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Title Page

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Processing performance of vitrified bonded fixed-abrasive lapping plates for sapphire wafers

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Abstract: To enhance the lapping effects of sapphire wafers, two vitrified bonded fixed-abrasive lapping plates with different mechanical properties were developed and used to lap sapphire wafers to evaluate the effects of lapping time and dressing cycle on the lapping process effect and the stability of the lapping plates. The results indicate that the lapping material removal rate (*MRR*) and surface roughness (*Ra*) of the workpiece decrease with increasing lapping time; the higher the hardness of the lapping plate, the larger the *MRR* and *Ra*. There are differences in the primary wear forms between the two types of plates, with the high-hardness plate being mainly abrasive wear and abrasive breakage, while the low-hardness plate being mainly abrasive peeling off and abrasive wear. The two plates have the same trend in material removal for sapphire wafers -increasing the lapping time, the *MRR* is found to be gradually decreased and plateaued after 30 min, which is only about 20% of that of the initial lapping time, resulting in the plates needing to be dressed. After dressing the lapping plates, the plate processing performance returns to its initial state; the *MRR* deviation is less than 10% within the same period of use after several dressings.

Key words: Fixed-abrasive lapping plate; sapphire wafers; lapping; lapping plate wear; lapping plate dressing.

1 Introduction

Single crystal sapphire, the main component of which is alumina (Al_2O_3), has excellent characteristics such as high hardness (its Moh's hardness is greater than 9), high strength, a high melting point (2045 °C), corrosion resistance, and good stability at high temperature. It is widely used in aeronautics and astronautics, biomedicine, mobile communication, semiconductors and other devices, typical applications such as infrared optical windows, foreword fairings, reflectors, LED epitaxial substrate materials, *etc.* [1,2].

The elastic modulus and fracture toughness of single crystal sapphire reach 380 GPa and 3.5 MPa m^{1/2} respectively, making it a typical brittle material [3-5]. Its processing generally consists of cutting, lapping, and polishing [6,7]. Among them, lapping is a key process between cutting and

polishing. Its main function is to remove the cutting marks from the surface of the cutting sheet rapidly, improve the flatness of the workpiece, and the uniformity of the workpiece surface in preparation for subsequent polishing processing; however, the thickness of the sub-surface damaged layer of the workpiece after lapping greatly affects the subsequent polishing time and polishing quality [8,9]. How to obtain a sapphire lapping piece with a high surface quality in an efficient manner is a difficult problem facing engineers responsible for such processing operations.

For the lapping of sapphire wafer, scholars have studied the lapping plate type, processing form, process condition, processing efficiency, and surface damage. For example, for lapping with free abrasive, Yin [10] *et al.* have obtained a smooth surface having a surface roughness of 1.9 nm by lapping single crystal sapphire with free SiC abrasive, but the associated material removal rate (*MRR*) is only 508 nm/h, which is far lower than that when using a fixed-abrasive lapping plate. Lu [11,12] *et al.* the lapping plate with Fenton reaction is prepared, which can greatly improve the lapping *MRR*.

For lapping of fixed abrasives, Gao [13] *et al.* developed vitrified bonded diamond abrasive lapping plates with four different particle diameters to lapping sapphire wafers. Their results found that when the abrasive particle size is greater than 20 μm , the lapping plate removes the workpiece surface material via brittle material removal, which can attain high *MRR*, and is suitable for rough lapping. When the abrasive particle size is less than 7 μm , the lapping plate removes the material with ductility, and a lower surface roughness is obtained. Wang [14,15] *et al.* prepared three types of consolidated diamond abrasive lapping plates with hydrophilic resin and found that agglomerated diamond abrasive has a better lapping effect. Zhou [16] *et al.* evaluated the influences of different abrasive particle sizes on lapping uniformity, and the results showed that the particle size used is 3.5- μm B₄C abrasive lapping, the material is mainly in the form of plastic removal, and after lapping the macro and micro-uniformity of sapphire surface is good. Guo [17] *et al.* developed the ultraviolet curable resin lapping plate for lapping sapphire wafers. Compared with the general lapping plate, the workpiece surface roughness has decreased by 12% and *MRR* has increased by 25%. Yun [18] and Fang *et al.* [19,20] studied the influence of the form of arrangement of pellets on the lapping effect. The results show that the non-uniformity value of abrasive trajectories of different forms of arrangement of pellets is between 0.1 and 0.3. Reducing the non-uniformity of the trajectory can improve the change in the total thickness of the workpiece and the distribution of surface roughness. Chen [21] and Kim [22] studied the wear form of abrasive in the process of lapping single crystal

sapphire and found that the abrasive wear can be divided into three stages: abrasive wear, abrasive flattening, and abrasive peeling off and its material removal form can be divided into “2-body sliding” and “3-body rolling”.

To study the lapping performance of vitrified bonded diamond with different mechanical properties, two types of vitrified bonded diamond lapping plates were prepared under different processes. The effects of lapping time on lapping effect and dressing cycle on the stability of lapping plates were studied; the wear mechanism of the lapping plate in the lapping process and its influence on the lapping effect were investigated.

2 Preparation and experimental design of a lapping plate

2.1 Preparation and performance testing of a lapping plate

The production of vitrified bonded diamond lapping plates is mainly divided into two parts: the production of diamond pellets and the production of lapping plates. The production process is shown in Fig. 1. The manufacturing of diamond pellets proceeds as follows: even mixing of various components required for manufacturing diamond pellets in the desired proportions is followed by placement of the mixture into the lapping tool for cold pressing (the thickness of the diamond pellet thus formed is 5 mm to 6 mm); then the cold pressed diamond pellets are dried and sintered to obtain the corresponding diamond pellets; finally, the sintered pellets need to be polished and dressed to remove surface and edge burrs. The manufacturing steps of the lapping plates are: arranging the trimmed diamond pellets on the base in a certain way; then, a mixture of epoxy resin glue and 800# silicon carbide powder is used to fill the space around the diamond pellets, and it is put into a vacuum box to stand for more than 12 hours, waiting for the colloid to solidify naturally to obtain the vitrified bonded diamond lapping plate; before use, the lapping plate should be aligned and dressed to ensure the flatness of the lapping plate and the sharpness of the abrasive.

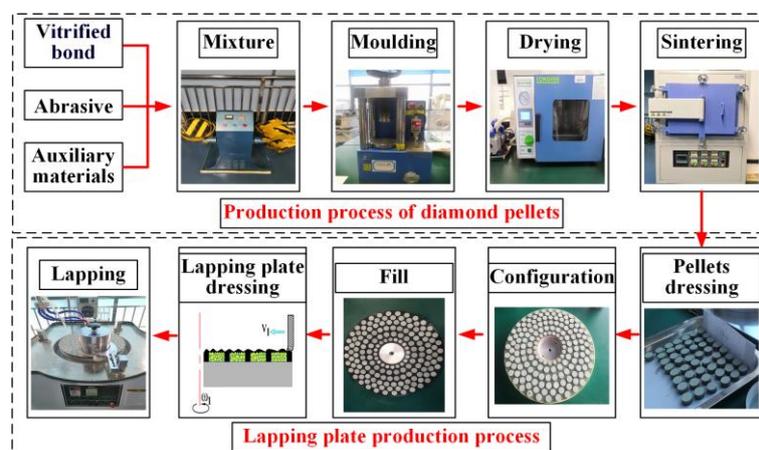


Fig. 1 The manufacturing process used to produce vitrified bonded diamond lapping plate

To study the machining performance of vitrified bonded diamond lapping plates with different mechanical properties, two different types of diamond pellets were prepared, and then two different types of diamond pellets were made into lapping plate. The preparation parameters of diamond pellets are listed in Table 1, the mechanical properties of diamond pellets were changed by application of different forming pressures and pore-forming agent concentrations. The hardness, porosity, and bending strength of the pellets were then measured.

The HR-150A Rockwell hardness tester was selected to measure the hardness of the diamond pellets, the indenter type is a round steel ball (Φ 1.588 mm), and the detection test pressure is that corresponding to an applied load of 600 N. Five diamond pellets were selected at random from the trimmed diamond pellets, and five test points chosen on both sides of each diamond pellet. An AGS-X-50KND electronic universal testing machine was used to measure the bending strength of the diamond pellets (by way of a three-point bending test, Fig. 2). Before testing, the diamond pellets were prepared into 40 mm \times 5 mm \times 6 mm square bar specimens (Fig. 3) according to the testing standard. The porosity of diamond pellets was calculated by the Archimedes drainage method, and the mass m_1 (dry mass) of diamond pellets in dry air, the mass m_2 of liquid discharged when the shot is immersed in liquid under saturated adsorption in the same liquid state, and the total mass m_3 (wet mass) after saturated adsorption in the same liquid were measured. The porosity P of the diamond pellets is the given by Formula 1:

$$P = \frac{m_3 - m_1}{m_2} \times 100\% \quad 1$$

where, P is the porosity of the shot, %; m_1 to m_3 are as defined.

The lapping sapphire wafers were cleaned by ultrasonic in alcohol and deionized water, and then the surface roughness was measured by Taylor-Hobson profilometer after drying. The detection position is shown in Fig. 4, and the detection length of each detection position is 0.8 mm. The calculated average surface roughness is used as a measurement index.

Table 1 Parameters governing the preparation of diamond pellets

Type	Briquetting pressure	Pore forming material	Other parameters
1#	7 MPa	0 wt.%	Abrasive: diamond; abrasive concentration: 32 wt.%; sintering temperature: 680 °C;
2#	5 MPa	3 wt.%	sintering time: 600 min.

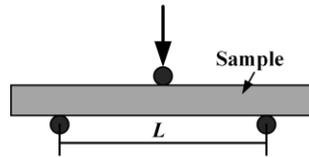


Fig. 2 Three-point bending strength measurement

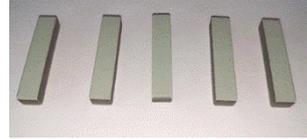


Fig. 3 Test specimens

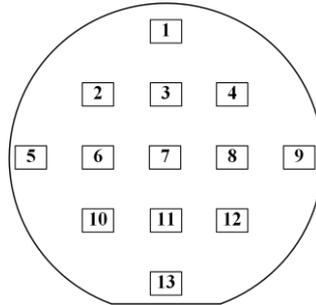


Fig. 4 Sapphire wafer surface roughness measurement point diagram

2.2 Lapping performance measurement: experimental design

To evaluate the lapping performance of two kinds of vitrified bonded diamond lapping plates (1# and 2# lapping plates) with different mechanical properties, the same sapphire wafer was used for lapping processing at different lapping times, and the surface roughness R_a and MRR of the sapphire wafer were measured and compared. As the lapping time increases, the removal ability of the lapping plate decreases, and the surface of the lapping plates needs to be dressed. To assess the stability of the two types of lapping plates after dressing, the same lapping cycle was used to conduct multiple lapping experiments on the dressing discs. The experimental parameters of the two sets of experiments are listed in Table 2.

The better to verify the lapping machining performance of the two lapping plates after dressing, in Experiment 2, sapphire substrates with the same initial state were selected, each workpiece was ground for 8 min, and the test was repeated seven times (the total lapping time was 56 min). After the lapping plate had been dressed, the previous experiment was repeated. The lapping plate was dressed four times. When the lapping plate had been dressed, a 220# Al_2O_3 oilstone was used for dressing, and the amount of lapping plates thus dressed thickness was between 10 and 15 μm .

Table 2 Lapping process parameters

Experimental type	Lapping plate	Lapping time for the same workpiece/min	Lapping plate time /min	Lapping plate dressing cycle/min	Other parameters
1	1#, 2#	4, 8, 12, 16	16	--	Lapping pressure: 34.5 kPa
2	1#, 2#	8	56	56	Lapping plate speed:60 rpm

For the lapping experiment, a 2-inch (Φ 50.8 mm) single crystal sapphire cutting wafer was selected: the wafer thickness is 500 μm . The original surface roughness R_a of the workpiece before lapping is 700 to 800 nm and its surface morphology is as shown in Fig. 5. There are many pits and textural features related to cutting on the surface. The lapping equipment is a single-sided lapping machine (Fig. 6).

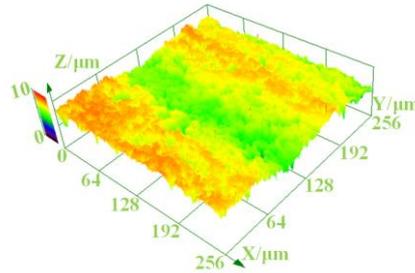


Fig. 5 Original surface morphology of the sapphire ($R_a = 730$ nm)

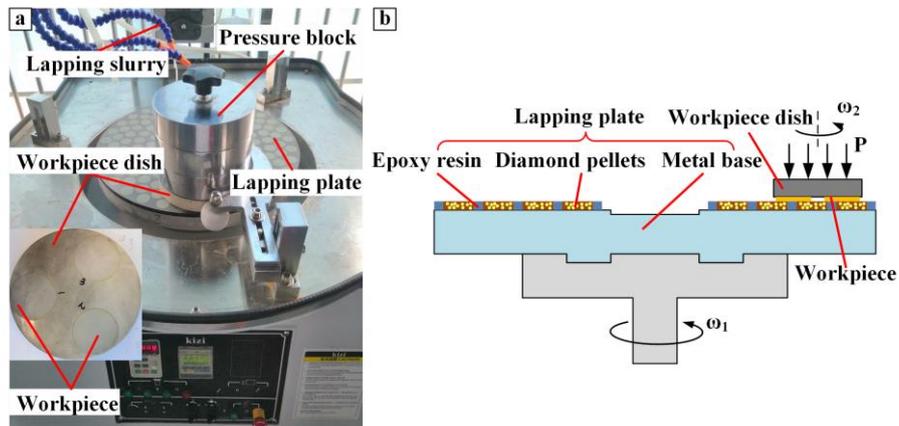


Fig. 6 Experimental equipment and processing principle: a 1# single-sided lapping machine; b 2# lapping principle

The abrasive material removal rate MRR was measured by a weighing method (Formula 2):

$$MRR = \frac{10^6 \Delta m}{\rho \pi r^2 t} \quad 2$$

where, MRR is the material removal rate, $\mu\text{m}/\text{min}$; Δm is the mass difference of the substrate before and after lapping, g, measured by a precision balance to ± 0.0001 g; ρ denotes the density of the single crystal sapphire substrate, taken as $4.1 \text{ g}/\text{cm}^3$; t represents the lapping time, min; r is the substrate radius, taken as 25.4 mm.

3 Experimental results and analysis

3.1 Surface morphology and mechanical properties of diamond pellets

The surface morphology of diamond pellets prepared under different process conditions is illustrated in Fig. 7. It can be seen that 1# diamond pellets surface is very rough, the diamond abrasive are not

breaking, and the surface abrasive particles are exposed with sharp edges, the abrasive and vitrified bonded are relatively complete, and the bond strength between abrasive particles and vitrified bonded is relatively high (Fig. 7a); while the abrasive particles in the 2# diamond pellets are surrounded by many fine ceramic bond particles, the combination of the abrasive and the ceramic binder is poor, and there are many pores around the abrasive particles (Fig. 7b), which is mainly affected by the pore-forming agent and forming pressure.

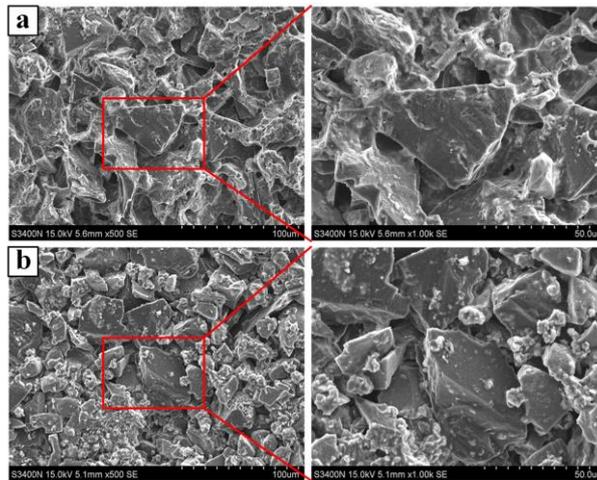


Fig.7 Surface morphology of different lapping plates before lapping: a 1# diamond pellet; b 2# diamond pellet

The mechanical properties of diamond pellets prepared under different process conditions are shown in Fig.8: the diamond pellets are affected by the pore former and the forming pressure during the preparation process. The porosity of 1# and 2# diamond pellets is 25% and 35%, respectively. The porosity of 2# diamond pellets is higher than that of 1# diamond pellets, because the addition of a pore-forming agent in the preparation of 2# diamond pellets can promote the formation of pores in the pellets. At the same time, the forming pressure of 1# diamond pellets is higher during the preparation of the diamond pellets, and the combination between binder and abrasive is tighter, resulting in a lower porosity. The hardness and bending strength of 1# diamond pellets are 81 HRB and 70 MPa respectively, and the hardness and bending strength of 2# diamond pellets are 55 HRB and 38 MPa respectively. The hardness and bending strength of 1# diamond pellets are much higher than those of 2# diamond pellets. The underlying cause of the difference in mechanical properties between the two types of diamond pellets is illustrated in Fig. 9. The hardness of diamond pellets can reflect the ease with which abrasive particles are spalled from the surface of the diamond pellets. 1# diamond pellets that are formed under a higher pressure during their preparation, have a tighter bond between the ceramic and diamond abrasive, and the probability of pores being formed at the abrasive interface is lower, the stronger the bonding force between ceramic binder and diamond abrasive, so

the greater the hardness of 1# diamond pellet. At the same time, the actual bonded area of the abrasive and the binder in the unit section of 1# diamond pellet is larger, that is, the brown area in Fig. 9a is larger than that in Fig. 9b, so the bending strength of 1# diamond pellets is greater.

The different mechanical properties of diamond pellets will affect the bonding strength of the diamond abrasive in the pellets, which will affect the *MRR* of the lapping process, the surface roughness *Ra*, and the wear form of the lapping plate.

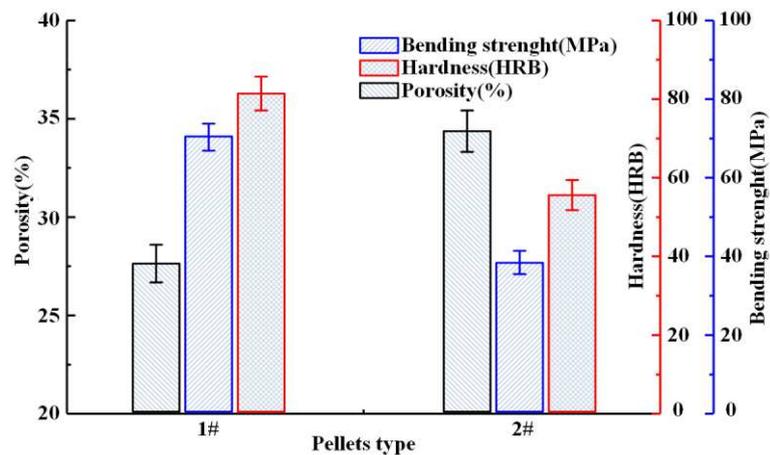


Fig. 8 Comparison of mechanical properties of two types of diamond pellets

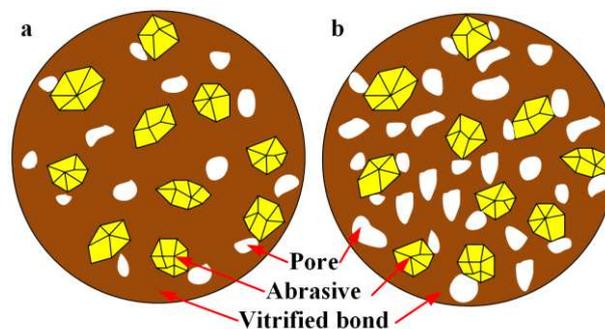


Fig. 9 The difference principle of the mechanical properties of the two types of diamond pellets: a 1# diamond pellet; b 2# diamond pellet

3.2 The influence of lapping time on lapping effect

Two types of lapping plates with different mechanical properties are used to lapping sapphire specimens. The changes in lapping *MRR* and workpiece surface roughness *Ra* of the same workpiece after the required lapping time are shown in Figs. 10 and 11. As the lapping time increases, the *MRR* and the workpiece surface roughness *Ra* gradually decrease, and *MRR* and workpiece surface roughness *Ra* decrease significantly in the early stage of lapping, and the downward trend is shallow, becoming stable in the later stage (Fig. 11). In the early stage of lapping, the workpiece surface is rougher, and the surface roughness *Ra* is larger. The principle of this rule is shown in Fig. 12. In the

early stage of lapping, the abrasive first contacts the asperity peak material on the workpiece surface, and the contact depth h between the abrasive and the material is large: simultaneously, the asperity peak material is more readily removed by the abrasive (Fig. 12a) and the MRR is larger. As lapping time increases, the surface asperity peak material of the workpiece is removed, and the surface roughness R_a of the workpiece decreases. At this time, the contact depth between the abrasive and the workpiece is smaller, and the material is more difficult to be removed (Fig. 12b), and the MRR decreases; when the surface roughness R_a reaches a certain level, it is difficult to continue to decrease the roughness with further increases in lapping time and the MRR is also relatively stable at that time.

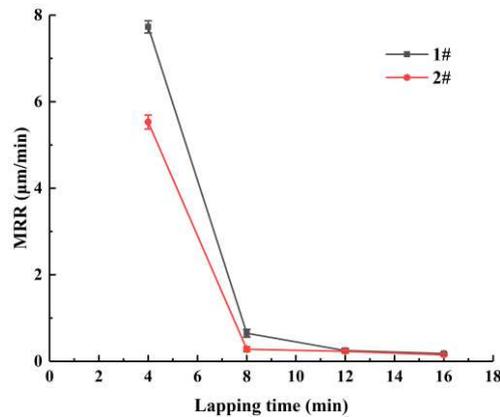


Fig. 10 Effect of lapping time on workpiece MRR

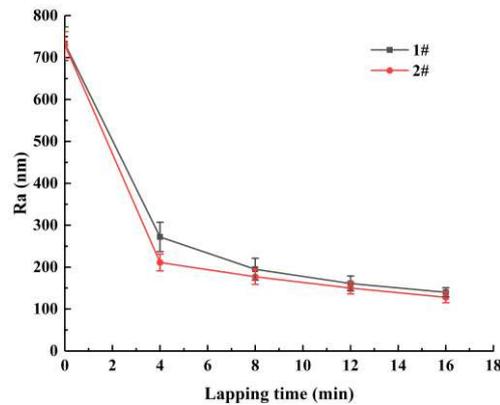


Fig. 11 Effect of lapping time on the surface roughness R_a of the workpiece

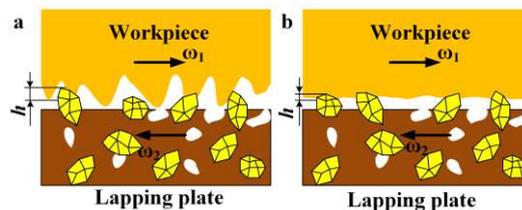


Fig. 12 Influence of workpiece surface morphology on MRR : a rough surface; b smooth surface

Comparing the lapping effects of the two lapping plates, Figs. 10 and 11 illustrate that in the early lapping stage (at 4 min), the material MRR of the 1# and 2# lapping plates is $7.73 \mu\text{m}/\text{min}$ and $5.33 \mu\text{m}/\text{min}$, respectively, the MRR of 1# lapping plate is 45% higher than that of 2# lapping plate. When

lapping the workpiece for 8 min, the *MRR* of the 1# and 2# lapping plates is 0.65 $\mu\text{m}/\text{min}$ and 0.28 $\mu\text{m}/\text{min}$, respectively: the *MRR* of the two types of lapping plates is significantly reduced, and the *MRR* of 1# lapping plate is slightly greater than that of the 2# lapping plate. With the increase of the lapping time to 12min, the *MRR* of the two lapping plates is consistent. When continuing to increase the lapping time, the *MRR* and changes therein of the two lapping plates remain consistent.

The surface morphology of the workpiece after lapping by the two types of lapping plates is shown in Fig. 13. Before lapping, the surface roughness R_a of the workpiece is about 730 nm, there are many pits on the workpiece surface, and there are few flat areas; after lapping for 4 min, the lapping *MRR* is large and the surface roughness R_a decreases significantly. After lapping for 4 min the surface roughness R_a of the workpiece in two types of lapping plates is 272 nm and 211 nm respectively, which decrease by 63% and 71% respectively compared with the unpolished surface, there are still many deeper pits on the surface, few flat areas and poor surface integrity; After lapping for 8 min, with the decrease of *MRR*, the decrease in surface roughness R_a also decreases. After lapping for 8 min in two types of lapping plates, the surface roughness R_a is 195 nm and 177 nm respectively, which decreases by 28% and 16% respectively compared with that after lapping for 4 min. The surface of the workpiece becomes smooth, indicating that many of the pits have been removed, the pit depth decreases, but the surface quality of the workpiece remains poor; After lapping for 12 min in two types of lapping plates, the surface roughness R_a of the workpiece is 161 nm and 150 nm respectively, the number of pits on the workpiece surface is significantly reduced, their depth decreases, the flat surface accounts for a large proportion, After lapping for 16 min, the surface morphology is similar to that after lapping for 12 min: there is no obvious pit on the surface, and the peak trough R_t value of the workpiece surface is smaller, and the surface roughness R_a value is also slightly smaller. After lapping for 12 min in two types of lapping plates, the workpiece surface roughness R_a is 140 nm and 128 nm respectively. As seen from Fig. 11, after lapping for 12 min, the reduction of workpiece surface roughness R_a with lapping time is small, and the workpiece surface roughness will not decrease when it reaches about 120-150 nm after lapping.

Compared with the processing effects of 1# and 2# lapping plates, the surface roughness R_a of the workpiece after lapping by the 2# lapping plate is smaller and the surface quality of the workpiece is better, because the 1# lapping plate is harder, the lapping *MRR* is larger, the cutting depth h of the abrasive is larger, the cutting marks left on the workpiece surface are deeper, the peak trough R_t value

of the surface is larger, and the surface roughness Ra is also larger.

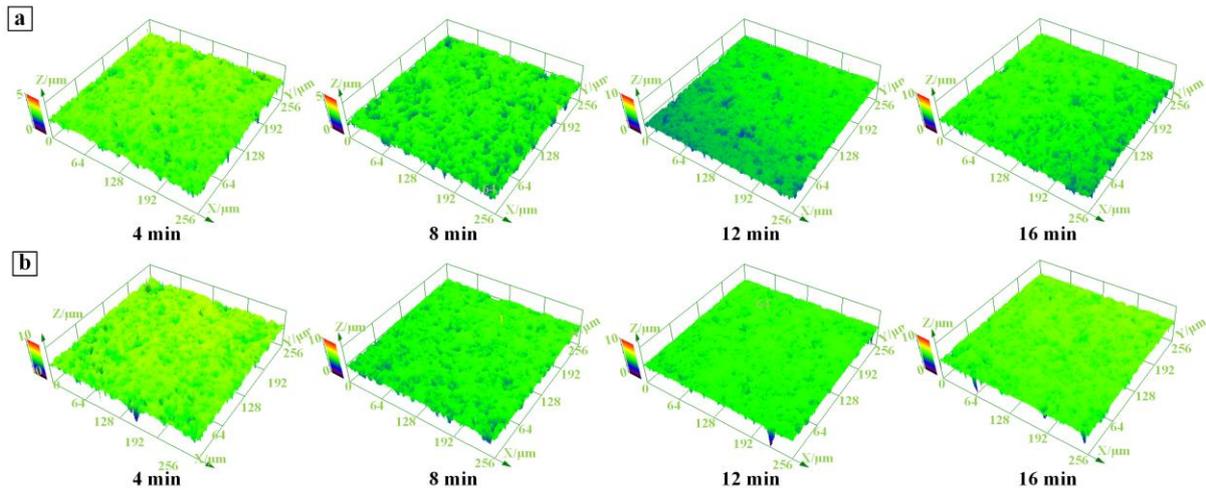


Fig. 13 Surface morphologies of workpieces after lapping with two types of lapping plates for different times: a 1# lapping plate; b 2# lapping plate

3.3 Processing stability of different lapping plates

To explore the stability of the lapping process of the lapping plates, the lapping plate was subjected to a long-term lapping process and regular dressing. The result is shown in Fig. 14: in the same dressing cycle of the two lapping plates, the *MRR* gradually decreases to a stable value with increasing lapping time, and the *MRR* of the 1# lapping plate is always higher than that of the 2# lapping plate, indicating that the material removal ability of 1# lapping plate is better than that of 2# lapping plate. Compared with the four different cycles, the two types of lapping plates demonstrate good repeatability across different cycles, and the *MRR* deviation of the same lapping time period in different dressing cycles is within $\pm 10\%$. For example, the *MRR* of 1# lapping plate in four dressing cycles is 4.37, 4.53, 4.43, and 4.28 $\mu\text{m}/\text{min}$ respectively after lapping for 8 min, and the deviation is only 2.9%. It can be considered that the machining stability of the two lapping plates after dressing is good, and their machining performance is consistent after each dressing operation.

In the early stage of use, the *MRR* of the two types of lapping plates is high, but as the lapping time increases, there are abrasive wear, abrasive breaking, and abrasive peeling off on the surface of the lapping plates, which will reduce the removal capacity thereof. The lapping plates need to be dressed timeously the better to determine the dressing time of the two types of lapping plates, and analyse the change in *MRR* over a single dressing cycle. For example, the *MRR* of the 1# lapping plate in a single dressing cycle is 4.37, 2.56, 1.47, 0.83, 0.65, and 0.58 $\mu\text{m}/\text{min}$ respectively; it can be found that, when lapping for 24 min and 32 min, the *MRR* is only 34% and 18% of that when lapping for 8 min,

and the MRR changes little after lapping for 32 min. At the same time, it is found that when the lapping time is 24 min, the MRR difference in the same lapping time of different dressing cycles is more than 5%, indicating that the stability of the trimmed plates decreases after lapping for 24 min. Therefore, the optimal dressing cycle when using the lapping plates is about 24 min.

We analysed the average \overline{MRR} of the two lapping plates in the first three “8-min” machining sequences over four dressing cycles. The average \overline{MRR} of its 1# lapping plate is 4.40, 2.48, and 1.33 $\mu\text{m}/\text{min}$ respectively, the average \overline{MRR} of the last two “8-min” cycles is 56% and 30% of the average \overline{MRR} of the first “8-min” cycle; the average \overline{MRR} of the 2# lapping plate in the first three “8-min” cycles is 3.19, 1.70, and 0.79 $\mu\text{m}/\text{min}$ respectively, the average \overline{MRR} of the last two “8-min” cycles is 53% and 24 % of the average \overline{MRR} of the first “8-min” cycle. This shows that the processing stability of the two lapping plates (*i.e.*, the self-tempered performance of the lapping plate) is lower. Relatively speaking, the processing stability of the 1# lapping plate is slightly better than that of the 2# lapping plate.

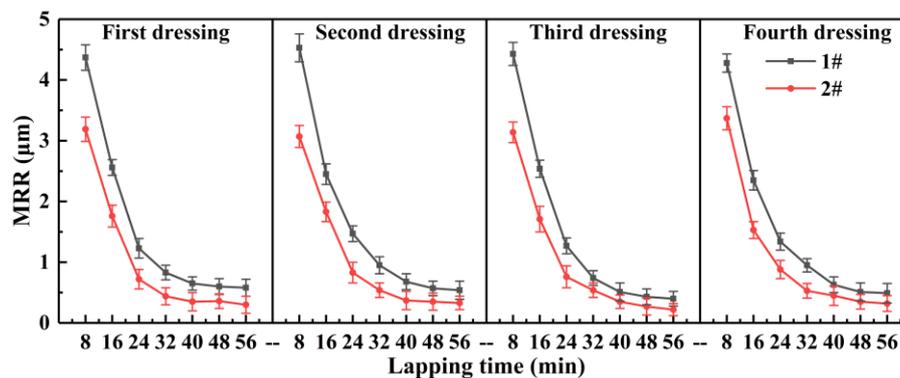


Fig. 14 Workpiece MRR of different lapping plates with increasing lapping time

2.4 Analysis of machining wear of vitrified bonded diamond lapping plates

In the actual lapping process of vitrified bonded diamond lapping plate, a series of changes will occur in the surface state of the lapping plate due to the effects of mechanical stress, chemical action, and lapping heat. These changes will exert an important impact on the machining performance of the lapping plate. Analysing these changing characteristics and mastering the wear mechanism of the lapping plate are great significance to improve the service life of the lapping plate and the lapping performance in the later stage. In general, vitrified bonded diamond lapping plates have several forms of lapping plates wear mechanisms, such as abrasive wear, abrasive breaking, abrasive peeling off, and bond breaking and fracture.

After the two types of lapping plates were used for lapping for 24 min, the changes in the surface

roughness Ra beforehand and afterwards are shown in Fig. 15, and the three-dimensional morphology of the surface before and after lapping is demonstrated in Fig. 16. The surface roughness Ra of the 1# and 2# lapping plates before lapping is 7.41 μm and 6.85 μm respectively, the surface roughness Ra of the 1# lapping plate is slightly higher than that of the 2# lapping plate. We observed the surface morphology of the two lapping plates before lapping (Figs. 7, 16). The abrasive of the 1# lapping plate combines well with the ceramic binder, and the abrasive is relatively sharp. This results in larger surface pits and greater surface roughness Ra on the surface of the 1# lapping plate. As there are many fine ceramic binder particles on the abrasive surface of the 2# lapping plate, which can fill those larger surface pits, so that the surface roughness Ra is relatively smaller. After two types of lapping plates are used for lapping for 24 min, the surface roughness Ra of the 1# and 2# lapping plates is 6.56 μm and 7.36 μm , respectively, due to the wear of the lapping plates. The changes of the surface roughness Ra of the two types of lapping plates are found to be mutually opposed. After lapping, the surface roughness Ra of the 1# lapping plate decreases and the surface becomes smooth, while the surface roughness Ra of the 2# lapping plate increases, and the surface becomes rough. The three-dimensional morphology of the surface was observed after lapping. The surface abrasive of the 1# lapping plate is shown to be worn, the surface crest is ground flat, and the depth of the surface pit is reduced, resulting in the reduction of the surface roughness Ra; however, for the 2# lapping plate, the surface abrasive is also worn, many pits appear on the surface, and their diameter is similar to that of the abrasive particle, which may be caused by abrasive peeling off, finally increasing the surface roughness Ra.

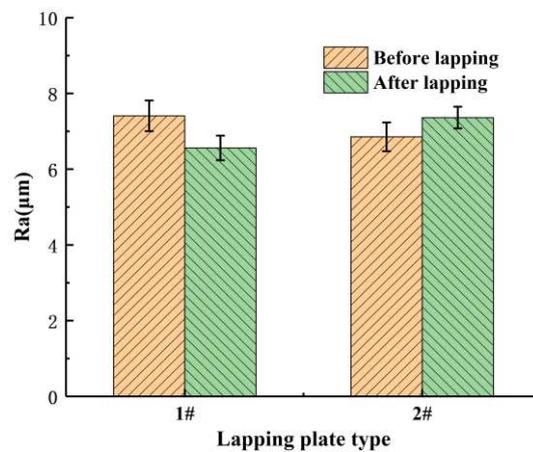


Fig. 15 Changes in surface roughness Ra of two types of lapping plates before and after lapping

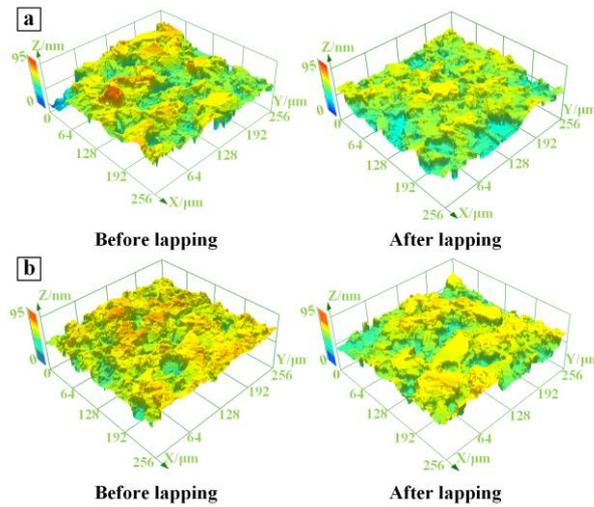


Fig. 16 Three-dimensional morphology of two types of lapping plates before and after lapping: a 1# lapping plate; b 2# lapping plate

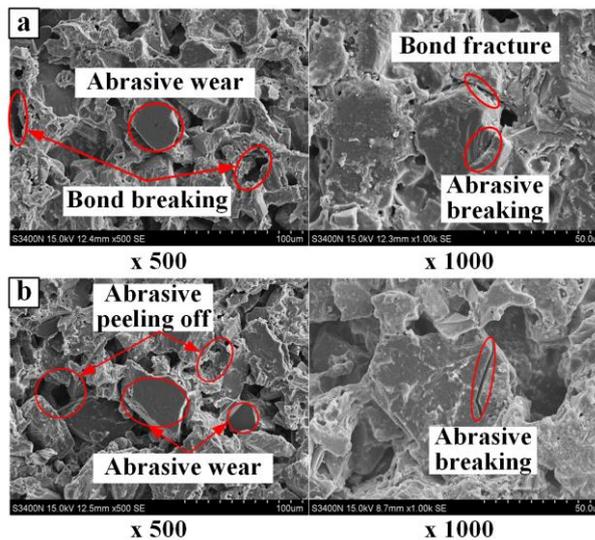


Fig. 17 Surface morphology after lapping with two types of lapping plates: a 1# lapping plate; b 2# lapping plate

The difference in the change of surface roughness R_a between the two types of lapping plates after lapping may be due to the difference in the wear forms of the lapping plates. The further to analyse the wear forms of the two types of lapping plates, the surface microstructure of two types of lapping plates after lapping for 24 min was observed using a scanning electron microscope. The morphology is shown in Fig. 17. Compared with the surface morphology before lapping (Fig. 7), the diamond abrasive on the surface of the lapping plate before lapping are relatively complete, exposing sharp edges; after lapping, abrasive wear, abrasive breaking, abrasive peeling off, bond fracture, and other phenomena will appear on the surface of the lapping plate. Analysing the surface morphology of the two types of lapping plates, it can be found that the 1# lapping plate mainly suffers abrasive wear, bond fracture, abrasive breaking (Fig. 17a), while the 2# lapping plate undergoes abrasive peeling

off, abrasive wear, abrasive breaking (Fig. 17b). Analysis of the reasons suggests that the cause is the lower porosity of the 1# lapping plate, its greater hardness, and the strong combination of abrasive and ceramic binder. When the abrasive is cutting the workpiece, the abrasive does not readily fall from the lapping plate surfaces, thereby it is easier to be worn, the surface of the lapping plate is smoother and the surface roughness R_a decreases. Meanwhile, due to the large cutting force on the abrasive, it is easy to break the abrasive, break the interface between the bond and the abrasive, or break the whole bond; whereas the 2# lapping plate has a higher porosity and a lower hardness, and the “holding” effect of ceramic binder on the abrasive is weaker. The abrasive more readily falls off under the action of the cutting force, resulting in the increased surface pitting after lapping and the increase of surface roughness R_a of the lapping plate.

4 Analysis and discussion

Based on the above experimental results, the wear process model of lapping plates is established as shown in Fig. 18. Due to the difference in the preparation process of the two types of lapping plates, the porosity of the 1# lapping plate is lower than that of the 2# lapping plate, the hardness and bending strength are higher than that of the 2# lapping plate. The 1# lapping plate ceramic binder exerts a greater holding force on the abrasive than the 2# lapping plate. In the process of machining, the 1# lapping plate is not easy spalled under the action of the abrasive peeling off (Fig. 18a), which are mainly removed by “2-body sliding abrasive” materials, and abrasive grains are mainly worn in the process of “sliding”, so the MRR is higher. At the same time, the abrasive are subject to large cutting force in the process of “sliding”, which readily causes abrasive wear and the bonding fracture; however, “sliding” material deepens “scratch” marks left on the workpiece surface, and the workpiece surface roughness R_a is increased. However, there are many unstable abrasive exerting a weak binding force in the 2# lapping plate: when these are affected by the cutting force during the lapping process, they will quickly fall from the substrate of the lapping plate to form free abrasive (Fig. 18b). In the lapping process, not only did “2-body sliding abrasive” cause material removal, but also “3-body rolling abrasive” action. Due to the “3-body rolling abrasive” forms of material removal, the abrasive cutting depth is smaller and the MRR is lower, but the smaller the removal mark left on the workpiece surface, the smaller the workpiece surface roughness R_a .

With the increase of lapping time, the two types of lapping plates will cause abrasive wear, the sharpness of the abrasive decreases, the removal ability decreases, and the lapping MRR is reduced.

When the sharpness of the abrasive is low, it is difficult for the abrasive to cut into the interior of the workpiece, the abrasive only slides on the surface of the workpiece without material removal. At this time, the abrasive have lost their ability to remove material. However, the cutting force on the abrasive is reduced, and there is no abrasive falling from the surface, resulting in less change in *MRR* in the later stages of the lapping process. When the lapping plate is trimmed again, the abrasive sharpness and material removal ability are restored.

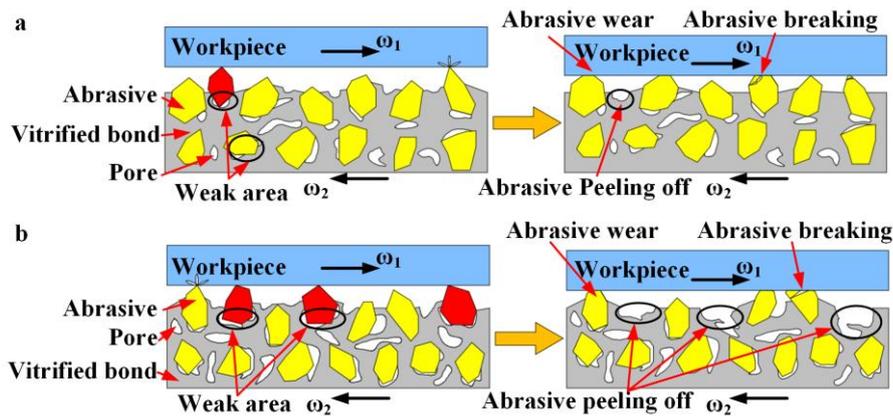


Fig. 18 Schematic diagram of wear process of different lapping plates: a 1# lapping plate; b 2# lapping plate

5 Conclusion

1. Pore-forming agent and forming pressure will affect the porosity of inside the diamond shot, resulting in significant differences in the mechanical properties of diamond pellets. As the porosity increases, the hardness and bending strength of diamond pellets decrease.

2. The variations in the *MRR* of two types of lapping plates lapping on the sapphire are consistent with that of the workpiece surface *Ra* with increasing lapping time, and both decrease with the increase of lapping time, but the *MRR* of lapping plates with a higher hardness is higher than that of a lapping plate with a lower hardness, and the surface roughness *Ra* is also greater.

3. The processing stability of the two types of lapping plates in different dressing cycles is good, and the *MRR* deviation in the same lapping time period in different dressing cycles is less than 10%, but the lapping plate will be worn with increasing lapping time. The *MRR* after lapping for 24 min is only about 20% of that measured initially, and the optimal dressing cycle lasts 24 min.

4. The lapping plates with different mechanical properties have different forms of wear. The stronger the “holding” effect of ceramic binder on abrasive in lapping plates with higher hardness, the higher the *MRR* and workpiece surface roughness *Ra*; the wear of lapping plates is mainly abrasive wear, while the wear of lapping plates with low hardness is mainly due to abrasive peeling off, and the lapping effect is opposite to that of lapping plates with higher hardness.

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Compliance with ethical standards

1. The material has not been published in whole or in part elsewhere;
2. The paper is not currently being considered for publication elsewhere;
3. All authors have been personally and actively involved in substantive work leading to the report, and will hold themselves jointly and individually responsible for its content;
4. The authors declare that they have no conflict of interest.

References

- [1] Gagliardi J J, Kim D, Sokol J J, et al. A case for 2-body material removal in prime LED sapphire substrate lapping and polishing. *J. Manuf. Process.* 2013; 15:348-354. <https://doi.org/10.1016/j.jmapro.2012.11.005>.
- [2] Li Z C, Pei Z J, Funkenbusch P D. Machining processes for sapphire wafers: a literature review. *P. I. Mech. Eng. B-J. Eng.* 2011; 225:975-989. <https://doi.org/10.1177/2041297510393667>.
- [3] Kim M H, Manivannan R, Moon d J, et al. Evaluation of double sided lapping using a fixed abrasive pad for sapphire substrate. *Wear.* 2013; 302(1-2):1340-1344. <https://doi.org/10.1016/j.wear.2012.11.075>.
- [4] Chen J P, Zhu Y W, Wang X B, et al. Relationship between mechanical properties and processing performance of agglomerated diamond abrasive compared with single diamond abrasive. *Diam. Relat. Mater.* 2019; 100:107595. <https://doi.org/10.1016/j.diamond.2019.107595>.
- [5] Wang L J, Hu Z W, Chen Y, et al. Material removal mechanism of sapphire substrates with four crystal orientations by double-sided planetary grinding. *Ceram. Int.* 2020; 46:7813-7822. <https://doi.org/10.1016/j.ceramint.2019.11.284>.
- [6] Chen J P, Sun T, Sun J X, et al. A novel agglomerated diamond abrasive with excellent micro-cutting and self-sharpening capabilities in fixed abrasive lapping processes. *Wear.* 2021; 464-465:203531. <https://doi.org/10.1016/j.wear.2020.203531>.
- [7] Zheng F Z, Zhu Y W, Zhu N N, et al. Parameter optimization of sapphire with fixed abrasive pad. *Diamond and Abrasives Engineering.* 2016; 36:11-15. <https://doi.org/10.13394/j.cnki.jgszz.2016.1.0003>.
- [8] Zheng F Z, Zhu N N, Zhu Y W, et al. Self-conditioning performance of hydrophilic fixed abrasive pad. *Int. J. Adv. Manuf. Tech.* 2017; 90:2217-2222. <https://doi.org/10.1007/s00170-016-9553-9>.
- [9] Dong Z C, Cheng H B. Study on removal mechanism and removal characters for SiC and fused silica by fixed

abrasive diamond pellets. *Int. J. Mach. Tool. Manu.* 2014; 85(5):1-13. <https://dx.doi.org/10.1016/j.ijmachtools.2014.04.008>.

[10] Yin T, Wang Z D, DOI T, et al. Characteristic of SiC slurry in ultra-precision lapping of sapphire substrates. *Int. J. Precis. Eng. Man.* 2021; 22:2021-2029. <https://dx.doi.org/10.1007/s12541-021-00521-1>.

[11] Deng J Y, Lu J B, Zeng S, et al. Preparation and processing properties of magnetically controlled abrasive solidification orientation–solid-phase Fenton reaction lapping–polishing plate for single-crystal 4H-SiC. *Surf. Interfaces.* 2022; 29:101646 <https://doi.org/10.1016/j.surfin.2021.101646>

[12] Deng J Y, Lu J B, Zeng S, et al. Processing properties for the Si-face of the 4H-SiC substrates using the magnetically-controlled abrasive solidification orientation–solid-phase Fenton reaction for the fabrication of the lapping–polishing plate. *Diam. Relat. Mater.* 2021; 120:108652. <https://doi.org/10.1016/j.diamond.2021.108652>

[13] Gao S, Kang R K, Dong Z G, et al. Surface integrity and removal mechanism in lapping sapphire wafers with novel vitrified bond diamond plates. *Mater. Manuf. Process.* 2016; 32:121-126. <https://doi.org/10.1080/10426914.2016.1140194>.

[14] Wang Z K, Niu F L, Zhu Y W, et al. Comparison of lapping performance between fixed agglomerated diamond pad and fixed single crystal diamond pad. *Wear.* 2019; 432-433:202963. <https://doi.org/10.1016/j.wear.2019.202963>.

[15] Wang Z K, Niu F L, Wang Z K, et al. Friction and wear characteristics of agglomerated diamond abrasives and lapping performance of fixed agglomerated diamond pads. *Wear.* 2021; 470-471:203598. <https://doi.org/10.1016/j.wear.2020.203598>.

[16] Zhou Z Z, Wen D H, Zhang K H, et al. Experimental investigation on the effect of abrasive grain size on the lapping uniformity of sapphire wafer. *China Mechanical Engineering.* 2008; 21:2549-2552. <https://doi.org/10.3321/j.issn:1004-132X.2008.21.008>.

[17] Guo L, Zhang X, Chen S B, et al. An experimental study on the precision abrasive machining process of hard and brittle materials with ultraviolet-resin bond diamond abrasive tools. *Materials.* 2019; 12:1-11. <https://doi.org/10.3390/ma12010125>.

[18] Yun J C, Wang B Y, Lee E S, et al. Effect of the properties of uniformly patterned micro-diamond pellets on sapphire grinding. *J. Korean. Phys. Soc.* 2018; 73(7):871-876. <https://doi.org/10.3938/jkps.73.871>.

[19] Fang C F, LIU C, ZHAO Z X, et al. Study on geometrical patterns of textured fixed-abrasive pads in sapphire lapping based on trajectory analysis. *Precis. Eng.* 2018; 53:169-178. <https://doi.org/10.1016/j.Precisioneng.2018.03.008>.

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- [20] Wang W S, Yu Y Q, Hu Z W, et al. Removal characteristics of sapphire lapping using composite plates with consciously patterned resinoid-bonded semifixed diamond grits. *Crystals*. 2020; 10(4):293 <https://doi.org/10.3390/cryst10040293>.
- [21] Chen J P, Zhu N N, Niu F L, et al. Influence of agglomerated diamond abrasive wear on sapphire material removal behavior. *Diam. Relat. Mater.* 2020; 108:107965. <https://doi.org/10.1016/j.diamond.2020.107965>.
- [22] Kim H M, Park G H, Seo Y G, et al. Comparison between sapphire lapping processes using 2-body and 3-body modes as a function of diamond abrasive size. *Wear*. 2015; 332-333:794-799. <https://doi.org/10.1016/j.wear.2015.02.029>.