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An Experimental Study on the Abrasive Machining Process of Electronic Substrate Material With A Novel Ultraviolet-Curable Resin Bond Diamond Lapping Plate

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ABSTRACT Sapphire is one of the most widely used electronic substrate materials in the industry. The manufacturing process of sapphire and such hard and brittle materials is extremely time and energy consuming because of their superior material properties in physical and chemical behaviors. In this study, the ultraviolet-curable resin is introduced into the fabrication of the diamond abrasive lapping plate as a bonding agent. A practical manufacturing process is established in the laboratory to develop an ultraviolet-curable resin bond fixed abrasive lapping plate for the precision machining of sapphire substrates, the machining performance of which is examined through a series of comparative experiments among the conventional fixed-abrasive lapping, the slurry-based lapping and this originally developed plate involved lapping. The surface topography and surface roughness of the machined sapphire workpieces are measured to evaluate the surface quality, and the weight loss of the workpieces in each machining process is recorded to estimate the respective machining efficiency. The promising results achieved from the ultraviolet-curable resin plate lapping process, in terms of a relatively higher material removal rate and better surface quality, indicate that the occurrence of a corporate action integrating both the advantages of the fixed abrasive grains and loose abrasive grains. A summarized hypothesis is drawn to describe the dynamically balanced state of the hybrid precision abrasive machining process, in which the 2-body abrasion and 3-body abrasion material removal mechanism participate simultaneously and interconvert to each other continuously.

INDEX TERMS Material processing, sapphire substrate, tool manufacturing.

I. INTRODUCTION

A. MATERIAL AND MACHINING PROCESS

Sapphire is the single crystal form of the compound Al_2O_3 (α-alumina), and it is the second hardest natural material after diamond. As one of the most recognized high-quality opto-mechatronic materials in the industry, it has been used broadly in various fields covering consumer electronics and military equipment. For instance, because of the superior material properties in physical strength, hardness, and high-temperature resistance, sapphire possesses the capability to endure the severe conditions of GaN film deposition, and which make sapphire became the predominate substrate material for light emitting diode (LED) applications [1]–[3]. Moreover, sapphire is also a wide gap (up to 0.9 eV) insulator presenting multiple favorable properties including the refractory behavior and transparency over a wide wavelength range, which enables sapphire to be employed as the laser diodes, optical materials or even insulator in a nuclear reactor [4], [5]. The machining process of sapphire substrate usually starts from the sawing of a sapphire cylinder bar of 50mm to 150mm in diameter, and following a sequence of precision

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machining steps generally including the edge profiling, flattening and surface finishing [6]. Owing to its outstanding physical and chemical material properties, the machining of sapphire substrate can be a significant challenge that requires much higher load than conventional machining process, and therefore results in rapid tool wear [7]. On the other hand, because the raw material cost of sapphire and alike hard, brittle materials are usually expensive, achieving a superior surface finish with proper material removal to avoid material waste could be more challenging in the flattening and finishing process [8].

In the finishing process of the sapphire substrate, lapping and polishing are the two abrasive machining processes that mainly applied to get a dimensional accurate flat surface with nanoscale roughness. The lapping and polishing process usually utilized by the employment of abrasive grains on a base plate. It can be fabricated with metals like cast iron (Fe) or copper (Cu) to provide a relatively higher material removal rate in the lapping process, or it can be made with softer materials as tin(Sn)/lead(Pb) metal or metal-resin composite to deliver an atomic level surface finish in the polishing process. The abrasives are introduced between the workpiece and lapping plate through a carrier in the form of liquid or paste. A fine-abrasive machining process is therefore performed, in which the abrasive grains are kept rolling under the lapping load and pushing their sharp points into the workpiece to abrade microchips of the material. This kneading or abrading action on the workpiece is considered as 3-body abrasion, and the process is named as loose abrasive machining where the 3-body abrasion is repeated millions of times to remove the material randomly with barely directional marks produced. The 2-body abrasion is also existing in the lapping process other than 3-body abrasion, and in which the abrasive grains are embedded on the plate by the bonding agent that can be either metallic or resinoid. The abrasive machining process performed as 2-body abrasion is considered as the fixed abrasive lapping process, in which the protruding abrasive grains are sliding against the workpiece to remove material, like tens of thousands of micro-cutting tools. According to Kim et al. [9], a relatively higher material removal rate can be obtained through 2-body abrasion lapping, while a dense abrasive slurry and time consuming are needed for a 3-body abrasion to achieve the same rate. In addition to this efficiency problem, both the process waste and cost significantly increased in the slurry-based lapping and polishing process, and environmental pollution could be another potential issue.

B. MACHINING TOOL FABRICATION

Researchers have started to study the possibility of combining the 2-body and 3-body abrasion to integrate their advantages in machining efficiency and surface finish. Yuan *et al.* [10] presented a laboratory-based technique that employing thermal-curable polymer as the bonding agent to solidify a fixed abrasive plate at 60°C for 24 hours, the surface damage reduction and surface quality improvement was

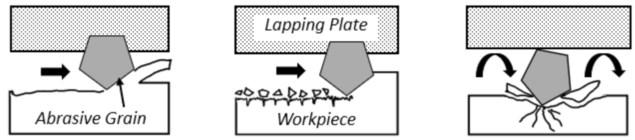

FIGURE 1. **2-body and 3-body abrasion mechanism in lapping process: 2-body plastic removal by sliding of fixed abrasive grains (a); 2-body brittle removal by sliding of fixed abrasive grains (b); 3-body brittle removal by rolling of loose abrasive grains (c).**

validated by experiments to illustrate the existence and contribution of both the pre-fixed abrasive machining and loose abrasive machining. Luo *et al.* [11] tried to develop a so-called semi-fixed abrasive tool with sol-gel technology to form a softer bond between the abrasive grains and the bonding agent. During the machining process, the fall-off semi-fixed abrasive grains could work in 3-body abrasion mode with the fixed grains working in 2-body abrasion mode. The fabrication process was based on the cross-linking reaction of the sodium alginate (AGS) at certain conditions. Therefore, the reaction completion and process parameter control could potentially limit the application of this technology. Pyun *et al.* [12] fabricated a high-performance copper-resin plate for sapphire machining to combine the 2-body and 3-body abrasion mode, and examined the influence of different amounts of curing agent as a function of resin weight. The interface between the Cu and resin and the hardness of the lapping plate were found to be the primary factor affecting the material removal and thereby caused the temporary 2-body abrasive transformed into 3-body abrasive. However, the fabrication of this copper-resin plate was still based on the sintering process that needs relatively higher energy and time-consuming. The byproduct of the process could also be harmful to the environment and operators.

Based on the investigations from the previous researches discussed above, a conclusion could be drawn that all the attempts in integrating the 2-body and 3-body abrasion mode into one machining process, is established on the recognition of their advantages in the superior surface finishing capacity while retaining moderate material removal efficiency [12], [13]. Therefore, the development of the new manufacturing process to fabricate machining tools delivering the unique machining performance has been extensively researched recently and became one of the objectives in this study.

C. ORIGINAL CONTRIBUTION

In this paper, we proposed a new abrasive machining tool that fabricated with the ultraviolet-curable resin and diamond abrasive grains. Resin bond is one of the most widely used bonding agent types (metallic bond, vitrified bond) in the manufacturing of abrasive tools including grinding wheel, lapping plate and even polishing pad [14]. For the past few decades, the thermal-curable resin has been primarily selected as the bonding agent. However, the development of prototyping technology attracted attempts from researchers to testify the feasibility of utilizing light-curable resin in the fabrication of abrasive machining tools [15]. The creative idea of this research is based on the application of ultraviolet-curable resin prototyping technology. It inspired us to develop an abrasive tool with the capability of generating a fusion material removal mechanism of 2-body and 3-body abrasion during the sapphire wafer machining process, and thereby to obtain relatively better results regarding surface quality, machining efficiency, and process cost saving. Compared to the latest and most widely-applied fabrication methods discussed in the previous section, the main advantages of the rapid prototyping method established in this study can be summarized as follows [16]:

a) Time-consuming reduction in solidifying;
b) Process flexibility and consistency;
c) Energy cost saving and environmental-friendly.

In order to verify the influence of this unique ultraviolet-curable resin bond on machining performance of the tool, we also conducted a group of comparative experiments among the fixed abrasive lapping plate, slurry-based lapping plate, and our newly developed ultraviolet-curable resin bond lapping plate. It is hoped that this study could be undertaken to help to guide a new direction of the precision machining technology of sapphire and other alike brittle materials.

II. MATERIALS AND METHODS

A. MATERIALS PREPARATION

The lapping process on hard and brittle material like sapphire can be extreme time-consuming unless the proper tools are applied, and the abrasives forming the tool always play the core role to influent the characteristics of the tool. For this reason, high-quality graded abrasive grains with a consistent, predictable mean particle size and tight standard deviation are primarily selected. Compared with the conventional abrasive grains including silicon carbide and aluminum oxide, the diamond abrasives offer superior characteristics in material properties to perform aggressive material removal for better productivity, and they have a high potential to develop a one-step lapping and polishing process for reduced cycle time. Therefore, the diamond abrasive grain was selected for this study.

A batch of mono-crystalline diamonds with an average size of 15μm was purchased from Engis Corporation (Wheeling, USA), the scanning electronic microscope (SEM) observation of these diamond grains is shown in Fig.2. In the theoretical study, the diamond grain is usually assumed as a geometrically-perfect shape to simplify the modeling and simulation. However, in practice, the appearance, geometric shape, and size of the micro-scale abrasive diamond grains are randomly distributed due to the manufacturing technique characteristics. As a result, the size distribution and deviation of a certain batch of abrasive grains dominantly determine the machining performance of the fabricated tool. In this research, the abrasive size variation is mainly located within the range of 10μm to 20μm, and the abrasive grain diameter size distribution measured with a laser diffraction method is also provided in Fig.3.

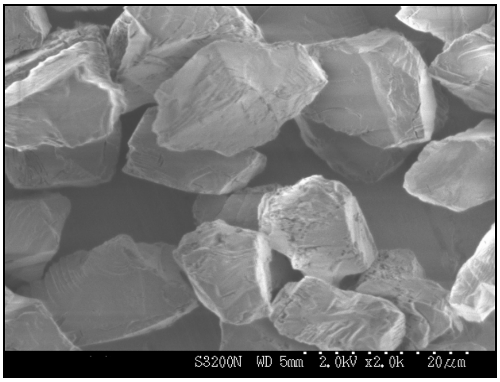

FIGURE 2. A scanning electron microscope observation of the diamond grains used in this study.

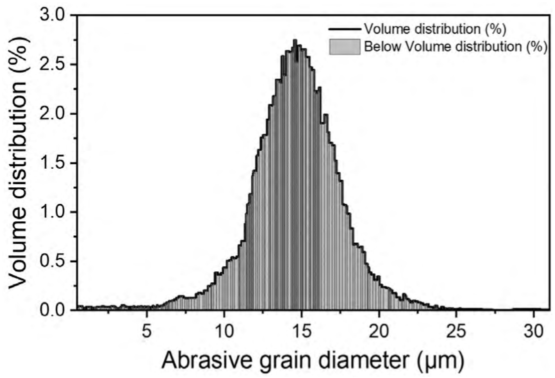

FIGURE 3. The diameter size distribution of the diamond abrasive grains measured by the laser diffraction method.

TABLE 1. Technical specification of the ultraviolet-curable resin [19].

Material Property of Dymax 425	Technical Specification
Density	1.07 g/ml
Viscosity (20rpm)	4000 cP
Hardness (Durometer)	D80
Tensile Stress (Uniaxial)	42.75 MPa
Elongation	7.3%
Modulus of Elasticity	3447.38 MPa

The ultraviolet-curable epoxy resin prepared for this study was supplied by Dymax Corporation (Torrington, USA) and labeled as Light-Weld 425 optically clear structural adhesive. In the previous study [17], [18], we have compared the material properties of the cured ultraviolet-curable resin that purchased from varies vendors. The 425-resin mentioned above showed some favorable advantages over the others, in terms of the properties of hardness, strength and wear resistance to meet the requirement to be employed as the bonding agent in the manufacturing of abrasive tools. The technical specification of the cured transparent 425 resin is listed in Table 1.

TABLE 2. Technical specification of the sapphire workpieces [20].

Material Property of Sapphire Workpiece	Technical Specification
Hardness (Knoop)	15.0-16.3 GPa
Young's Modulus	34-37 GPa
Tensile Stress (Uniaxial)	2250 MPa
Bulk Modulus of Elasticity	250 GPa

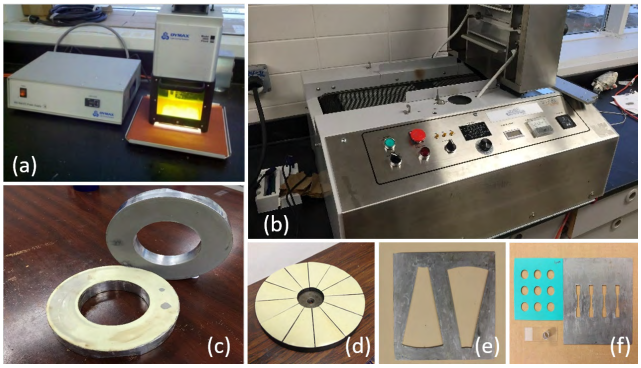

FIGURE 4. The equipment and manufacturing process: Dymax 5000 small-scale ultraviolet curing system (a); Dymax customized large-scale ultraviolet curing system (b); one-step cured machining tool (c); assembled cured machining tool (d); fan-shape part curing mold (e); curing molds for cured-resin material properties test (f).

A batch of Kyropoulous-method grown c-plane sapphire samples (99.999% α-alumina) from Nanjing Co-Energy (Nanjing, China) was selected as the workpiece. These workpieces were shaped into a short cylindrical bar in 2 cm diameter, and a photo of two of them is given within Fig.5. There are three sets of workpieces were prepared for each abrasive machining process. All these sapphire workpieces had been preliminarily ground to ensure an equal initial surface quality (Average $R_a = 0.80\mu m$). The detailed technical specifications of the sapphire workpiece are listed in Table 2.

B. FABRICATION AND EXPERIMENTAL SETUP

In the fabrication process, the mixture of ultraviolet-curable resin, diamond abrasive grain, filler additives were uniformly mixed by stirring machine. Then the mixture was kept in vacuum condition for 1 hour to remove the air bubbles. Next, the prepared mixture in liquid form was coated on top of a metal base plate or injected into a shaping mold, depending on the use of the cured part. For the small size part or test samples used for cured-resin material properties test, the curing molds as shown in Fig.4 (f) were used to shape the part, and the Dymax 5000 flood lamp curing system, as shown in Fig.4 (a) was primarily employed to complete the solidification process. The curing of the whole surface-coated plate shown in Fig.4 (c) or the large-scale piece like the fan-shaped part shown in Fig.4 (e) was cured in the Dymax customized large-scale curing system, as shown in Fig.4 (b). In addition to the whole plate curing, the machining tool can also be fabricated through the assembly of several cured fan-shaped pieces as the Fig. 4(d) shows.

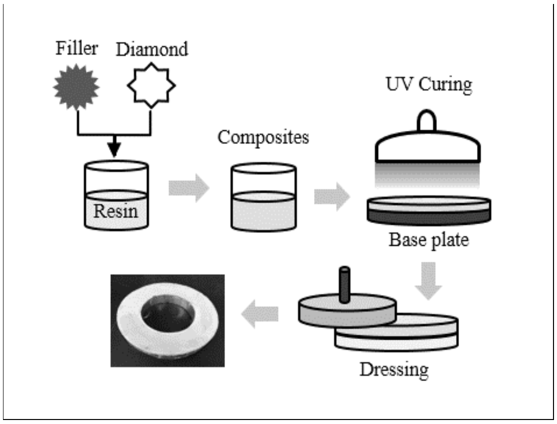

FIGURE 5. The fabrication process of the ultraviolet-curable resin bond diamond lapping plate.

TABLE 3. Machining parameters of the sapphire lapping process.

Lapping Machine	Melchiorre
The diameter of the lapping plate	22 cm
The diameter of the workpiece holder	5.5 cm
Minimum rotation speed	5 rpm
Maximum rotation speed	50 rpm
Round count precision	$\pm 0.5^{\circ}$
Lapping pressure	2.0 KPa
Lapping period	20 minutes

The coated part or loaded mold was exposed under ultraviolet mainly within the wavelength range of 320 nm to 390 nm. The customized curing system ensured that the curing process could be completely finished within 60 seconds. A schematic diagram of the fabrication process to prepare ultraviolet-curable resin bond fixed abrasive diamond plate from raw material is shown in Fig.5, in which a dressing procedure is presented. It is designed to reduce the influence of the curing process flaw, which can be the uneven surface caused by the non-uniform thermal distribution in the whole plate curing, or the thickness differences between fan-shaped pieces caused by assembling inaccuracy.

The comparative machining performance experiments were conducted on the 210-3P fine-grinding machine manufactured by Melchiorre corporation (Bollate, Italy) and the experimental setup is shown in Fig.7. The process parameters of the machining test on the sapphire workpiece can be found in Table 3. Three sapphire workpieces were loaded in the holder each time to perform the machining process. The fixed abrasive lapping was utilized with a mesh #800 (approximate 15 μm in average grain size) diamond plate bonded with thermal-curable resin. The slurry-based lapping was examined on copper base lapping plate with medium concentration diamond slurry that purchased from Engis in standard concentration, which is 400 g of diamond abrasives per 750 ml according to the provided technical specifications. The ultraviolet-curable resin bond diamond lapping plate

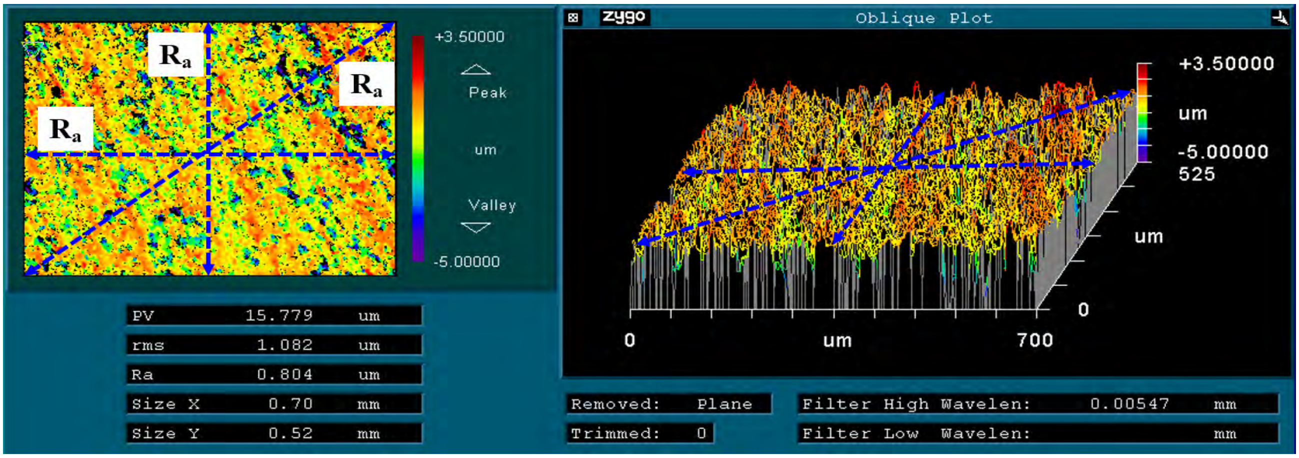

FIGURE 6. **The user interface of the surface roughness measurement on Zygo optical profiler.**

was fabricated at 25% diamond concentration. The diamond concentration is particularly used as a standard to evaluate the weight of the diamond in a unit volume of the tool matrix, and it is defined that where each cubic centimeter contains 0.88 grams diamond, the concentration is 100%. In precision machining of hard and brittle materials, a relatively lower abrasive concentration is preferred. On the other hand, the amount of ultraviolet passing through the resin and diamond composite strongly depends on the abrasive grain size and concentration, the increase in diamond concentration would decrease the energy absorbed by the sub-surface and bottom layer of the resin composite, and thereby decrease the cure depth of the resin plate. For this reason, the diamond abrasive concentration selected in this study is 25% to satisfy the requirement of cure depth, the percentage value number indicates that each cubic centimeter of the cured resin matrix contains 0.22 grams diamond grains.

C. MEASUREMENTS AND CALCULATION

After the machining test, each of the sapphire workpieces was cleaned through ultrasonic washing in de-ionized water and left until dry, and the weight loss of each workpiece was examined by the electronic balance. The surface roughness was measured by the Zygo optical profiler, in which ten times magnification Mirau interference objective was equipped. In the surface roughness measurement, filtering is used to highlight the roughness (high-frequency, short-wavelength component) or waviness (low-frequency, long-wavelength component) of a test part. The filtering method in Zygo optical profiler employed in this series of measurement was set to low pass with a specified wavelength of the higher cutoff point at 5.47 μm.

The surface topography was also observed from the Zygo optical profiler. To maintain the consistency of the experiments, the roughness parameter R_a was based on the symmetry line and diagonal line of a rectangular area of 0.70 mm by 0.52 mm on the surface of each machined workpiece.

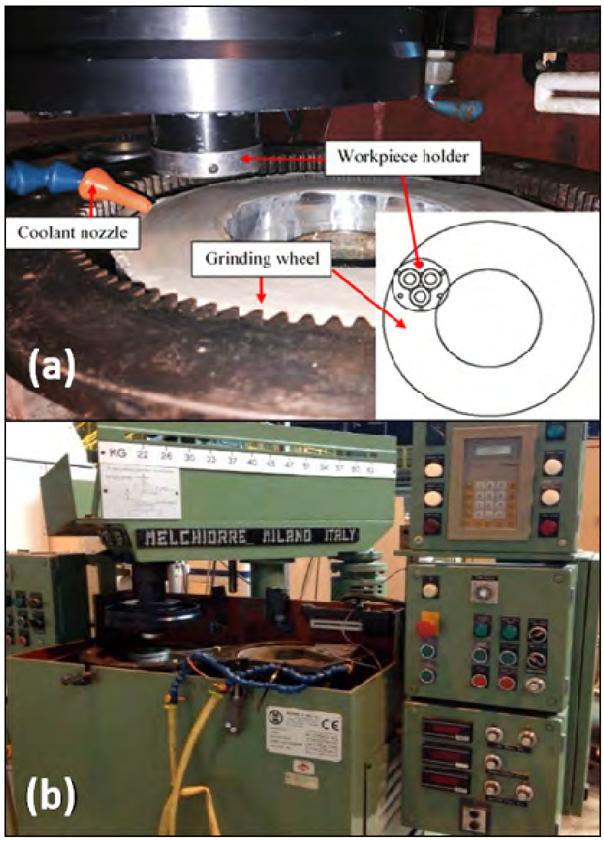

FIGURE 7. **The experimental setup for abrasive machining test on sapphire workpieces (a); and the melchiorre find-grinding machine (b).**

An illustration diagram on the surface measurement interface of the Zygo optical profiler is shown in Fig.6. After that, an average was taken on the roughness parameter R_a from three of the dimensional lines in all the machined workpieces. As mentioned, the weight loss of each workpiece was also evaluated on an electronic balance to study the material removal efficiency of the respective machining process.

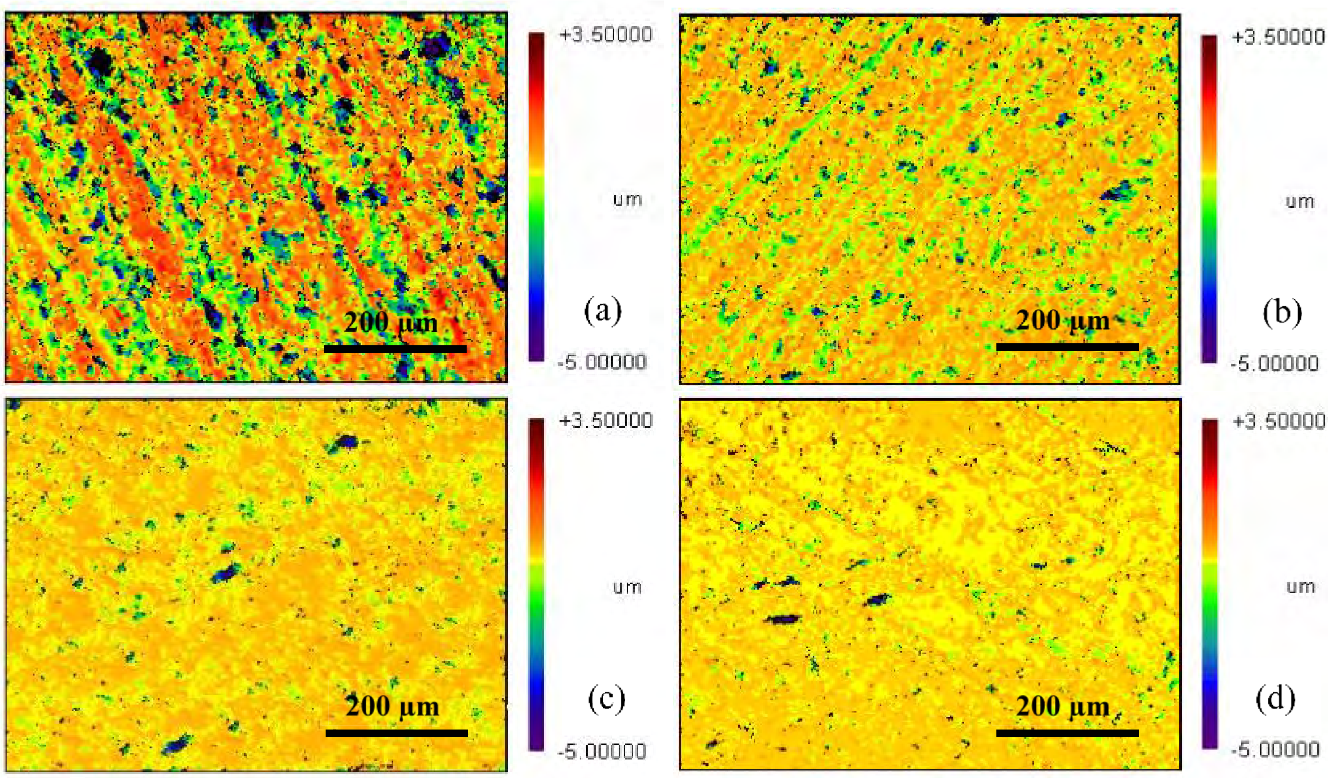

FIGURE 8. Surface topographies of the initial ground sapphire workpiece (a); the workpiece that machined with the fixed diamond lapping plate (b); the substrate machined with the diamond slurry lapping plate (c); the substrate machined with ultraviolet-resin bond diamond lap-grinding plate (d).

III. RESULTS AND DISCUSSION

A. SURFACE TOPOGRAPHY

In Fig.8, the surface topography from one of the original sapphire workpieces and the machined ones from different abrasive machining processes are compared. The prefinished surface topography of the sapphire workpiece with 0.8 μm shown in Fig.8 (a) is relatively rougher, and it is clear to see the grooves and marks generated by the initial grinding process. After that, the sapphire machining test was respectively conducted with the fixed diamond lapping plate, diamond slurry-based lapping plate and the ultraviolet-curable resin bond diamond lapping plate for 20 minutes. The surface topographies observed from the Zygo optical interferometry profiler are shown in Fig.8 (b), (c), and (d).

The Fig.8 (b) shows the surface topography of sapphire sample lapped with mesh #800 lapping plate. In this case, it is considered as a fixed abrasive lapping plate and the abrasive diamonds of which work in the mode of 2-body abrasion mechanism. The ideal semi-ductile removal properties with grooves and scratches can be obviously seen on the surface. However, the width of these grooves is much thinner than that in Fig.8 (a), which was generated by the previous grinding process. This can be explained by the difference in the grain size of the abrasive machining tools. [21]. To maintain the initial surface quality of the workpieces at the same level, the mesh #400 grinding tool with abrasive size in 40 μm approximately was initially employed. Therefore, the sliding of the protruding larger grains removed materials from the sapphire workpiece and left the relatively wider grooves and rougher surface quality. In Fig.8(c), The diamond abrasive slurry involved loose abrasive lapping process produced a classic brittle removal mode on the surface of the sapphire substrate. It is considering the very few amounts of diamond grains that been pressed into the machining tool due to the plastic deformation of the copper base plate under extreme pressure on a single grain. Hence, the pitted surface of the workpiece is primarily considered a result of the indentation crack caused by freely rolling abrasive grain that dominating the 3-body abrasion material removal mechanism.

In the case of the ultraviolet-resin bond diamond lapping, it is assumed that all the diamond grains were embedded in the solid resin matrix of the abrasive tool and worked as fixed abrasive grain at the beginning. As the machining process continues, the resin matrix started to wear out due to the relatively lower hardness and wear resistance. As a result, some of the initially fixed abrasive grains began to fall off from the bonding matrix and turned into loose abrasive grains that produced 3-body abrasion. Meanwhile, the abrasive grains buried in the underlayer of the resin matrix was revealed and worked as fixed abrasive grain renewedly. On the other hand, because of the lapping load, it is possible that some of the loose abrasive grains could be pressed back into the softer resin matrix again due to pressure-initiated plastic deformation. Thus, a hypothesis can be reasonably made that

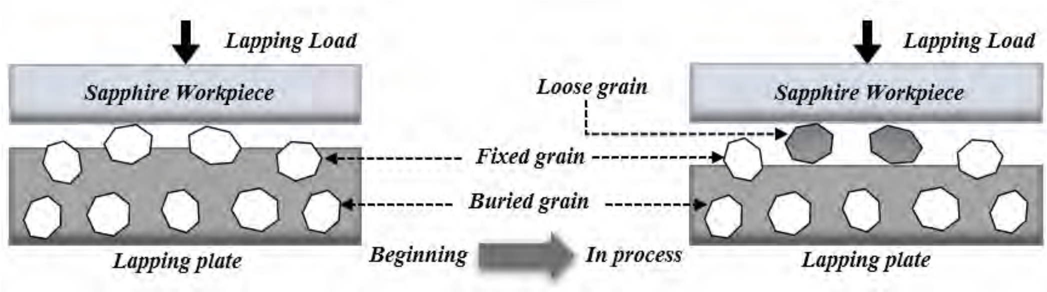

FIGURE 9. Schematic diagram of the ultraviolet-curable resin bond lapping plate.

TABLE 4. Surface roughness and PV value of the sapphire workpiece machined with various lapping process.

Sapphire	Prefinished workpiece		Fixed abrasive lapping		Slurry-based lapping		Ultraviolet-curable resin lapping	
Results	R_a*(μm)	PV**(μm)	R_a(μm)	PV(μm)	R_a(μm)	PV(μm)	R_a(μm)	PV(μm)
Workpiece 1	0.812	19.192	0.325	10.805	0.188	5.484	0.220	6.702
Workpiece 2	0.807	18.740	0.330	11.428	0.164	4.712	0.236	6.440
Workpiece 3	0.820	20.024	0.329	9.688	0.193	4.668	0.228	7.102
Average	0.813	19.319	0.328	10.640	0.182	4.955	0.228	6.748

* R_a of average taken on the symmetry line and diagonal line of a 0.70mm*0.52mm square area
** Maximum Peak-to-Valley height

a balanced state at some point could be achieved in which the fixed abrasive grains and loose abrasive grains simultaneously work to remove materials from the sapphire substrate. That is to say, the abrasive wear mode of 2-body and 3-body mechanism could exist at the same time in the machining process utilized with ultraviolet-curable resin bond plate. In Fig.8 (d), the surface topography in possession of both the characteristics of ductile removal marks and brittle removal pits confirms the possibility of the hypothesis mentioned above.

Additionally, in this case, the transition of material removal mode is illustrated in Fig.9. Generally, the fixed abrasive lapping process of the ultraviolet-curable resin bond plate can be summarized as a hybrid process in which the two-body abrasion and three-body abrasion removal mechanism corporately contribute to the machining process, while the interconversion between fixed grains and loose grains is dynamically balanced as the machining continues.

B. SURFACE ROUGHNESS

The surface roughness of the machined sapphire substrates was examined under Zygo optical surface profiler as mentioned before, and the measurement value was based on the roughness parameter R_a of the symmetry line and diagonal line from a small area of 0.70 mm by 0.52 mm on the surface of the workpiece. For each workpiece, three randomly selected areas were measured to get an average value. The maximum Peak-to-Valley (PV) value was also evaluated at the same time. The comparison results obtained from the respective lapping process are shown in Table 4.

From the table, the machined surface average R_a of the diamond fixed abrasive lapping, slurry-based lapping, and resin bond lapping is 0.32 μm, 0.18 μm, and 0.22 μm respectively, and the PV value is10.64 μm, 4.95 μm, and 6.74 μm. The lowest roughness and PV were obtained from diamond slurry lapping process. The diamond fixed abrasive lapping delivered the highest roughness at 0.32 μm, that is nearly 80% higher than the value that in the slurry-based lapping. Meanwhile, the PV value obtained from the diamond fixed abrasive lapping is 10.64 μm, which is also 50% higher than the latter. This difference could be firstly explained by the advantages of two-body abrasion mechanism on material removal than that in three-body abrasion. According to the research of Bujis and van Houten [22], [23], most of the abrasive grains in 3-body abrasion, which was performed by the diamond slurry lapping in this study, has relatively limited influence on the material removal efficiency, and only a small amount of abrasive grains are embedded in the base plate undertaking lapping pressure and work in the mode of 2-body abrasion. The rolling action of the grains in 3-body abrasion takes off less material than that the sliding action does in fixed diamond lapping and produces less surface ''damage'' which could negatively affect the surface quality, thereby to increase the surface roughness and generate subsurface cracks. Hence, both the surface roughness and the PV height value from the slurry-based lapping process is 45% and 53% lower respectively than that in the fixed abrasive lapping process, as shown in Fig.10. However, in the 3-body lapping process, since it is assumed that only a small amount of grains has been pressed into the base plate working as 2-body abrasive grains, and the material removal by sliding is negligible. As a result, the material removal rate should be accordingly lower than that in fixed abrasive lap-grinding. This presumption reasonably matches the 71% dropdown in

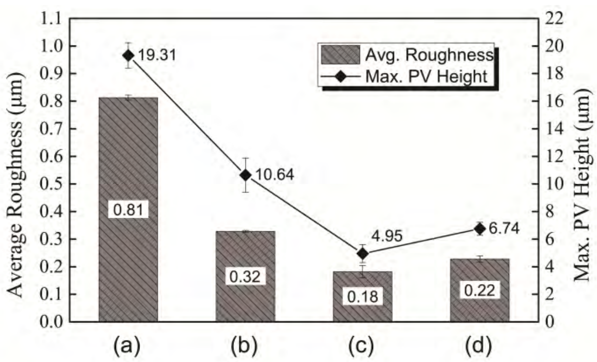

FIGURE 10. **Surface roughness and Peak-to-Valley height of the prefinished sapphire workpiece (a); the workpiece machined through fixed abrasive lapping process (b); the workpiece machined through the slurry-based lapping process (c); and the workpiece machined through ultraviolet-curable resin bond lapping process (d).**

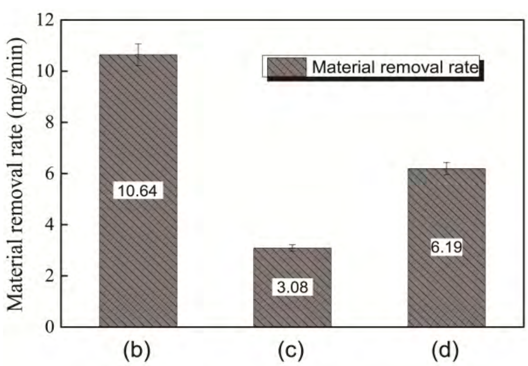

FIGURE 11. **The material removal rate of sapphire workpiece machined through the fixed abrasive lapping process (b); the workpiece machined through the slurry-based lapping process (c); the workpiece machined with ultraviolet-curable resin bond lapping process (d).**

material removal rate from 10.64 mg/min to 3.08 mg/min in Fig. 11.

In the case of ultraviolet-resin bond diamond lapping process, the average surface roughness of the sapphire substrates achieved is 0.22 μm, which is between those in the fixed abrasive lapping and slurry-based lapping process. The machined sapphire substrate surface quality is slightly rougher than that machined through slurry lapping, which is clear to tell through the comparisons of surface topographies in Fig.8. However, the roughness obtained from the lapping process of the ultraviolet-curable resin bond plate is approximately 30% better when compared to 0.32 μm, which is the value from the fixed abrasive lapping process. Moreover, ultraviolet-curable resin bond diamond lap-grinding is capable of carrying out an efficient material removal rate at 6.19 mg/min in this series of the experiment. Even though it is about 40% lower than that in fixed abrasive lap-grinding, but two times higher than that in the slurry-based diamond lapping process. The reason for this machining performance of ultraviolet-curable resin bond plate could be explained by the hypothesis theory of 2-body and 3-body corporately involved hybrid machining mechanism. As mentioned above, in this case, from the very beginning to the in-process machining, the mainly active abrasion transformed from the fixed abrasive machining in 2-body mechanism to loose abrasive machining in 3-body mechanism, meanwhile, the ultraviolet-resin bond diamond lap-grinding wheel keeps generating new and sharp fixed abrasive layer continuously due to the lower wear resistance of the resin bond matrix. This process could be understood as a classic "self-dressing" of the fixed abrasive plate. The integration of these processes and their interconversion could be balanced at a certain period of the machining process, and thus help to build a dynamically stable process with both the advantages of fixed abrasive machining and loose abrasive machining.

C. ABRASIVE GRAINS RETENTION

Respecting the characteristics of the cured ultraviolet-curable resin, the bonded diamond lapping plate by which is also considered as a type of fixed abrasive machining tool. The diamond grain performs the work-material removal while the bond provides the right level of grains retention forces and wear resistance for optimal tool performance, which is characterized by the appropriate balance between the wear of the diamond grains and the timely wear of the bonding agent. This phenomenon is known as the self-sharpening effect [24]. The wear resistance of the grains and the bond is mostly determined by the respective material properties [25], [26], while the abrasive grains retention force can be adjusted by the fabrication process of the tool, and the machining performance of which can be therefore influenced. In this study, the ultraviolet curing process in the fabrication of the fixed abrasive lapping plate enhances the flexibility of adjustment in grain retention. In addition to the chemical bonding, the mechanical bonding achieved through the polymerization and cooling shrinkage of the resin-diamond matrix primarily determines the retention efficiency [27], where the diamond abrasive grains are squeezed and locked by the shrinking composite matrix. Therefore, a FEM modeling simulation of the diamond retention stress embedded in the cured resin matrix is conducted in this study to develop a method for the theoretical research to predict the machining ability of the fabricated tool.

To quantitively evaluate the retention force in the fabrication of the ultraviolet-curable resin bonding diamond lapping plate. A basic model of a diamond abrasive grain embedded in the resin matrix was established with the finite element method using Abaqus program version 6.14 to analyze the stress and strain distribution. An illustration of the simulation 3D model and meshed assembly can be seen in Fig. 12.

In the numerical simulation of light-curable resin solidification, the shrinkage of the resin from the liquid-to-solid phase transaction during the solidification can be considered as the cooling shrinkage of the solidified resin matrix [28]. Thus, the finite element simulation is based on the cooling process of the cured resin matrix from the highest temperature to room temperature, the highest temperature is calculated through the ultraviolet density, the distance from the lamp

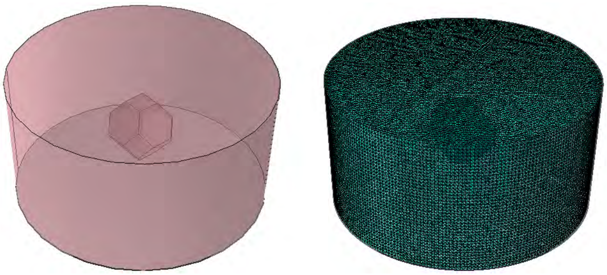

FIGURE 12. The 3D model and meshed assembly of a diamond abrasive grain embedded in the ultraviolet-curable resin matrix.

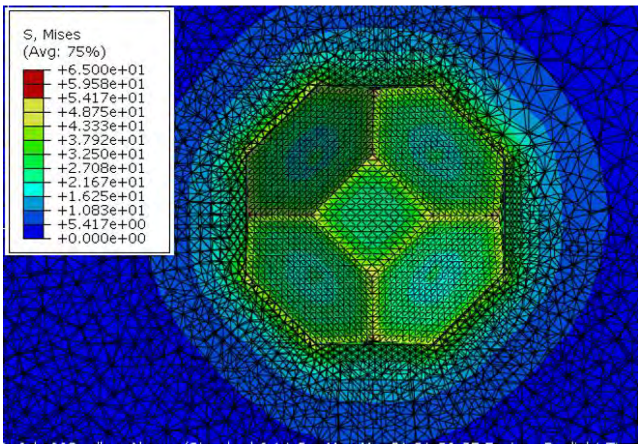

FIGURE 13. The simulation results of the resin matrix shrinking process from 190° to 20°.

to the resin matrix, the area that exposed to the light, and other relative parameters. In practical, the geometry shape of the micro-scale diamond grains is uncertain and randomly distributed. In order to simplify the simulation process, it is assumed that the diamond grit is in a perfect shape of cubo-octahedral and the matrix part where the retention stress distributed is also simplified as a cylinder shape. The diamond grain part is meshed with hexahedral elements of type C3D8R, and the resin matrix is meshed with linear tetrahedral elements of type C3D4. The simulation results are shown in Fig.13 and Fig.14.

The Abaqus simulation results demonstrate the evidence that the diamond abrasive grain is surrounded by the plastic zone and an uneven distribution of stress and strain in the matrix surrounding the diamond grain. The highest values can be seen in the areas adjacent to the sharp edges and tips of the abrasive grain. The maximum von Mises stress in this simulation is about 65 MPa, while the number obtained in the cobalt-based bonding and copper-based bonding diamond tools is approximately from 500 MPa to 900 MPa [29]–[31]. Eventually, the lower maximum stress leads to a relatively weak bond between the abrasive grains and the resin matrix. Therefore, the premature loss of the abrasive grains and outstanding self-sharpen characteristic of the ultraviolet-curable resin bond plate can be reasonably explained.

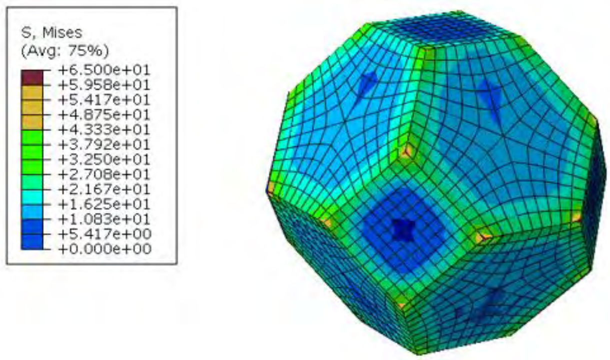

FIGURE 14. The simulation results of the mechanical bonding force generated on the diamond grain after cooling down of the resin matrix.

D. ECONOMIC AND ENVIRONMENTAL SCOPE

According to these abrasive machining comparative experiments based on sapphire substrates, a statement can be drawn that, the ultraviolet-curable resin bond abrasive tool utilized machining could carry out not just superior surface quality regarding surface roughness and PV height, but also preserve the material removal rate at a relatively higher efficiency. As we know from the general manufacturing process of sapphire substrates, the machining of the sapphire workpiece from raw material can be summarized into four key steps: saw slicing, profiling, flattening and final surface finishing. It is hoped that the development of this ultraviolet-curable resin bond abrasive wheel could be introduced into the flattening and surface precondition of sapphire machining. Therefore, the two steps could be replaced with a much more efficient process that offers a better surface quality without taking off too much material.

On the other hand, compared with the conventional thermal-curable resin bond abrasive tool from an economic and environmental perspective, the ultraviolet-curable resin has brought a series of advantage to the production of the abrasive tool. Firstly, the hot pressing or sintering process of the conventional thermal-curing resin bond tool is not just an energy-costly process but also time-consuming, which differs from hours to days, while the ultraviolet curing time only takes seconds to minutes to finish the solidifying. Secondly, the ultraviolet-curing process is completed through the monomers and oligomers polymerization that triggered by photo-initiators, there is nearly no harmful byproduct produced during the reaction. The chemical and physical evaporation generated from the thermal-solidifying and sintering process would be a potential risk to the environment, and it would cost extra efforts for the post-treatment. Additionally, the ultraviolet-curing process is likely an additive manufacturing process with much flexibility, the scale of the curing equipment only depends on the model size of the abrasive tool, therefore, to waive the requirement of large field facility and human effort.

IV. CONCLUSION

This study proposed a new type of fixed abrasive lapping plate for the surface precision machining process of the sapphire substrate, in which the ultraviolet-curable resin was selected as the bonding agent in the fabrication of the abrasive tool to deliver a rapid, flexible, economical and environment-friendly manufacturing process. The performance of the ultraviolet-resin bond diamond lap-grinding wheel was examined through the comparative experiments including the fixed abrasive lap-grinding and slurry-based lapping.

The results highlighted a strong relationship between the workpiece surface finish and the material removal mode driven by the motion mode of the abrasive grains during the lapping process. Due to the material properties of the cured resin matrix and relatively weaker diamond grain bonding retention, the ultraviolet-curable resin bonding tool enabled a hybrid abrasive machining process integrating both the fixed abrasive grains and loose abrasive grains, where the 2-body abrasion mode and 3-body abrasion mode work simultaneously, and dynamically transform to each other as the machining process continued. Among the comparative experiments on sapphire workpieces, the ultraviolet-curable resin tool fabricated in this study achieved 0.22 μm in surface roughness evaluation, it is a 45% reduction comparing to the conventional fixed abrasive lapping. Though the slurry-based lapping process delivered 0.18 μm at the same working condition, the material removal rate of which was only 3.08 mg/min. The continues regenerating fixed abrasive diamond grains in the ultraviolet-curable resin plate helped to enhance the process material removal rate to 6.19 mg/min, an approximate 100% improvement in machining efficiency than the slurry-based lapping. In conclusion, the fabricated ultraviolet-curable resin tool is capable of producing the same level surface finish as the slurry-based lapping process does and avoiding the material removal efficiency lost.

It is hoped that this study could inspire the application of the ultraviolet-curable resin bonding tool, and ultimately integrate the two-step precision flattening procedure into one hybrid machining process in the semiconductor material manufacturing industry.

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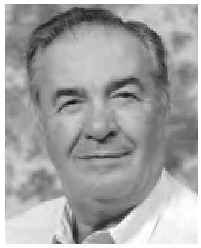

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