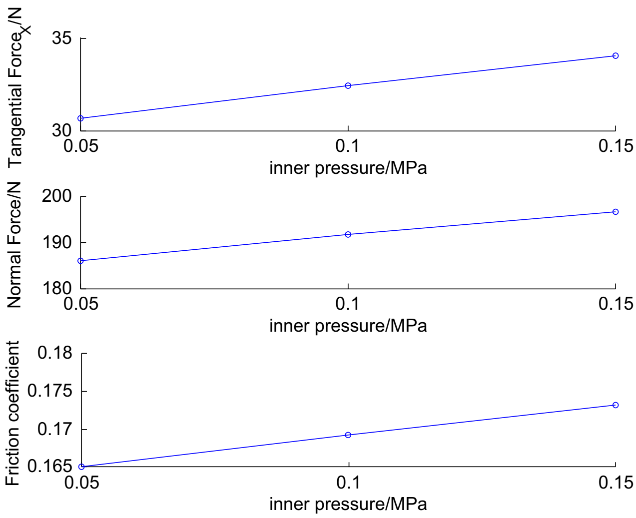


Fig. 9 Correlation of polishing forces, friction coefficient, and tool inner pressure

Consequently, the tool inner pressure is demonstrated to affect the polishing forces and tool removal characteristic by changing the surface contour of the polishing tool. However, not only the polishing forces but also the workpiece material removal efficiency varies slightly (less than 10%) with the increase of the tool inner pressure. The main reason is a steel sheet used to enhance the hardness as well as reducing the flexible of the bonnet is embedded in its internal structure [16], thus the deformation of the tool caused by the increase of inner pressure decreases, therefore the impact on the mechanical characteristic also reduces.

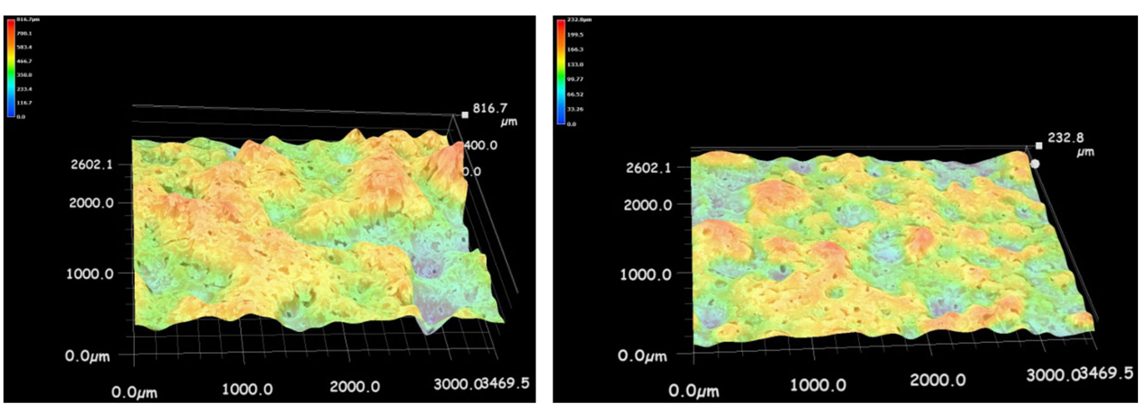
3.2.4 The influencing mechanism of the tool surface condition on the polishing process

In our previous study [18], we found the tool surface wear influences the material removal of workpiece, consequently the tool surface condition is first selected as a key parameter to be studied. At the beginning of this experiment (group 4 in Table 1), a severe worn bonnet (long-time used, poor efficiency, whose profile is revealed in Fig. 10a, measured by Keyence digital microscope) is chosen to polish the workpiece. After that, via the conditioning process, the tool surface is broke to generate a new surface, whose profile is shown in Fig. 10b. Subsequently, the conditioned tool surface is applied to polish the specimen with identical conditions. Within both the polishing processes above, the polishing forces are collected and revealed in Fig. 11, while the polished spots are measured and shown in Fig. 12, in this way, how the tool surface condition affects the contacting properties, the polishing forces, and tool removal characteristic (corresponding to material removal of workpiece) during the polishing process is presented.

Figure 11 reveals the collected polishing forces and the calculated friction coefficient. Both the normal force and tangential force are non-periodic when severe worn bonnet tool is adopted, while on the other hand, they are basically periodic when the conditioned tool is used. Moreover, the values of both the normal and tangential forces of the latter are in higher level, implying that not only the value but also the regularity of the forces are affected by the tool surface condition. In addition, the friction coefficient of the tool after conditioning is found larger than that of severe worn tool.

Regarding the spot shape, Figure 12a reflects that the spots obtained by the severe worn tool are irregular. Indeed, the shapes are close to triangle but not a standard ellipse in theory. In contrast, according to Fig. 12b, the spots polished by conditioned tool surface are all regular ellipses, close to the spots obtained by the above experimental groups. This illustrates that the tool surface condition affects the shape and the area of the contacting zone.

Figure 13 shows the quantitative change of the polishing forces, friction coefficient, and workpiece material removal efficiency, therein, the SW and AC represent “severe worn tool” and “tool after conditioning,” respectively. To be



(a) severe worn tool (b) tool after conditioning

Fig. 10 Profile of severe worn tool and the tool after conditioning

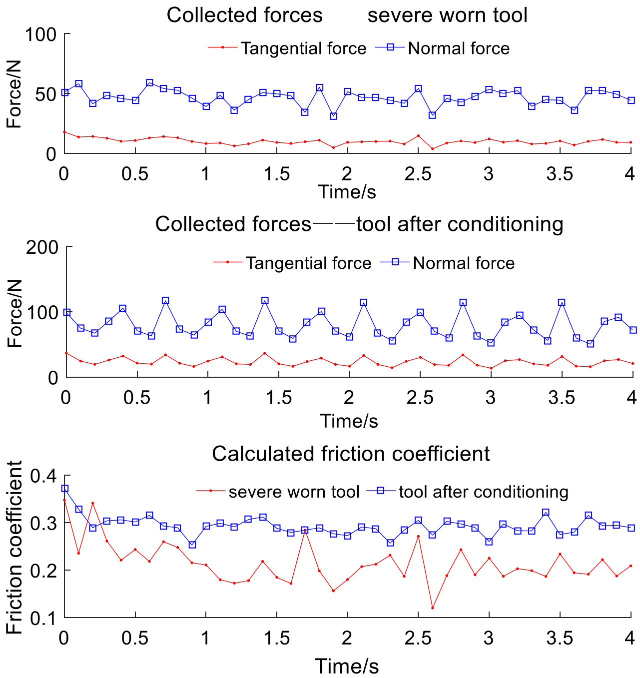


Fig. 11 The collected polishing forces and the calculated friction coefficient during polishing process using tool various surface conditions

specific, under the identical conditions, the normal force in the polishing process using the conditioned tool is obviously larger than the severe worn surface (79.301 to 48.779 N).

The reason for the above results is, see Fig. 10, the profile of severe worn surface is apparently rougher, comparing to that of the conditioned surface. Indeed, the peaks and valleys are irregularly distributed on the worn surface. On this occasion, when the severe worn tool rotates and polishes the specimen, the peak zones of the tool surface are fully contact with the workpiece surface, while the contact state of valley areas is either incompletely contact or non-contact with the workpiece. This results in either uneven contact or non-continuous contact and consequently affects the following:

1) the shape and the area of the contacting zone
2) The value and irregularity of the normal force, which is dominated by the contacting zone.

Since the above situation does not appear in the polishing process using the conditioned tool, explaining why the normal force is greater and the spots have larger size and more regular shape, when the conditioned tool is used.

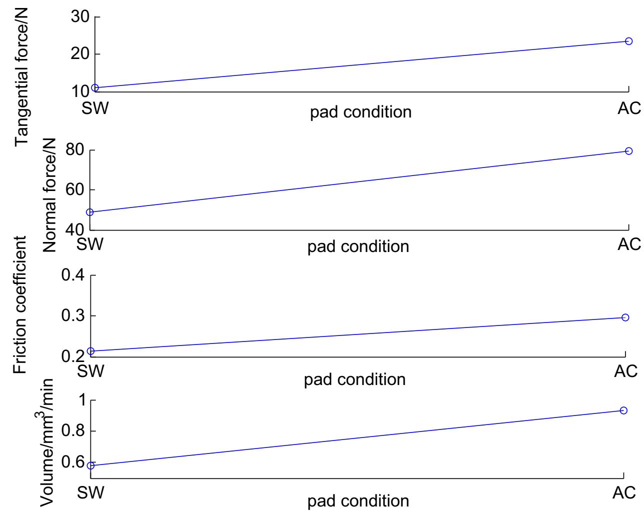


Fig. 13 Correlation of polishing forces, friction coefficient, workpiece material removal efficiency, and tool surface condition

The friction coefficient between tool surface and specimen of severe wear and conditioned surface is 0.213 and 0.295, respectively, implying a 38.50% increase after conditioning. According to Fig. 14, this result can be explained as follows: most places on the surface of the severe worn tool are glazed after a long-time usage (see Fig. 14a); therefore, the frictional coefficient is small. Conditioning is used to break the glazed areas to generate new sharpening areas (close to the rough surface shown in Fig. 14b), which increases the friction coefficient between the tool and specimen during polishing process.

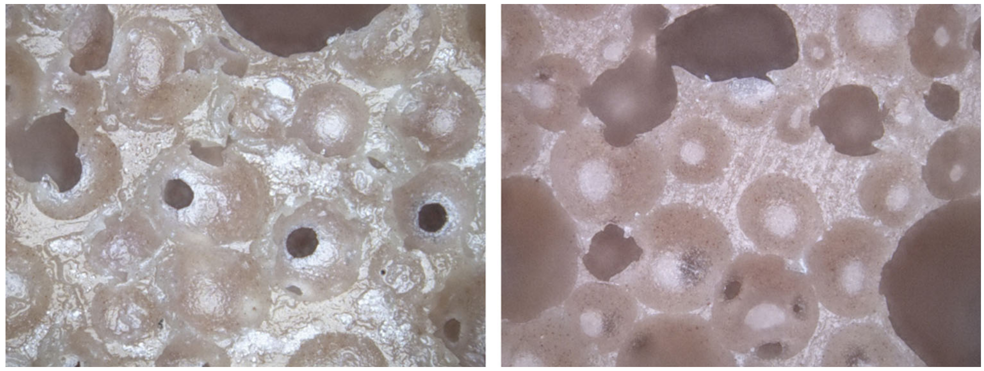
According to Eq. (1), the increase of the normal force and friction coefficient results in the increase of the tangential force; it increases by 114.29% from 10.990 to 23.550 N after conditioning. Since polishing forces are the main causes for the material removal of the workpiece, therefore, the removed material of workpiece enhances inevitably after conditioning due to the increase of the polishing forces, which is consistent with the result shown in Fig. 13. That is, the workpiece material removal efficiency increases by 60.94% from 0.5781 to 0.9304mm^3/min.

Based on the results, the tool surface condition is an important factor in polishing process, which cannot only affect the contacting area, therefore influences the normal force, but also determinates the friction coefficient between polishing tool and workpiece. Moreover, the conditioning process for the bonnet polishing tool can enhance the workpiece material removal efficiency by promoting the normal force and friction coefficient.

Fig. 12 Polishing spots of bonnet tools with different surface conditions

(a) spots polished by severe worn tool surface (b) spots polished by conditioned tool surface

Fig. 14 Partial detail of various tool surfaces



(a) severe worn tool surface (b) new tool surface

4 Discussions

By synthesizing the above result, the mechanism of the key parameters affecting the polishing process can be summarized as follows:

The variation of the polishing spot size influences the interaction force between polishing tool and workpiece, as well as the number of the involved particles during polishing process, which results in noticeable change of the normal force. On the other hand, although the friction coefficient is rarely affected, the tangential force still changes obviously; since the variation of the spot size greatly affects the polishing forces, the workpiece material removal efficiency is sensitive to the change of the spot size.

The increase of the tool rotational speed has little effect on the normal force, but greatly decreases the friction coefficient, therefore reduces the tangential forces. Even so, the material removal efficiency still increases largely because the removal frequency in unit time increases with a major magnitude.

The inner pressure of the bonnet tool is demonstrated to have an effect on the polishing process by changing the tool surface contour. However, since the special structure of bonnet tool, both the polishing forces and the friction coefficient change slightly with the increase of the tool inner pressure; therefore, its impact on the material removal efficiency is minor.

The tool surface condition has evident influences on not only the polishing spot size between polishing tool and workpiece which involves with the normal force, but also the roughness of the tool surface which determinates the friction coefficient; consequently, the tangential force and material removal efficiency are affected.

Thus, according to the above mechanism, there are some suggestions for the optimization of the polishing process: the tool removal efficiency is sensitive to the variation of both the spot size and the tool rotational speed; therefore, they are supposed to be better factors to control the material removal process. However, if the friction between tool and specimen is taken into consideration, the rotational speed is supposed to be the best, because it reduces the friction coefficient. Moreover, the tool surface condition should be concerned before polishing process, and the conditioning process for the bonnet polishing tool can enhance the tool removal efficiency.

5 Conclusions

In order to better understand the material removal mechanism during bonnet polishing process, an experimental study on the correlation of key parameters, polishing forces/friction coefficient, and the workpiece material removal is presented and the following conclusions are obtained:

1) During bonnet polishing process, the normal force is invariably larger than the tangential force. Besides, the increase of spot size has little effect on the friction coefficient between the bonnet tool and the workpiece, but greatly enhances both the normal and tangential force, which results in the increase of the workpiece material removal efficiency. Along with the increase of the rotational speed, the normal force varies slightly, while the friction coefficient decreases apparently due to the variation of the friction state of the contacting face. Thus, the tangential force decreases as well. Nevertheless, since the increase of the removal frequency, the workpiece material removal efficiency also increases. The inner pressure affects the polishing forces and tool removal characteristic by changing the surface contour of the polishing tool. However, the influence is not obvious.
2) The spot size affects the polishing forces and the workpiece material removal efficiency the most; the tool rotational speed does less and the inner pressure does the least; therefore, the former two are supposed to be better factors to control the removal process. However, if the friction between tool and specimen is taken into consideration, the rotational speed is supposed to be the best, because the friction is supposed to be one of the important causes of tool wear.

3) The surface condition has impact on not only the friction coefficient between tool and workpiece, but also the contacting characteristic between tool and specimen, therefore influences the material removal of workpiece. For this reason, the tool surface condition should be concerned in the polishing process. Moreover, this study also reveals the tool removal characteristic can be obviously improved via conditioning.

The finding of this study is crucial to better understand the material removal mechanism during bonnet polishing process, which provides theoretical base for the modeling of material removal. Nevertheless, since the polishing process is complex and affected by a lot of factors besides the mentioned parameters, to establish an accurate model to describe the material removal of workpiece, further study is needed.

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