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Research and Progress on Truing and Sharpening Process of Diamond Abrasive Grinding Tools

Song Cai [1,2,3], Wenhao Liu [1], Jinchao Song [1], Kai Deng [1] and Yinghong Tang [1,*]

[1] School of Mechanical Engineering, Hunan University of Technology, Zhuzhou 412007, China; happy9918@sina.com (S.C.); lwh9706@126.com (W.L.); 17720163097@163.com (J.S.); dk123dk@163.com (K.D.)
[2] School of Mechanical Science & Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[3] Green Fan Manufacturing Collaborative Innovation Center in Hubei Province, Wuchang Institute of Technology, Wuhan 430065, China
* Correspondence: aaa492938174@sina.com

Abstract: With respect to the truing and sharpening of diamond abrasive grinding tools, traditional machining methods are briefly described, and new dressing methods, such as the laser dressing method, are described in detail. It is pointed out that laser dressing of diamond abrasive tools is a green processing method with high efficiency and no environmental pollution. Numerical simulation research on pulse laser dressing of a bronze diamond abrasive grinding wheel was carried out, and a cumulative heat transfer model of laser dressing energy was developed. The temperature evolution law of the bronze bond and diamond abrasive grains dressed by pulsed fiber laser was determined by numerical analysis of the model. An experiment on the laser dressing grinding wheel was carried out; it was found that when the laser power density was 2.52×10^8 W/cm^2~3.36×10^8 W/cm^2, the bronze bond materials could be properly removed, and the diamond abrasive grains could be better sharpened. The laser dressing method can achieve the combination of diamond abrasive grinding tool sharpening and truing. The experiment not only demonstrated the correctness and feasibility of the theoretical model but also provided process optimization for research into pulse laser dressing of diamond abrasive grinding tools.

Keywords: diamond abrasive grinding tools; truing and sharpening; data analysis; dressing technology

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1. Introduction

With the continuous development of science and technology, super-hard abrasive grinding tools have gradually replaced ordinary abrasive grinding tools and become the main means of high-quality, efficient, and precise machining of difficult-to-machine materials. Super-hard abrasive grinding wheels often employ synthetic diamond and cubic boron nitride (CBN) as abrasives and use ceramics, metals, and resins as the bonds, which have high processing durability and can improve the surface quality of workpieces, making them more suitable for automated production. Super-hard abrasive grinding wheels are the basis for high-speed and ultra-high-speed grinding, and high-efficiency, ultra-precision grinding [1].

Diamond abrasive grinding tools are the most widely used super-hard abrasive grinding tools. During the grinding process, the abrasive grains will be gradually rounded and blunted under the action of friction and extrusion force. During grinding, the grains will slip with the workpiece and may cause vibration and noise, which will affect the shape accuracy and roughness of the workpiece surface and reduce grinding efficiency and grinding performance. The dressing technology of diamond abrasive grinding tools, which is often restricted by a series of factors, such as dressing efficiency, dressing accuracy, dressing tools, and complex surface dressing, is presently an urgent problem to be solved.

2. Dressing Status of Diamond Abrasive Grinding Tools

The development of grinding technology has experienced three stages: ordinary grinding, precision grinding, and ultra-precision grinding [2]. With the development of various new materials, the ordinary grinding wheel cannot meet their increasing processing requirements. The role of the diamond abrasive grinding wheel is prominent and its application is increasing rapidly. In addition, the shaping accuracy and topography are important indicators for the quality evaluation of diamond abrasive grinding tools, because the shaping accuracy determines the dimensional accuracy and surface quality of the grinding workpiece, and the topography determines the holding force of abrasive grains and the chip holding space around them.

The dressing of diamond abrasive tools mainly includes two steps: truing and sharpening. Truing refers to cutting blunt diamond abrasive grains to make their tips finely broken and obtain appropriate shape accuracy to form a sharp grinding edge. Sharpening refers to removing the excess bond materials between diamond abrasive grains, making them possess appropriate chip holding space, and making the grinding edge higher than the bond to obtain the ideal abrasive grain height and form the cutting edge [3]. The dressing technology of diamond abrasive grinding tools has developed step-by-step from the traditional single "hard touch" dressing [4], and a series of effective dressing methods have been obtained, as shown in Figure 1. It can be seen from Figure 1 that improvements in traditional machining technologies, such as the diamond pen truing method, grinding method, rolling method, free abrasive grain sharpening method, consolidated dressing tool sharpening method, and the innovation of new processing technologies, such as the electric discharge machining (EDM) dressing method and laser dressing method, can provide feasible schemes for the development of diamond abrasive grinding tools dressing technology.

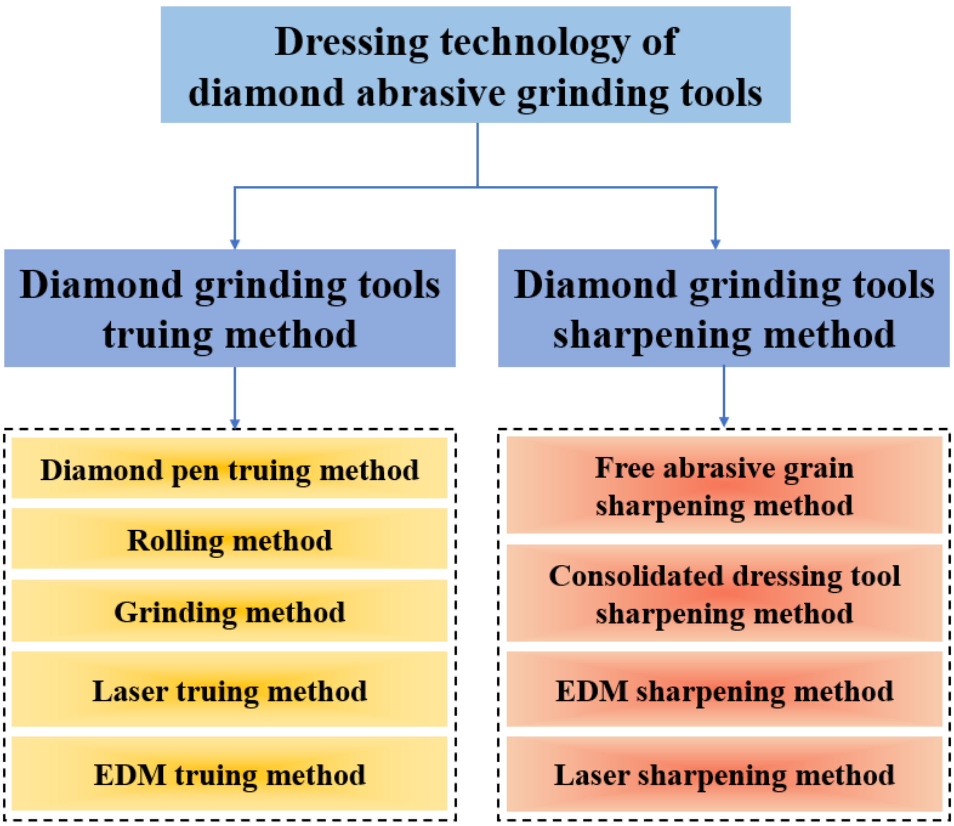

Figure 1. Diamond abrasive grinding tools dressing technology.

3. Dressing Method of Diamond Abrasive Grinding Tools

3.1. Truing Technology of Diamond Abrasive Grinding Tools

Truing technology of diamond abrasive grinding tools refers to the process of micro-dressing diamond abrasive grains to make their tips finely broken and obtain appropriate shape accuracy to obtain the grinding edge. At present, the truing technology of diamond abrasive grinding tools mainly includes the diamond pen truing method, rolling method, grinding method, EDM truing method, and the laser truing method.

3.1.1. Diamond Pen Truing Method

The diamond pen truing method is a traditional mechanical truing method; a schematic diagram is shown in Figure 2. The diamond abrasive grinding wheel rotates clockwise. The diamond pen is installed on the fixed frame and forms a 90° angle with the diamond abrasive grinding wheel. The tip of the diamond pen aims at the high point of the abrasive grains on the diamond abrasive grinding wheel. The abrasive grains are slightly broken. The abrasive grains fall off due to the removal of the bond material.

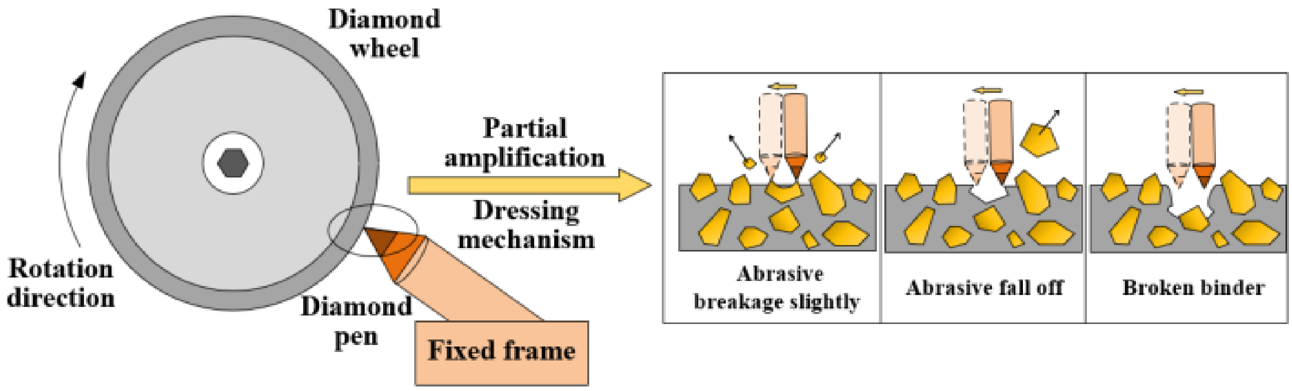

Figure 2. Schematic diagram of diamond pen dressing diamond abrasive grinding wheel.

LEI et al. [5] set the diamond pen to grind each high point on the surface of the diamond abrasive grinding wheel to meet the grinding requirements of the diamond abrasive grinding wheel. When using the diamond pen truing method to dress the diamond abrasive grinding wheel, the grinding wheel speed should be maintained at a low speed, otherwise, it is difficult to achieve the expected dressing effect.

Due to its simple structure and low investment cost, the diamond pen truing method is widely used in the field of grinding, but the wear of the diamond pen is quite serious, and the shape accuracy and dimensional accuracy are not high, which affects the surface integrity of diamond abrasive grinding tools. The grinding surface roughness (expressed as *Ra*) gradually decreases with increase in dressing times (Figure 3). When the dressing times reaches about 500 times, *Ra* tends to be stable [6], and the dressing efficiency is approximately 30∼40%. Therefore, scholars have sought to improve and develop the traditional diamond pen truing method which is organically integrated with other dressing methods. For example, based on the principle of vibration cutting, Zhao et al. [7,8] employed an ultrasonic vibration dressing method together with a diamond pen. This technology could eliminate the shortcomings of the traditional turning dressing of diamond pens and obtain good morphology, to achieve the purpose of improving the shape accuracy and grinding performance of the grinding wheel, and greatly improve efficiency.

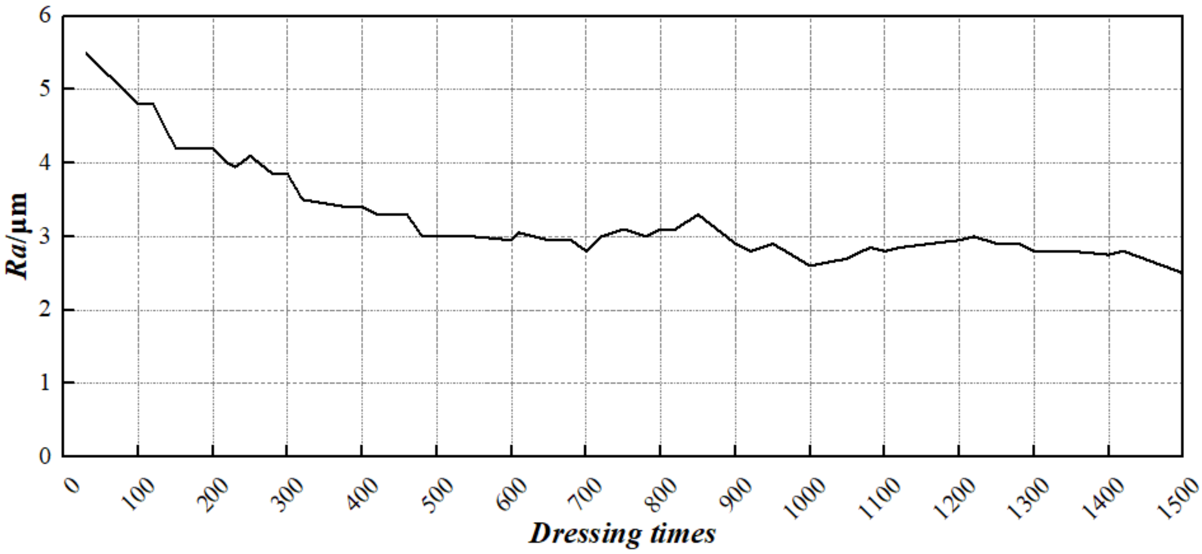

Figure 3. Variation law of grinding surface roughness Ra with the dressing times [6].

3.1.2. Rolling Method

With a view to addressing the problems of the serious wear and tear of tools in the diamond pen truing method, the rolling method came into being. The diamond pen truing method achieves the purpose of dressing according to the action of shearing force, and the rolling method mainly breaks and lets fall the abrasive grains through the action of pressure. Figure 4 shows a schematic diagram of the rolling method, in which a green silicon carbide (SiC) or white corundum grinding wheel is generally selected as the dressing grinding wheel, and the bottom is a diamond abrasive grinding wheel. The diamond abrasive grinding wheel is fixed and rotated clockwise. The dressing grinding wheel rotates and reciprocates back and forth through the grinding machine for grinding. After grinding by the rolling method, the diamond abrasive grains are sharper. It can be seen from the dressing principle that the rolling method has high requirements on the rigidity of the grinding machine.

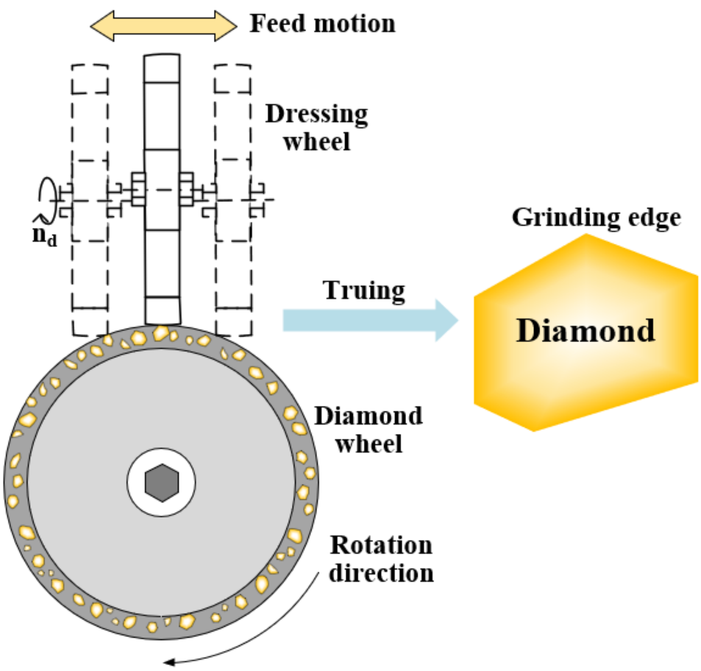

Figure 4. Schematic diagram of the rolling method.

Drazumeric Radovan et al. [9] studied the lateral dressing of diamond abrasive grinding wheels, which employed an Al_2O_3 or SiC dressing wheel to break and drop off the diamond abrasive grains and shortened the dressing time under the condition of constraining the dressing force through the basic relationship between geometry, kinematics, and the removal mechanism. Liang et al. [10] studied the tangential grinding of V-shaped tips of resin-bonded and metal-bonded diamond abrasive grinding wheels with SiC dressing grinding wheels and found that both kinds of diamond abrasive grinding wheels after dressing could meet the requirements of microstructure processing. Figure 5 shows the topography of the diamond abrasive grinding wheel surface after dressing by the rolling method [11]. It was found that the diamond abrasive grains protruded from the bond material and had appropriate shape accuracy, and the dressing efficiency was approximately 45∼55%.

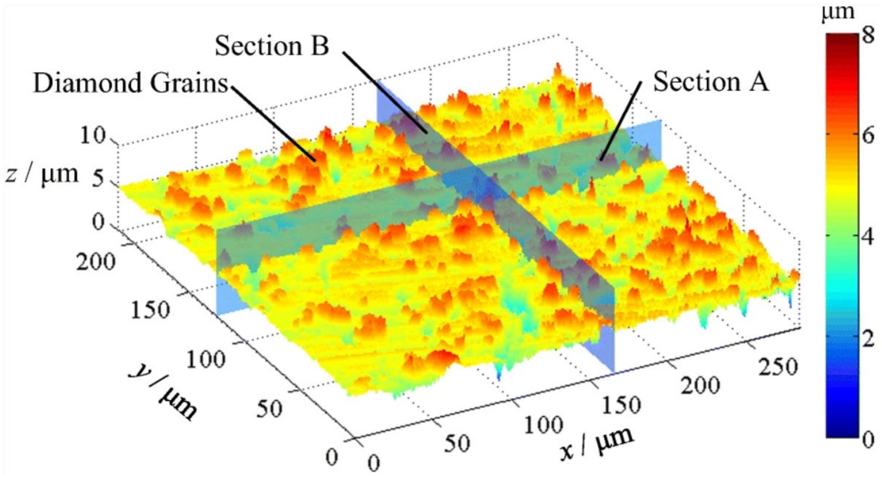

Figure 5. The micro-morphology of the surface of the diamond abrasive grinding wheel after dressing [11].

Some researchers have integrated the ultrasonic vibration dressing method into the rolling method to achieve higher quality grinding. Wada et al. [12] designed a dressing device for truing and sharpening the grinding surface of the diamond abrasive grinding wheel by using an ultrasonic vibration device. Chen et al. [13] developed a method of using "mid-frequency vibration-assisted grinding with self-induced grinding forces" to produce micro-groove arrays on single crystal diamond (MCD) for super-hard material removal; the experimental results showed that there were no obvious burrs and cracks on the single crystal diamond, which could ensure high-quality grinding.

Although the rolling method has the above dressing characteristics, the residual bond materials easily block the surface of the grinding wheel and reduce its grinding ability, which is the key to restricting the development of the rolling method.

3.1.3. Grinding Method

To realize precision grinding and obtain a minimal amount of dressing removal, the grinding method is applied to the dressing of diamond abrasive grinding tools. The grinding method refers to the dressing of diamond abrasive grinding wheels with ordinary abrasive grinding wheels. Grinding methods include the cup-shaped grinding wheel truing method (this method solves the problems of flat abrasive surfaces and increased grinding force during the dressing process), the low carbon steel or mild steel grinding truing method (due to a large number of abrasive grains falling off in the truing process, it is not suitable for high-precision surface truing), and diamond roller truing. Figure 6 shows a schematic diagram of the grinding method dressing; the left side of Figure 6a is a diamond abrasive grinding wheel and the right side is a dressing grinding wheel, both of which rotate counterclockwise. Due to the difference in hardness between the two, when the dressing grinding wheel and the diamond abrasive grinding tool are ground at the meshing position, the ordinary abrasive grains will cut the bond material to make the abrasive grains fall off and meet the dressing requirements of the diamond abrasive grinding wheel, as shown in Figure 6b.

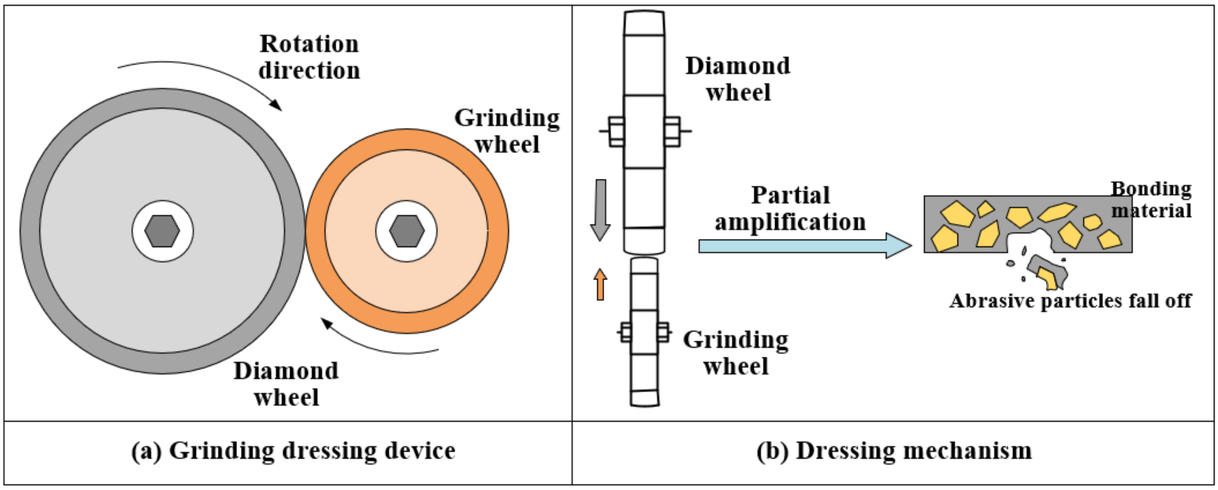

Figure 6. Schematic diagram of grinding method dressing.

Lin [14] employed the high-speed rotating diamond roller to dress the diamond abrasive grinding wheel installed on the grinding machine. This method was simple to operate and could improve the service life of the diamond abrasive grinding wheel. Zhang et al. [15] conducted dressing experiments on coarse-grained and fine-grained bronze-bonded diamond abrasive grinding wheels on a surface grinding machine with an abrasive water-jet system and combined abrasive water-jet (AWJ) and contact dressing technology. It was found that the dressing wheel could achieve less grinding force and better surface roughness. Zheng et al. [16] found that, compared with the conventional scratch test, the scratch force of the ultrasonic vibration-assisted method decreased significantly and the volume of removed materials increased significantly. As shown in Figure 7 [17], after dressing by the grinding method, the surface of diamond abrasive grains was relatively smooth, the edge angle was sharp, the grinding edge was protruding, and the dressing efficiency of the grinding method was approximately 55∼65%.

Figure 7. Surface condition before and after diamond abrasive grinding [17].

The dressing process of truing a diamond abrasive grinding wheel by the grinding method is cumbersome and inefficient and high-precision surface truing cannot be carried out. Given the above problems, researchers have proposed a series of new processing methods, such as the EDM truing method and laser truing method, hoping to obtain a better dressing effect with higher efficiency.

3.1.4. Electric Discharge Machining (EDM) Truing Method

EDM truing methods, including the electrolysis method and the electric spark method, are suitable for dressing a grinding wheel with a conductive material as a bond. Among them, the electrolytic method refers to the dissolution and etching of metal bonds through an electrolyte anode with the assistance of a formed cathode and mechanical friction. The electric spark method refers to the use of electric corrosion to remove the bond materials and diamond abrasive grains by use of a pulsed electric spark. Wu et al. [18] carried out electrochemical machining dressing on a multi-layer brazed coarse-grained diamond abrasive grinding wheel containing a CMS electrolyte. This method could effectively improve the machining surface quality. CMSs could increase the electrolytic capacity of the electrolyte, enabling the wear abrasive particles to fall off smoothly, and reducing the occurrence of processing defects, such as grinding surface breakage and cracks of the diamond abrasive grinding wheel. Wang et al. [19] proposed a novel active gap capacitance electric discharge machining (AGC-EDM) method for efficient machining of polycrystalline diamond. Borisov et al. [20] discussed the electrochemical dressing method of diamond abrasive grinding wheels and found that this method would not reduce the surface grinding quality in the hybrid technology of electrochemical treatment. He et al. [21] studied the electric-contact discharge after dressing to ensure the uniformity of the height of the abrasive grain protrusion. Zhou et al. [22] found that the electric spark discharge current affected the height of diamond abrasive grains protruding from the metal bond and the size of the chip holding space and that the pulse width affected the surface roughness of the diamond abrasive grinding wheel. Wang et al. [23] carried out EDM truing experiments on the small ball-end fine diamond abrasive grinding wheel and analyzed the relationship between the electrical parameters and contour accuracy; a reduction in the graphitization of the diamond abrasive grinding wheels, and ideal dressing quality was achieved.

The surface effect of electric machining truing aluminum-based diamonds is shown in Figure 8 [24]. It was found that the surface of the diamond abrasive grains was smooth and bright, and the grinding edges were sharp. The EDM truing method had a high dressing efficiency of approximately 60∼70% and had certain advantages in machining workpieces that could not be machined by conventional machine tools, but it had disadvantages in machining non-conductive materials. Moreover, the power supply of the electrolytic machining method was expensive and the EDM truing method was difficult to process due to the existence of a discharge gap. Especially for large abrasive grains, it was difficult to process. Therefore, lasers began to be applied to truing diamond abrasive grinding tools.

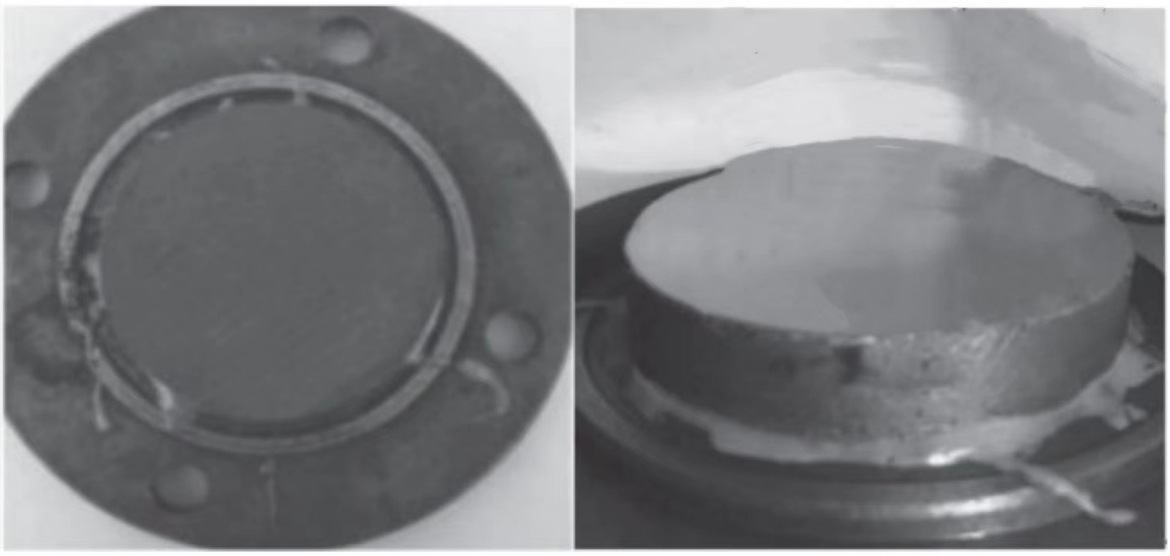

Figure 8. Surface renderings of the aluminum-based diamond before and after Electrolytic in-process dressing technology (ELID) processing [24].

3.1.5. Laser Truing Method

The laser truing method refers to adjusting the parameters of the focused laser and controlling the position movement of the grinding wheel relative to the laser beam in the three-dimensional mobile platform to make the laser directly irradiate the diamond abrasive grinding tools. Through this non-contact processing method, the ideal geometric accuracy can be obtained, and the grinding edges can be formed. Laser dressing of diamond abrasive tools has attracted the attention and recognition of researchers at home and abroad due to its high processing efficiency, high degree of automation, and reduced pollution [25]. Therefore, the application of laser technology in diamond abrasive grinding tools dressing has become a hot topic in recent years.

Liu and others [26,27] found that the average power of fiber lasers and the overlap rate of the light spot was roughly proportional to the dressing efficiency and determined the key laser process parameters to achieve better dressing effects. Chen et al. [28] established a set of high-precision laser inspection and tangential dressing V-shaped concave diamond abrasive grinding wheel systems, took the fiber laser as the detection and dressing equipment, adopted the digital image processing technology, and controlled the average error of the geometric parameters of the V-shaped concave contour to within 3% with the optimization of process parameters.

With the development of laser technology, Cai et al. [29] employed the blowing assisted dual laser (nanosecond and femtosecond laser) method to dress the diamond abrasive grinding tools, which could reduce the return of plasma particles generated after the removal of bond gasification to the surface of the grinding tool, achieve the height of the abrasive grains protruding from the bond and improve the grinding performance. This method could also avoid the phase explosion effect, form the surface of diamond abrasive grinding tools, quickly reduce the heat around the abrasive grains, and reduce the thermal damage defects of thermal cracks and graphitization on the surface of abrasive grains, to improve the dressing effect and the quality and accuracy of fine-machining. This study also had certain limitations. For example, the dual-laser device was more expensive than the single-beam laser and belonged to a process method of rough dressing diamond abrasive grinding tools.

As shown in Figure 9 [30], compared with blunt diamond abrasive grains, the diamond abrasive grains after laser dressing had sharp grinding edges and ideal shape accuracy, while the dressing efficiency was approximately 70∼80%.

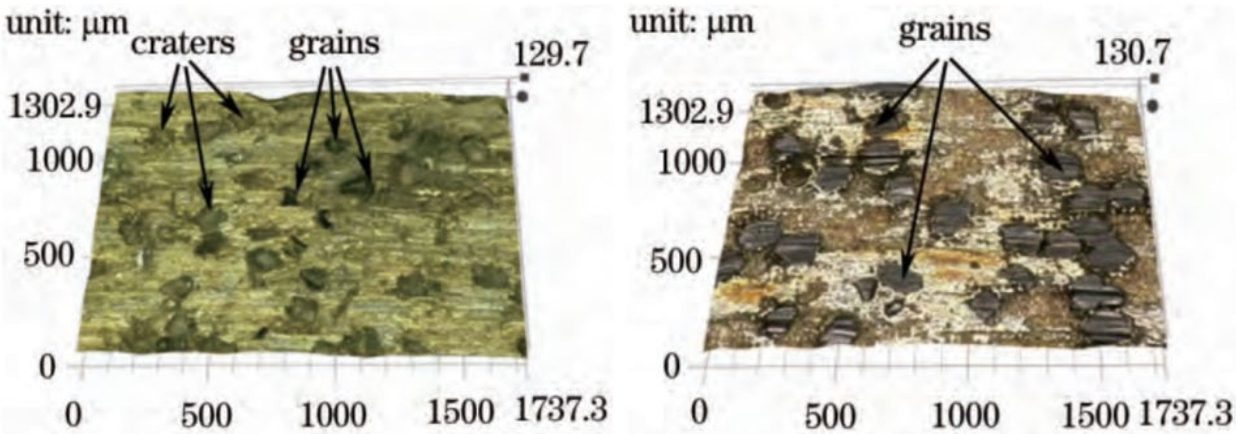

Figure 9. The micro-topography of the grinding wheel surface before and after laser dressing [30].

Although laser truing of diamond abrasive grinding tools has the advantages of high precision and high efficiency, the diffusion of plasma after laser dressing, environmental pollution, and the establishment of a heat transfer model in the dressing process are still difficult problems to be considered and solved in subsequent development.

3.2. Sharpening Technology of Diamond Abrasive Grinding Tools

Sharpening technology of diamond abrasive grinding tools refers to the process of cutting the excess bond material between the diamond abrasive grains, making them possess appropriate chip holding space, making the grinding edge higher than the bond, obtaining the ideal abrasive grain height, and forming the cutting edge. With the rapid development of science and technology, the sharpening technology of diamond abrasive grinding tools has generated the free abrasive grain sharpening method, the consolidated dressing tool sharpening method, the EDM sharpening method, and the laser sharpening method.

3.2.1. Free Abrasive Grain Sharpening Method

The free abrasive grain sharpening method mainly includes ultrasonic vibration sharpening, free abrasive jet sharpening, and free abrasive extrusion sharpening. Among these, the free abrasive jet sharpening method is a high-efficiency sharpening method, which can obtain an ideal sharpening effect in a short time. Cui et al. [31] proposed a dressing method combining grinding grains extrusion and dressing under the constraint of a diamond surface and found that this method could enable rapid forming and precision dressing of super-hard abrasive grinding wheels. When selecting appropriate parameters, such as the grinding force and grinding ratio, the dressing efficiency was approximately 23∼30%.

To improve the surface topography characteristics of abrasive tools and achieve the purpose of dressing, numerous researchers have used the ultrasonic vibration sharpening method in combination with other methods. Soleimanimehr et al. [32] studied the ultrasonic vibration dressing method and analyzed the influence of the cutting ratio on the diameter error in ultrasonic vibration-assisted turning. Yang et al. [33] carried out a laser ultrasonic vibration collaborative dressing experiment on diamond abrasive grinding wheels and studied the removal behavior of laser-assisted ultrasonic dressing of diamond abrasive grinding wheel material through simulation and experimental methods. The experiments showed that the simulation results could be used effectively for the selection of process parameters. The abrasive grains had an ideal shape and protrusion in this dressing mode, and the grinding wheel had a large chip holding space.

The efficiency of dressing diamond abrasive grinding tools by the free abrasive grain sharpening method is low, so it has not been popularized and applied in industrial production. However, the integration of the ultrasonic vibration sharpening method and other dressing methods is still a worthwhile research direction for future dressing technology.

3.2.2. Consolidated Dressing Tool Sharpening Method

Consolidation dressing tool sharpening methods include the oilstone sharpening method, the ordinary grinding wheel grinding sharpening method, and the silicon carbide (SiC), or corundum block cutting sharpening method. These methods mainly utilize the difference in hardness between the sharpening tool and the diamond abrasive grains to make the abrasive grains fall off by cutting the bond material between the abrasive grains. The dressing effect is shown in Figure 10 [34]. Klink et al. [35] employed internal cooling grinding tools and an electric corrosion process to dress the abrasive grains, which could achieve the ideal sharpening effect. Zhou et al. [36] dressed the diamond abrasive grinding wheel through three-axis linkage circular arc interpolation movement, which had a simple structure, high dressing accuracy, and high processing efficiency. Chen et al. [37] used three-axis linkage machine tools and sharpening tools, such as carbide grinding rods, to dress resin-bonded V-shaped diamond abrasive grinding wheels to achieve accurate in situ dressing. Xue [38] designed a twist drilling device for dressing diamond abrasive grinding wheels with a large dressing area, high efficiency, and high accuracy. Liu et al. [39] employed oilstone as a grinding tool to remove the bond material of the diamond abrasive grinding wheel and drove the oilstone to dress the end face of the grinding wheel by rotating the dressing shaft. This design was effective, low cost, and showed an ideal dressing effect.

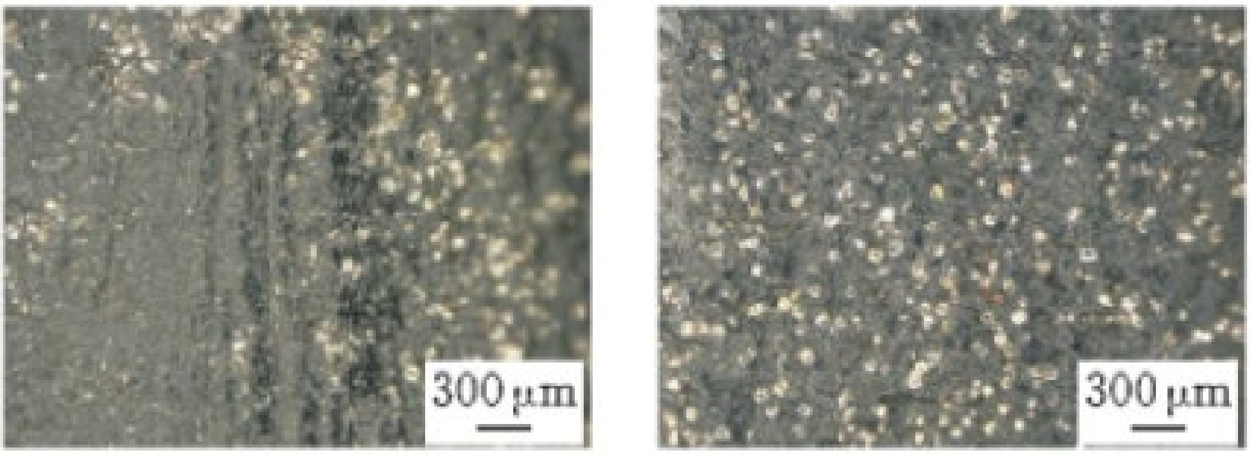

Figure 10. Comparison of grinding wheel surface morphology before and after grinding wheel dressing [34].

Through the above research at home and abroad, it was found that, compared with the free abrasive grain sharpening method, the dressing efficiency of the consolidated dressing tool sharpening method was improved to a certain extent, by approximately 35∼45%. The surface roughness of the grinding wheel after sharpening was reduced and a large number of new abrasive grains were exposed. Although some progress has been made in the consolidation dressing tool sharpening method, it cannot be used for large cutting quantities and the sharpening efficiency is low. This is still an aspect that needs to be improved in the development of the consolidation dressing tool sharpening method in the future.

3.2.3. Electric Discharge Machining (EDM) Sharpening Method

EDM sharpening methods mainly include the EDM dressing method and the electrolytic online dressing method. EDM grinding wheel dressing technology was first proposed by Suziki et al. [40]. Figure 11 shows a schematic diagram of the EDM dressing technology. The diamond abrasive grinding tool rotates clockwise and is connected to the positive pole of the power supply, while the tool electrode is connected to the negative pole of the power supply. The discharge medium, such as working fluid, is introduced between the diamond abrasive grinding wheel and the tool electrode to make the pulse voltage pass through, thereby generating a pulsed spark and forming a discharge channel. The phenomenon of electric corrosion eliminates the bond material and achieves the purpose of sharpening the diamond abrasive grinding wheel. Yu et al. [41] conducted experimental research on EDM dressing of the bronze-bonded diamond abrasive grinding wheel using an internal impact arc copper tungsten electrode and found that the surface abrasive grains were prominent, large in number, and high in density.

Electrolytic in-process dressing technology (ELID) was developed in Japan in the early 1990s for precision mirror grinding of dressing grinding wheels. Figure 12 shows a schematic diagram of the electrolytic in-process dressing technology. The working principle of ELID is to use tool electrodes and diamond abrasive grinding wheels as cathode and anode, while the nozzle sprays special electrolytic grinding fluid between the two poles. Under the action of the power supply, the diamond abrasive grinding wheel is dressed online through the anode dissolution effect. When the bond material is eroded, a layer of dense oxide film is formed on the surface of the grinding wheel, which can slow down the electrolysis speed, prevent excessive electrolysis and avoid excessive wear of the grinding wheel. However, as the oxide film becomes thinner and the conductivity increases, the electrolysis speed of the bond materials is accelerated to realize the cycle of online electrolytic sharpening. During the sharpening process, the surface of the grinding wheel can maintain the most ideal morphology and achieve ultra-precision mirror grinding. Chen et al. [42] proposed an ultrasonic-assisted electrolytic process sharpening method, which combined the high-frequency ultrasonic vibration method with the electrolytic method in parallel and carried out comparative experiments on this. It was found that the method could improve the removal rate and machining surface quality and overcome the difficulty of continuous dressing of the fine diamond abrasive grinding wheel in the machining process. Kundrák et al. [43] found that electrochemical machining could remove the metal bond to make abrasive grains protrude and maintain their cutting ability.

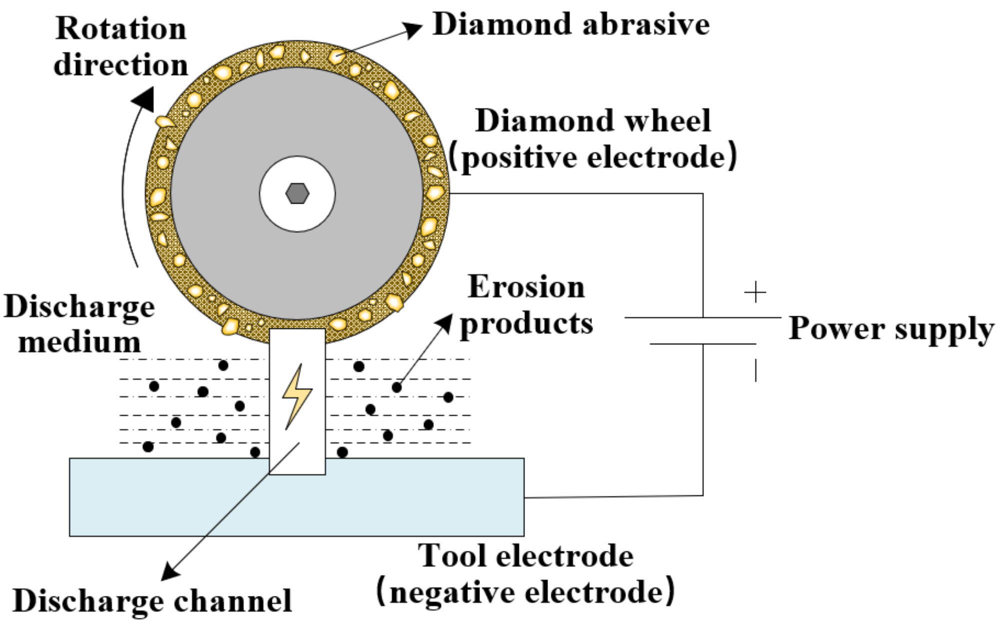

Figure 11. Schematic diagram of electric spark dressing technology.

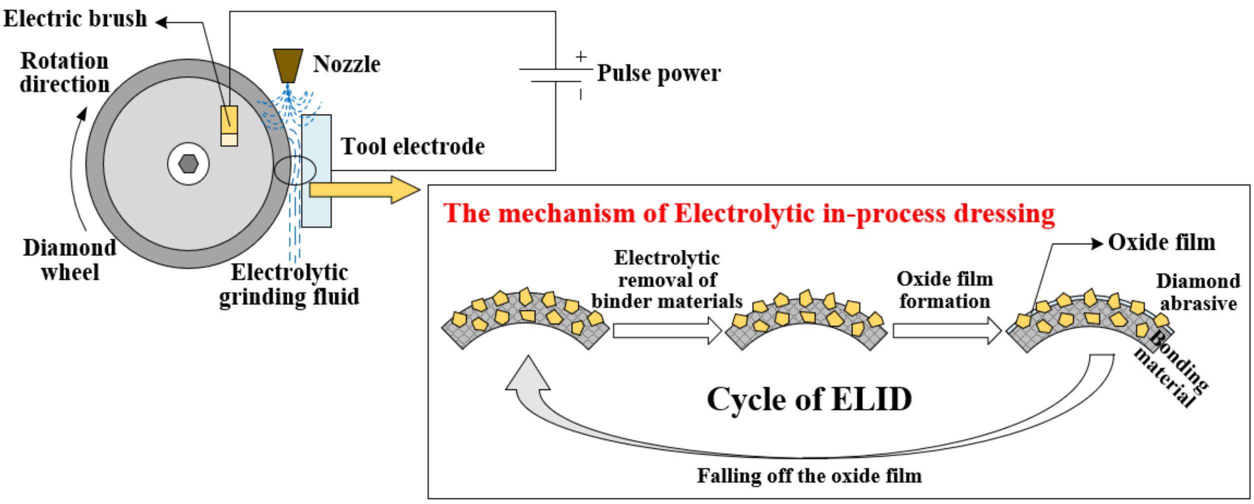

Figure 12. Schematic diagram of electrolytic in-process dressing technology.

Figure 13 shows a comparison of the grinding wheel surface before and after EDM dressing [44]. It can be seen from the figure that the grinding wheel surface after the dressing is smooth and flat, the outer contour is clear and has a sharp cutting edge. The research showed that the dressing efficiency of the EDM sharpening method was high—approximately 50∼60%. After dressing, the surface of the abrasive grinding tool had chip space, and the abrasive protruding bond height was ideal.

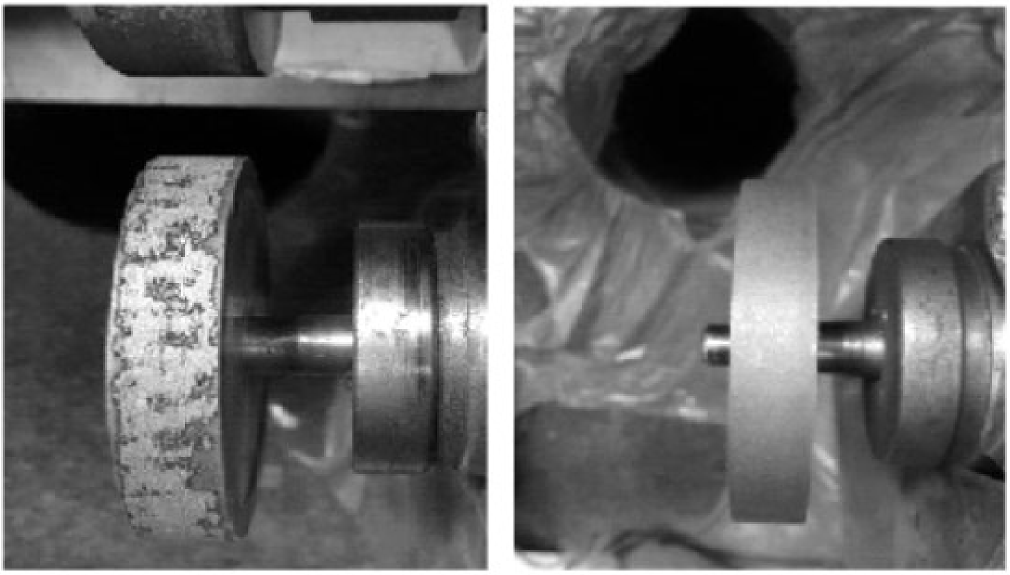

Figure 13. The surface condition of the grinding wheel after electric machining [44].

Although the EDM dressing method, the electrolytic in-process dressing method, or other compound EDM dressing methods can better achieve the precision dressing of diamond abrasive grinding tools, their disadvantages, such as high cost, insufficient environmental protection, and easy to form thermal damage, restrict the development of their technology.

3.2.4. Laser Sharpening Method

Figure 14 shows a schematic diagram of the laser sharpening diamond abrasive grinding tool. Its working principle is that the laser beam, with a certain power density, is directly irradiated on the diamond abrasive grinding tool as a “processing tool”, and the surface temperature of the grinding tool rises rapidly. Using the difference between the melting point of the bond material and the diamond abrasive grains, the bond material is heated, melted, and gasified, then separated from the diamond abrasive grinding wheel in a gaseous or plasma state to achieve the purpose of sharpening.

At the end of the 20th century, Westkämper [45] of the University of Brunswick in Germany, first proposed the application of laser technology to the dressing of superhard abrasive grinding tools. Deng et al. [46] carried out laser ablation experiments on resin-bonded diamond abrasive grinding wheels based on the nanosecond laser dressing process parameters to realize low-damage and ultra-precision dressing of the resin-bonded diamond abrasive grinding wheels and proposed a new laser dressing method based on layered scanning to solve the problem of the degradation of abrasive performance caused by ablation heat. Witt T [47] irradiated the pulsed laser on the surface of diamond abrasive grinding tools, which could obtain ideal abrasive grain protrusion height and cutting of the abrasive grain binding force. Our team [48–50] studied the theory and numerical modeling of plasma isothermal expansion produced by nanosecond laser ablation of bronze-bonded diamond abrasive grinding wheels and deduced the dynamic equation of plasma expansion, which could provide a reference for future research on plasma characteristics. A new method of dressing bronze-bonded diamond abrasive grinding wheels with water-column-flow-assisted pulsed fiber laser was proposed. The ideal dressing effect was obtained through the dressing test, as shown in Figure 15, which was of significance for optimization of the dressing process.

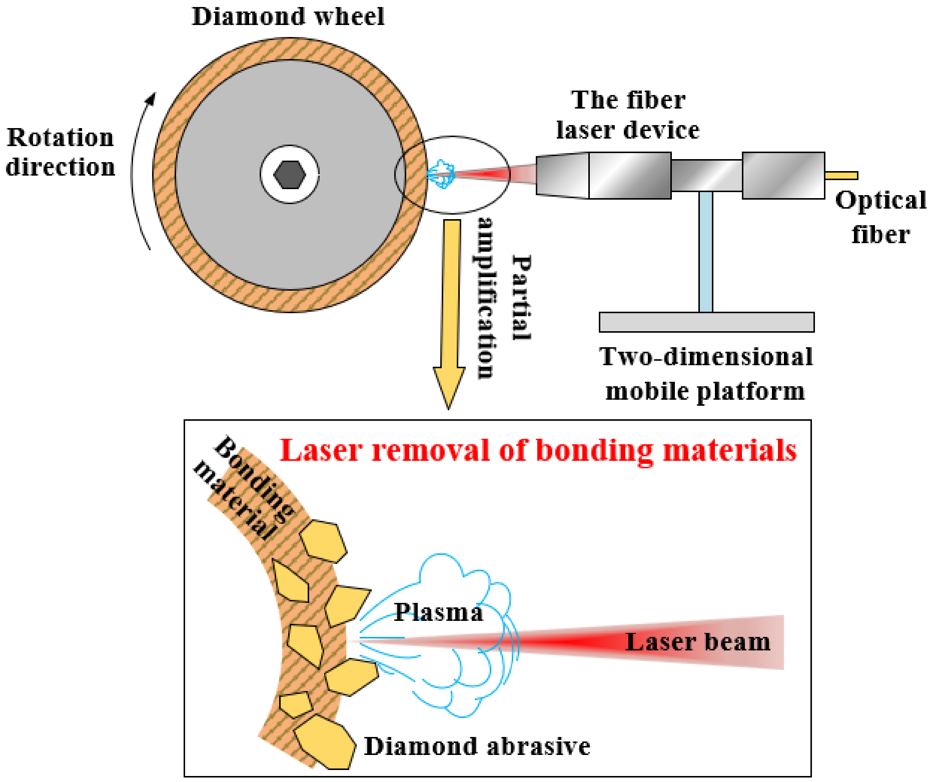

Figure 14. Schematic diagram of laser dressing diamond abrasive grinding wheel.

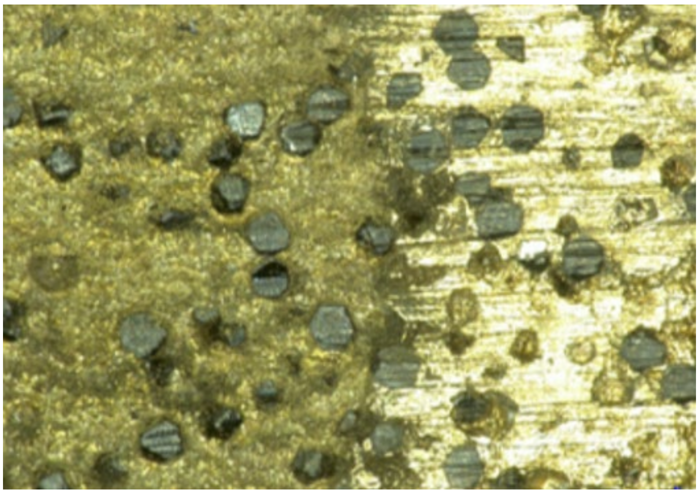

Figure 15. Topography and landform of bronze diamond abrasive grinding wheel after multi-pulse fiber laser dressing.

Through the above-mentioned domestic and foreign research, it was found that the diamond abrasive grains, after laser sharpening, protruded by one-third of the height of the bond, there was chip holding space around the abrasive grains, and the dressing efficiency was approximately 80~88%.

4. Numerical Simulation and Experimental Research on Laser Dressing Bronze Diamond Abrasive Grinding Wheels

Dressing diamond abrasive grinding tools is mainly divided into two steps: truing and sharpening. Among the truing methods, the laser truing method has the highest efficiency—approximately 70~80%. Similarly, the dressing efficiency of the laser sharpening method ranks first among all sharpening methods at approximately 80~88%. Laser processing is a comprehensive, efficient, and green dressing method. Therefore, numerical simulation analysis and related experimental research have been carried out for the method of laser dressing of diamond abrasive grinding tools.

When a pulsed fiber laser is vertically incident on the surface of a bronze-bonded diamond abrasive grinding wheel, a variety of complex physical phenomena are involved, such as serial energy superposition and the accumulation effect. Different from the continuous laser, the working mode of the pulsed laser is to produce a laser output at a certain interval. After the end of the previous pulse, except for a small part of the heat transferred to the air, most of the heat is deposited in the bronze-bonded diamond abrasive grinding wheel and provides energy for the next laser pulse to reach the surface of the grinding wheel. With the superposition of laser pulses, the laser energy accumulates in the bronze-bonded diamond abrasive grinding wheel layer by layer, which affects its ablation threshold. When considering the effect Q of the optical fiber laser pulse energy accumulation on the bronze-bonded diamond abrasive grinding wheel in the literature [3], it is only regarded as a simple superposition of θ times of pulse energy, and the calculation expression is:

$$Q = \frac{S\left(1 - S^{\theta}\right)}{1 - S} \tag{1}$$

where S is the energy accumulation coefficient of bronze material, θ is the number of laser pulses, and the numerical value is 12. Equation (1) shows that S% of each laser pulse energy is accumulated in the bronze diamond grinding wheel, and when the grinding wheel is irradiated for the last time (the θ time), the θ-1 pulse energy previously stored on the surface of the bronze-bonded diamond abrasive grinding wheel will all be converted to the last (the θ time) incident laser pulse energy. However, since the laser energy decay process follows an exponentially decreasing law [51,52], when establishing the heat transfer model, the serial energy superposition and accumulation effect Q_C is regarded as the exponential form. Compared with the simple superposition, it is more in line with the objective law and easy to calculate; its calculation expression is:

$$Q_C = \mathrm{e}^{\frac{S\theta^{\frac{1}{2}}}{\sqrt{3}}} \tag{2}$$

In summary, considering the superposition accumulation effect of the serial energy Q_C in the process of dressing the bronze-bonded diamond abrasive grinding wheels by a pulsed fiber laser, the relevant heat transfer model is established based on the Fourier heat transfer model as follows:

$$\rho_l c_l = \frac{\partial}{\partial x}\left(k_l \frac{\partial T_l}{\partial x}\right) + b\beta \mathrm{e}^{-bx} I_0(t) \mathrm{e}^{\frac{S\theta^{\frac{1}{2}}}{\sqrt{3}}} \quad (0 \le t \le \tau,\ 0 \le x \le S(t)) \tag{3}$$

where subscript l indicates that the material is in the liquid phase, k is the thermal conductivity, b is the absorption rate of bronze material, β is the absorption speed of bronze material, x is the depth of the laser dressing bronze diamond abrasive grinding wheel, and I_0(t) is the laser energy density of the Gaussian incident laser; its calculation expression is:

$$I_0(t) = I_0 \exp\left(-\frac{\left(t - \frac{\tau}{2}\right)^2}{2\sigma^2}\right) \tag{4}$$

where I_0 is the peak value of the pulsed laser energy density, τ is the laser pulse width, and σ is a parameter that can change the time shape of the laser pulse.

Set the initial condition as approximately 300 K at room temperature, and establish the boundary conditions as follows:

$$T|_{t=0} = 300\ \mathrm{K} \tag{5}$$

$$-k\frac{\partial T}{\partial t} = \beta I_0(t) \qquad (0 \le t \le \tau) \tag{6}$$

$$-k\frac{\partial T}{\partial x}\bigg|_{x=d} = 0 \qquad (0 \le t \le \tau) \tag{7}$$

The finite difference equations for Equation (3) and boundary conditions (Equations (5)–(7)) are established as follows:

$$\rho_l c_l \frac{T_i^{j+1} - T_i^j}{\Delta t} = k_l \frac{T_{i+1}^j - 2T_i^j + T_{i-1}^j}{(\Delta x)^2} + b\beta e^{-bi\Delta x} I_0 \exp\left(-\frac{\left(j\Delta t - \frac{\tau}{2}\right)^2}{2\sigma^2}\right) \exp\left(\frac{S\theta^{1/2}}{\sqrt{3}}\right) \tag{8}$$

$$-k\frac{T_1^j - T_0^j}{\Delta x} = \beta I_0 \exp\left(-\frac{(j\Delta t - \tau/2)^2}{2\sigma^2}\right)(0 \le t \le \tau) \tag{9}$$

$$T_d^j = 0;\ T_i^0 = 300\ \mathrm{K} \tag{10}$$

After finishing, we can obtain:

$$T_i^{j+1} = \frac{k\Delta t}{\rho c (\Delta x)^2} T_{i+1}^j + \left(1 - \frac{2k\Delta t}{\rho c(\Delta x)^2}\right) T_i^j + \frac{k\Delta t}{\rho c(\Delta x)^2} T_{i-1}^j + \frac{\Delta t}{\rho c} b\beta e^{-bi\Delta x} I_0 \exp\left(-\frac{\left(j\Delta t - \frac{\tau}{2}\right)^2}{2\sigma^2}\right) \exp\left(\frac{S\theta^{1/2}}{\sqrt{3}}\right) \tag{11}$$

Establish the grid Fourier number $F0_1 = \frac{k\Delta t}{\rho c(\Delta x)^2}$, and convert Equation (9) into:

$$T_i^{j+1} = F0_1 T_{i+1}^j + (1 - 2F0_1) T_i^j + F0_1 T_{i-1}^j + \frac{\Delta t}{\rho c} b\beta e^{-bi\Delta x} I_0 \exp\left(-\frac{\left(j\Delta t - \frac{\tau}{2}\right)^2}{2\sigma^2}\right) \exp\left(\frac{S\theta^{1/2}}{\sqrt{3}}\right) \tag{12}$$

The thermophysical parameters of the bronze and diamond and the calculation parameters are shown in Tables 1 and 2.

Table 1. Thermophysical parameters of the bronze and diamond.

Material	Name	Symbol	Unit	Numerical Value
Bronze	Atomic mass	m	kg	1.038×10^{-25}
	Density	ρ_s	$\mathrm{kg \cdot m^{-3}}$	8620
	Melting temperature	T_m	K	1173
	Gasification temperature	T_l	K	2770
	Thermal diffusivity	k	$\mathrm{cm^2 \cdot s^{-1}}$	0.14
	Thermal conductivity	k_s	$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	41.9
	Specific heat capacity	c_s	$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$	352
	Absorption rate	β	—	0.38
Diamond	Density	ρ_s	$\mathrm{kg \cdot m^{-3}}$	3.52
	Melting temperature	T_m	K	3550
	Gasification temperature	T_l	K	4830
	Refractive index	n	—	2.42
	Thermal diffusivity	k	$\mathrm{cm^2 \cdot s^{-1}}$	3.11
	Thermal conductivity	k_s	$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$	2000
	Specific heat capacity	c_s	$\mathrm{kg^{-1} \cdot K^{-1}}$	1827
	Absorption rate	β	—	0.25

Table 2. Calculation parameters.

Name	Symbol	Unit	Numerical Value
Laser wavelength	λ	nm	1064
Electron mass	m_e	kg	9.1×10^{-31}
Average ionization energy	U	eV	7.63

Table 2. *Cont.*

Name	Symbol	Unit	Numerical Value
Pulse repetition rate	f	kHz	50
Energy accumulation coefficient	s	—	0.85
Spot diameter	D	μm	38
Pulse width	τ	ns	210
Absorption coefficient	b	m^{-1}	4.76×10^6
Boltzmann constant	k_b	$J{\cdot}K^{-1}$	1.38×10^{-23}
Grinding machine speed	r_v	$r{\cdot}min^{-1}$	300

Set the laser power density to be 1.68×10^8 W/cm^2, 2.52×10^8 W/cm^2 and 3.36×10^8 W/cm^2. Calculation parameters combining the thermophysical parameters (Table 1) and the calculated parameters (Table 2) for bronze and diamond are shown in Table 3.

Table 3. Combined calculation parameters.

Name	Unit	Numerical Value	
		Bronze	Diamond
Laser ablation time	min	6	6
Number of cycles	times	3	3
Pulse width	ns	210	210
Distance in the X-direction	μm	16	4.8
Time step	ns	0.21	0.021
Spatial step	μm	1	0.12
$k\Delta t/(\rho c(\Delta x)^2)$	—	0.0029	0.4541

Since $k\Delta t/(\rho c(\Delta x)^2)$ is less than 0.5 for both the bronze and diamond cases, the numerical solution is stable and convergent. The temperature evolution law of the bronze bond and diamond abrasive grains dressed by pulsed fiber laser was obtained by computer programming through MATLAB, as shown in Figure 16.

The temperature change of pulsed fiber laser dressing bronze material is shown in Figure 16a. When the laser power density reached 1.68×10^8 W/cm^2, the maximum temperature of the bronze material was approximately 4400 K, which was higher than the gasification temperature of bronze (2770 K). The solid-phase bronze material can be directly gasified in one laser pulse to remove the excess bronze bond and realize the purpose of sharpening the bronze-bonded diamond abrasive grinding wheel.

Figure 16b–d shows the temperature change of pulsed fiber laser dressing diamond. When the laser power density was 1.68×10^8 W/cm^2, as shown in Figure 16b, the maximum temperature of the diamond surface after the dressing was approximately 3800 K, which was slightly higher than the melting point temperature of diamond (3550 K). Due to the short dressing time of the pulsed laser, the laser energy had little effect on the diamond abrasive grains and they maintained their original shape. When the laser power density increased to 2.52×10^8 W/cm^2, as shown in Figure 16c, the maximum temperature of the diamond surface reached 5900 K, which was higher than the gasification temperature of the diamond (4830 K). At this point, the laser energy can gasify the diamond in a short time, therefore the diamond abrasive grains were obviously deformed, and the truing effect of the diamond abrasive grinding tools was achieved. With gradual increase in the laser power density to 3.36×10^8 W/cm^2, as shown in Figure 16d, the maximum temperature of the diamond surface was as high as 7850 K. Excessive laser energy can lead to a large amount of diamond removal. However, due to the short time of pulsed fiber laser dressing of the bronze-bonded diamond abrasive grinding wheel, only part of the diamond will be removed, leaving large or small pits on its surface.

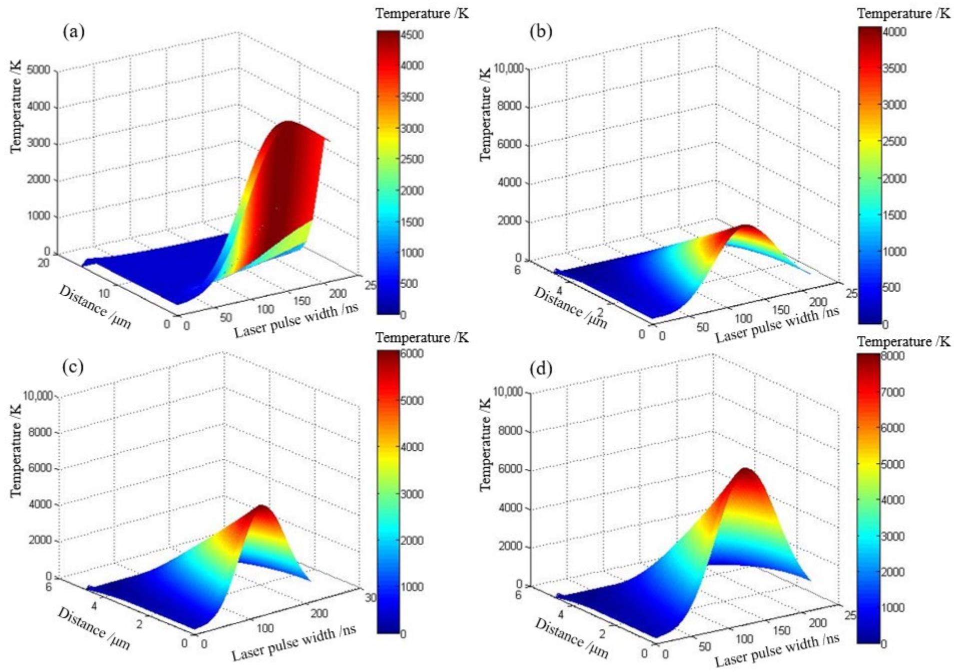

Figure 16. Temperature changes in the pulsed fiber laser dressing bronze material and diamond. (**a**) Bronze material, laser power density: 1.68 × 10^8 W/cm^2; (**b**) Diamond, laser power density: 1.68 × 10^8 W/cm^2; (**c**) Diamond, laser power density: 2.52 × 10^8 W/cm^2; (**d**) Diamond, laser power density: 3.36 × 10^8 W/cm^2.

Figure 17 shows the experimental equipment for laser dressing the bronze-bonded diamond abrasive grinding wheels. In the experiment, the wavelength of the fiber laser was 1064 nm, the pulse frequency was 50 kHz, the pulse width was 210 ns, and three laser power densities of 1.68 × 10^8 W/cm^2, 2.52 × 10^8 W/cm^2, and 3.36 × 10^8 W/cm^2 were selected for the dressing experiment. As can be seen from Figure 17, the single-mode optical fiber was focused by a lenticular lens with a focal length of 180 mm inside the pulsed laser ablation head, and then the surface on the bronze-bonded diamond abrasive grinding wheel was vertically irradiated; the defocus amount was 0. During the laser dressing process, the bronze-bonded diamond abrasive grinding wheel (model is 100D × 10T × 5X × 31.75H × 80#) was fixed on the surface grinding machine and was driven by the main shaft to rotate counterclockwise at a speed of 300 r/min.

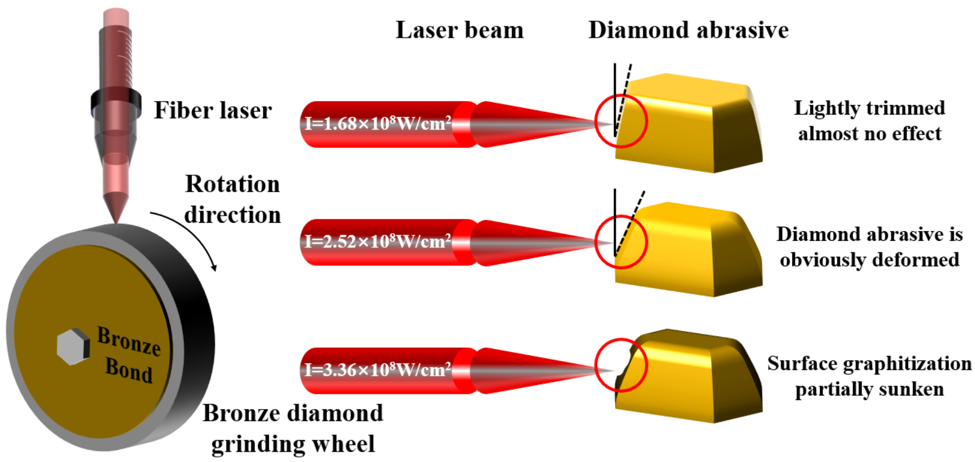

Figure 17. Laser dressing the bronze-bonded diamond abrasive grinding wheel experimental equipment.

The surface topography of the bronze-bonded diamond abrasive grinding wheel ablated by pulsed fiber laser was photographed with a three-dimensional ultra-depth-of-field microscope under magnification (200 times). Through observation, it was found that the topography of the bronze-bonded diamond abrasive grinding wheel dressed by different laser power density was different.

Figure 18a shows the surface topography of the bronze-bonded diamond abrasive grinding wheel when the laser power density was 1.68×10^8 W/cm^2. At this time, the ablation threshold of the bronze bond material had been reached and the removal of the bronze material had been realized. There was almost no change in the diamond abrasive grains and the dressing effect was slight. Figure 18b shows the surface topography of the bronze-bonded diamond abrasive grinding wheel when the laser power density was 2.52×10^8 W/cm^2. The morphology of the diamond abrasive grains changed significantly, showing a sharp grinding edge. The removal rate of the bronze material was high, the height of the diamond abrasive grains protruding from the bronze bond was ideal, and a certain chip-holding space was reserved. When the laser power was increased to 3.36×10^8 W/cm^2, as shown in Figure 18c, graphitization occurred on the surface of the diamond abrasive grains after dressing, and part of the surface had deep or shallow depressions and cracks.

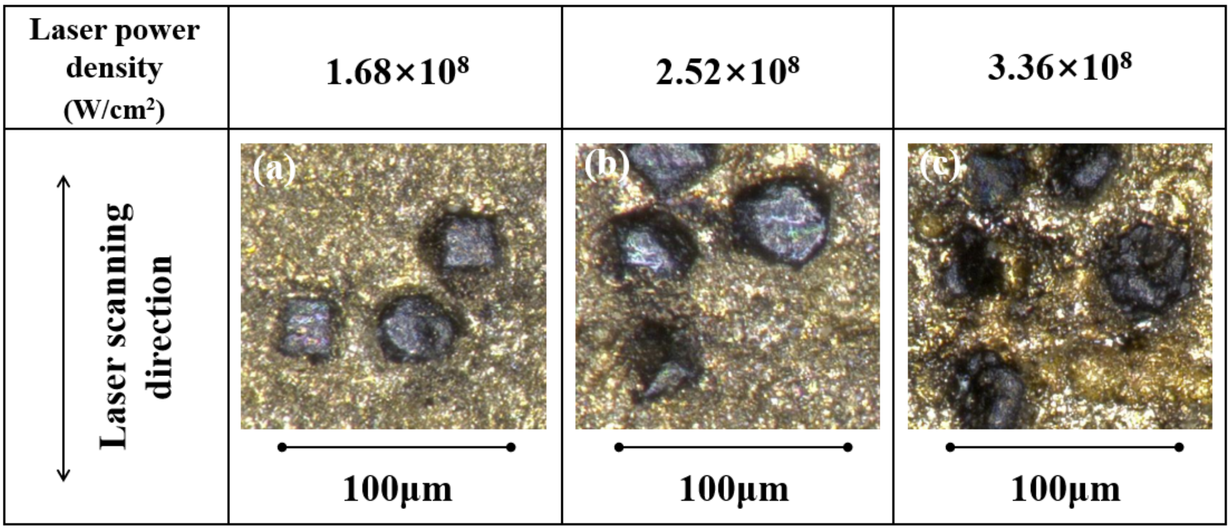

Figure 18. Topography of the bronze-bonded diamond abrasive grinding wheel after pulsed fiber laser dressing. (**a**) Laser power density: 1.68×10^8 W/cm^2; (**b**) Laser power density: 2.52×10^8 W/cm^2; (**c**) Laser power density: 3.36×10^8 W/cm^2.

In the process of increasing the power density of the pulsed fiber laser from 1.68×10^8 W/cm^2 to 3.36×10^8 W/cm^2, the removal rate of the bronze material gradually increased. When the laser power density was 1.68×10^8 W/cm^2, the bronze material could be removed; thus there was a suitable chip holding space between the diamond abrasive grains, and the ideal abrasive grain height could be obtained, and the sharpening of the bronze-bonded diamond abrasive grinding wheel could be realized. When the power density of the pulsed fiber laser was 2.52×10^8 W/cm^2, the diamond abrasive tip was finely broken with appropriate shape accuracy, which could achieve the micro-shaping of the diamond abrasive grains and achieve the purpose of combining the truing and sharpening of the diamond abrasive grinding tools. However, when the power density of the pulsed fiber laser continued to increase to 3.36×10^8 W/cm^2, the diamond abrasive grains were greatly deformed, the surface was graphitized, and some depressions appeared, which needs to be avoided as much as possible to obtain an ideal dressing effect. Therefore, for laser truing and sharpening diamond abrasive grinding tools, ideal laser process parameters should be selected. Among them, a pulsed fiber laser with a power density of 2.52 × 10^8 W/cm^2∼3.36 × 10^8 W/cm^2 is the most suitable for dressing the diamond abrasive grinding tools. It can not only properly remove the bronze bond materials, but also enable truing of the diamond abrasive grains in a small amount, and achieve truing and sharpening of the diamond abrasive grinding tools at the same time.

5. Conclusions

(1) From the perspective of the truing and sharpening of diamond abrasive grinding tools, traditional processing methods, such as the diamond pen dressing method, grinding method, and rolling method, and new dressing methods, such as the EDM dressing method and laser dressing method, were described in detail. In comparison, it was pointed out that the laser dressing of diamond abrasive grinding tools was a green processing method with high efficiency and no environmental pollution.

(2) Considering the superposition accumulation effect of the serial energy Q_C and coupling of the Fourier heat transfer model, the energy accumulation heat transfer model for laser dressing was established, and numerical simulation of pulsed fiber laser dressing of the bronze-bonded diamond abrasive grinding wheel was carried out. The temperature evolution law of the bronze bond and diamond abrasive grains dressed by pulsed fiber laser was obtained by using the numerical analysis of the model. The numerical analysis showed that, when the laser power density was greater than 1.68 × 10^8 W/cm^2, the bronze-bonded diamond abrasive grinding wheel could be sharpened. When the laser power density was greater than 2.52 × 10^8 W/cm^2, the truing effect of the diamond abrasive grinding tools was achieved.

(3) An experiment on the laser dressing of a bronze-bonded diamond abrasive grinding wheel was carried out. The surface topography of the bronze-bonded diamond abrasive grinding wheel was photographed by a three-dimensional ultra-depth-of-field microscope. The results showed that, when the laser power density was 2.52 × 10^8 W/cm^2∼3.36 × 10^8 W/cm^2, it could not only properly remove the bronze bond, but also better sharpen the diamond abrasive grains. It was confirmed that the laser dressing method could achieve the combination of truing and sharpening of the diamond abrasive grinding tools. The experiment not only demonstrated the correctness and feasibility of the theoretical model but also provided process optimization for research into the pulsed laser dressing of diamond abrasive grinding tools.

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