Research Article

Zhibo Yang, Wang Sun, Dongyu He, Daocheng Han, Wei Wang*, Qiang Guo, and Yanru Zhang

Effect of laser-assisted ultrasonic vibration dressing parameters of a cubic boron nitride grinding wheel on grinding force, surface quality, and particle morphology

<https://doi.org/10.1515/rams-2021-0054>

received April 26, 2021; accepted July 16, 2021

Abstract: In this article, the laser-assisted ultrasonic vibration dressing technique was applied to the cubic boron nitride (CBN) grinding wheel to study the effect of various process parameters (namely, laser power, dressing depth, feed rate, and grinding wheel speed) on the grinding force, surface quality, and morphological evolution of CBN abrasive particles. The results showed that abrasive particles' morphology mainly undergoes micro-crushing, local crushing, large-area crushing, macro-crushing, and other morphological changes. The dressing force can be effectively reduced by controlling the dressing process parameters. Besides, grinding tests are performed on the grinding wheel after dressing to reveal specimens' surface quality. Excellent grinding characteristics and grinding quality of the grinding wheel were obtained by the proposed technique with the optimized process parameters.

Keywords: CBN grinding wheel, laser-assisted ultrasonic vibration dressing, abrasive shape, morphology, dressing force

1 Introduction

Due to high bonding strength and abrasive hardness, metal-bonded cubic boron nitride (CBN) grinding wheels were widely used in precision and ultra-precision grinding,

and high-speed and high-efficiency grinding of difficult-to-machine materials, such as titanium alloys, ceramics, and optical glass [1,2]. However, some CBN wheels' deficiencies, including long dressing time, great dressing difficulty, rapid wear, and low dressing efficiency, need to be mitigated and addressed by numerous researchers [3,4]. Thus, Huang et al. [5] quantitatively analyzed the effect of dressing feed rate, dressing speed difference, and other dressing parameters on the CBN grinding wheel's surface quality. von Witzendorff et al. [6] and Stompe et al. [7] carried out experiments on the laser-assisted dressing of composite (metal–ceramic bond) CBN grinding wheels. They revealed that abrasive particles on the grinding wheel surface had sharp micro-cutting edges after dressing. The chip space and the abrasive particles' protrusion height on the grinding wheel surface increased with the laser pulse width. Cao [8] conducted electric-spark dressing tests on a 120# bronze-bonded CBN grinding wheel and experimentally assessed electrical parameters' effect on its grinding performance. Gao et al. [9] and Zhao [10] independently used the elliptical ultrasonic-assisted mechanical dressing technology to perform dressing tests on metal-bonded CBN grinding wheels. The proposed dressing method accelerated removing the surface material of the grinding wheel, improving its surface morphology and dressing quality. The laser dressing method was first proposed by Babu and Radhakrishnan [11]. Grinding wheels with different binders and different types of abrasive particles were used in the YAG pulse laser for dressing experiments, and good grinding wheel dressing effects were achieved. Rabiey et al. [12] of ETH Zurich carried out the sharpening experiment of the CBN grinding wheel and obtained the qualitative relationship between the laser process parameters and the grinding force, grinding performance of the wheel, and the quality of the processed surface.

The analysis of available super-abrasive grinding wheel dressing methods revealed some limitations in their dressing performance due to excessive wear of the dressing tool, low dressing efficiency, or environmental pollution.

* **Corresponding author: Wei Wang**, School of Emergency Management, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China, e-mail: wangweihpu@126.com

Zhibo Yang, Wang Sun, Dongyu He, Daocheng Han, Qiang Guo: School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China,
Yanru Zhang: Institute of Orthopedics, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China

During grinding wheel dressing, the CBN grinding wheel was clamped on the spindle of the machine tool through a special clamp, rotating at a certain speed to adjust the laser head, ensuring that the focused laser beam irradiates to the surface of the grinding wheel with a fixed spot diameter, appropriate incident angle, and distance to ensure the controllable laser power density. In front of the dressing area of the grinding wheel, the laser beam heats the rotating grinding wheel at a certain axial and circumferential distance. Under the heating effect of the laser beam, the surface bond temperature of the grinding wheel increased, and the material in the dressing area of the grinding wheel was softened by heat. In a short time before the dressing area of the grinding wheel moves to the dressing area, the cutting performance of the material changed. The removal mode of the binder material changed from brittle fracture to plastic flow.

The aim of this article is to mitigate the aforementioned problems by taking good advantage of ultrasonic vibration dressing of super-abrasive grinding wheels, combined with the fiber laser-assisted dressing technology. It substantiates a new process technology by combining mechanical dressing and special machining theories: two-dimensional ultrasonic vibration mechanical compound dressing CBN grinding wheel technology based on the laser thermal effect.

The shape variation of abrasive particles was tracked during the dressing process, and the formation patterns of the grinding wheel's topography under the laser-assisted ultrasonic vibration dressing (LUD) method were examined. The effect of various dressing process parameters on the dressing force was also studied. Finally, grinding tests of grinding wheels after dressing were conducted to reveal their surface quality formation behavior (Figure 1).

2 Experimental study on LUD of a CBN grinding wheel

In the process of laser-assisted heating and ultrasonic-assisted vibration composite dressing of CBN grinding wheels, the CBN abrasive particles on the grinding wheel's surface were often irregularly and randomly distributed. Considering the characteristic morphology of the abrasive particles and the grinding wheel surface morphology formed by the spatial distribution of the abrasive particles, the morphology of abrasive particles under different dressing parameters were compared, and the shape characteristics of abrasive particles under different dressing parameters were investigated via the method of single abrasive particle tracking.

2.1 Determination of test plan and test parameters

The LUD experimental device is depicted in Figure 2. During the CBN grinding wheel's dressing process, it was necessary to ensure a high concentricity of the grinding wheel to minimize its circumferential runout and to improve the test's accuracy. Therefore, a machine tool with high spindle rotation accuracy was required. Considering these requirements, an ultra-precision machine tool SPHERE360 produced by Beijing Gongken Seiki Co., Ltd., with a minimum resolution of 5 nm, was used as the experimental setup's basic tool in Figure 2. The precise path and position control of the dressing tool during the dressing process guaranteed high test accuracy. To ensure the laser-assisted ultrasonic vibration, a 1.06 μm YAG laser heating system produced by Wuhan Cres Optoelectronics Technology Co., Ltd, combined with a two-dimensional ultrasonic vibration device was applied.

Figure 1: Process of CBN wheel dressed by laser-ultrasonic vibration.

Figure 2: Device of laser-ultrasonic composite dressing of CBN grinding wheel.

Figure 3: Structure diagram of the wedge grinding wheel.

Besides the aforementioned ultra-precision machine tool was the main component of the experimental setup, the auxiliary equipment comprised an ultrasonic generator, dynamometer, and tool setting instrument. The dynamometer and the two-dimensional ultrasonic vibration device were connected by bolts and fixed on the machine tool's working platform. The transmitter part of the laser heating system was fixed on the worktable by a bracket with a magnetic base to ensure the laser's relative position. The dressing tool position was stable during the dressing process.

To facilitate the observation of the grinding wheel's abrasive particles' shape after dressing, the test used a detachable wedge metal-bonded CBN grinding wheel of 1A1 100 × 32 × 10 × 5 40/50 specification, as shown in Figure 3. The adopted dressing conditions are listed in Table 1.

Before dressing, some abrasive particles were selected to perform calibration of the grinding wheel. In the composite dressing process, three dressing tests were carried

out for each process parameter, while each dressing contained five strokes. The test plan is presented in Table 2. The calibrated abrasive particles were observed after each dressing. The particular laser heating, ultrasonic vibration, and dressing parameters had a strong impact on the grinding wheel's dressing performance. Besides, this effect was coupled that involved the interaction of various parameters.

2.2 Analysis of experimental results

2.2.1 Analysis of dressing force

Figure 4 shows the variation trend of the principal cutting force in the process of laser heating-assisted ultrasonic vibration dressing of CBN grinding wheels with different dressing process parameters, such as laser power P , dressing depth a_d , feed rate f_d , and grinding wheel speed V_s .

Table 1: Dressing conditions

Categories	Item	Specifications or parameters
Grinding wheel type	CBN wheel	1A1 150 × 10 × 32 × 5 100/120 M 100
Dressing tool	Diamond dresser	Taper, apex angle of 60°
Dressing parameters	Speed of mainshaft	25–85 rpm
	Feed	0.030–0.080 mm·rev ⁻¹
	Depth	5–20 μm·pass ⁻¹
Ultrasonic generator	Frequency	25 kHz
Laser parameters	Power	20–100 W
	Laser power	100–400 W
	Pulse frequency	50–110 kHz
	Spot diameter	0.6–2 mm

Figure 4(a) shows that as the laser power increases, the principal cutting force showed a downward trend. This was due to the increase of laser power, which raised the temperature per unit area of the material's surface to soften the binding agent. This dropped the dressing tool's resistance in contact with abrasive particles, reducing the principal cutting dressing force. However, if the laser power was too high, the abrasive particles can fall off due to insufficient adhesive force of the binding agent during abrasive dressing and get oxidized. Both processes may seriously deteriorate the grinding wheel performance.

According to Figure 4(b), the principal cutting force increased with the dressing depth during the test. The main reason was that the dressing depth growth increased

the radial contact depth between the tool and abrasive particles. As a result, both the volume of removed abrasive particles and the number of abrasive particles will grow. The impact force acting on abrasive particles in the sharpening process increased, increasing the principal cutting dressing force.

Figure 4(c) shows that the principal cutting force grows with the feed rate. This was mainly because when the feed rate increased, the duration of contact between the tool and abrasive particles and that of the ultrasonic action were reduced. As a result, the squeezing and friction force acting on the dressing tool per unit time increase, accelerating its wear and increasing the dressing force.

Figure 4(d) shows that the grinding wheel speed increase will increase the principal cutting force. This was because the increase in the grinding wheel's speed will reduce the dressing area's heating time so that the binding agent's softening degree and depth would be insufficient. Meanwhile, the dressing tool's friction and squeezing effect were significant, leading to an increase in the principal cutting force of dressing. Although decreasing the grinding wheel's speed can effectively reduce the dressing force, it will increase the grinding wheel's surface temperature and deteriorate the dressing effect.

2.2.2 Morphology evolution analysis of single CBN abrasive grain dressing

The reason for different degrees of crushing was that the dressing tooltip contacted the CBN abrasive particles under the action of ultrasonic vibration. Because of the

Table 2: Test plan

No.	Ultrasonic frequency (kHz)	Dressing depth (μm)	Dressing feed rate (mm·rev ⁻¹)	Grinding wheel speed (rpm)	Laser power (W)	Principal cutting force (N)
1	35	5	0.04	40	350	12
2	35	10	0.04	40	350	14
3	35	15	0.04	40	350	28
4	35	20	0.04	40	350	38
5	35	10	0.02	40	350	10
6	35	10	0.04	40	350	14
7	35	10	0.06	40	350	19
8	35	10	0.08	40	350	23
9	35	10	0.04	20	350	12
10	35	10	0.04	40	350	14
11	35	10	0.04	60	350	24
12	35	10	0.04	80	350	26
13	35	10	0.04	40	150	30
14	35	10	0.04	40	250	22
15	35	10	0.04	40	350	14
16	35	10	0.04	40	450	8

Figure 4: The effect of four dressing process parameters on dressing force F : (a) laser power, (b) dressing depth, (c) feed rate, and (d) grinding wheel speed.

rotation of the grinding wheel and the feed of the tool, the abrasive particles were crushed by the high-frequency impact and extrusion of the tooltip on the moving track [13]. The abrasive particle sharpening effects under single-factor test parameters were compared through abrasive particle tracking. The dressing force analysis through single-factor test and comparison of dressing effects under various test parameters revealed that the best dressing effect was achieved at a dressing depth of $10 \mu\text{m}$, a feed rate of $0.04 \text{ mm} \cdot \text{rev}^{-1}$, the grinding wheel speed of 40 rpm , and the laser power was 350 W , which provided a continuous crushing of abrasive grains. Under these dressing parameters, eight abrasive particles with similar morphology were selected for the analysis. The abrasive particles were subdivided into four groups for the analysis according to the micro-fragmentation process morphology. From the beginning to the end of the tracking, four groups of abrasive particles had relatively consistent initial morphology. The volume removal of each abrasive particle and its crushing process were quite similar. Therefore, two abrasive particles per group were analyzed to confirm their behavior pattern, as shown in Figures 5–8.

As shown in Figure 5, during the single abrasive particle tracking process, Nos. 1 and 2 grinding particles had a sharp pyramid shape. In the first stage of dressing, the abrasive particles were broken mainly by tip micro-crushing. This occurred because the tool feed rate was low, and thus, only the tip of the abrasive particle collided with the dressing tool in a small area. Under the continuous ultrasonic impact, stress concentration was observed in the tiny part of the abrasive particle's tip, which causes brittle fracture in a small area of the abrasive particle, forming a small-scale fracture. Therefore, the overall shape of the abrasive particle changed a little. The abrasive particles' tip morphology was similar to the abrasive wear in the grinding process.

As shown in Figure 6, Nos. 3 and 4 abrasive grains had an oblique prism shape. The first stage of abrasive particle crushing mainly occurred via local micro-crushing. The tool first came into contact in the dressing process with the cutting edge of the abrasive particle's front edge. As the contact depth increased, the ultrasonic impact stress concentrated in the long chisel edge also increased. As a result, cracks formed at the edges of abrasive particles gradually expanded at a certain angle to the tool's contact direction.

Figure 5: The morphology of the first group of abrasive particles. No. 1 grinding particle and No. 2 grinding particle.

Figure 6: The morphology of the second group of abrasive particles. No. 3 grinding particle and No. 4 grinding particle.

Figure 7: The morphology of the third group of abrasive particles. No. 5 grinding particle and No. 6 grinding particle.

Figure 8: The morphology of the fourth group of abrasive particles. No. 7 grinding particle and No. 8 grinding particle.

At this time, plastic deformation occurred in the abrasive particles' more prominent edges, resulting in their local fragmentation.

As shown in Figure 7, abrasive particle Nos. 5 and 6 were oblique prisms with four main edges. For these particles, the crushing behavior in the first stage was mainly the tip breaking. When the dressing tool collided with the abrasive particles, the force at the abrasive particle tip in the shear direction suddenly increased, causing slight plastic deformation inside the abrasive particle. When the stress exceeded the abrasive particles' hardness limit under the action of continuous ultrasonic impact, the abrasive particles broke along shear force's direction, exhibiting the tip breakage. This was different from the first-stage crushing mechanism of Nos. 1 and 2 abrasive particles.

The analysis of Figure 8 revealed that Nos. 7 and 8 abrasive particles had prismatic shapes with multiple edges. In the dressing process, the first stage of abrasive particle crushing was micro-crushing at the tip due to the dressing tool's contact with the longitudinal edge of the abrasive particle. As the tool moved continuously, the contact area's length first increased and then dropped until the tool–particle separation. In the initial contact between the dressing tool and the abrasive particle, the latter underwent a small-scale elastic deformation. As the contact area and the cutting depth increased, the stress in the particle increased sharply. When the brittle fracture stress threshold of the material was reached, the abrasive particle's top rapidly broke, providing a symmetric breakage along the grinding wheel motion direction.

During the dressing test, through the continuous dressing of multiple CBN abrasive particles and the periodic tracking of their morphology variations, it was found that the abrasive particle crushing underwent different variation paths in the actual dressing process. Thus, it could start from purely crystal particle morphology and experience tip micro-crushing, micro-crushing, large-area crushing, and macro-crushing. Alternatively, it could start from purely crystal particle morphology to partial and large-scale crushing. It could also experience micro-crushing, breakage, and so on. This variety of possible patterns could be attributed to the qualitative difference among the CBN abrasive particle morphology, the difference in the tool's cutting position relative to the cutting edge of the abrasive particle during the dressing process, and the difference in the embedding depth of the abrasive particle in the binding agent. During the dressing process, the abrasive particles at the grinding wheel's largest diameter bore the largest dressing impact load. These abrasive particles were most likely to be locally broken.

Meanwhile, at the smallest diameter of the grinding wheel, the abrasive particle's crushing morphology near the abrasive particle's tip was mostly normal micro-crushing or partial crushing.

3 Experimental study on grinding titanium alloy with composite dressing CBN wheel

By surface grinding of titanium alloy, the surface morphology quality of specimen ground by grinding wheel dressed using the laser-assisted ultrasonic vibration dressing technique at a cutting depth of $10\text{ }\mu\text{m}$, a feed rate of $0.04\text{ mm}\cdot\text{rev}^{-1}$, wheel speed of 40 rpm, laser power of 350 W, and ultrasonic frequency of 35 kHz was investigated to test the dressing effect of this method.

3.1 Experimental conditions and scheme

Figure 9 shows the schematic diagram of the grinding device. The specimen was a titanium alloy block. The grinding wheel model selected for the grinding test was 1A1 100 $\times$ 10 $\times$ 32 $\times$ 5 40/50, while other grinding parameters are listed in Table 3.

The titanium alloy specimens were pre-ground before the test to improve their smoothness and flatness, thus reducing the discrepancy between similar grinding test results. Three grindings with the same parameter were

Figure 9: Schematic diagram of the grinding device.

Table 3: Experiment conditions and schemes

Category	Item	Specifications or parameters
Grinder	Model	M6025C universal tool grinder
Grinding wheel	Model	1A1 100 × 10 × 32 × 5 45/50
Grinding parameters	Grinding cut depth	5–20 μm
	Grinding wheel speed	2,650–7,600 rpm
	Workbench speed	12 $\text{m}\cdot\text{min}^{-1}$
	Grinding fluid	Yes

performed to ensure the test accuracy. To effectively characterize the changes in abrasive particles of the grinding wheel after dressing, the scratches on the specimen surface after grinding were detected, and the respective comparative analysis was performed. The experimental process was designed as a single-factor comparative test. During the test, the grinding fluid was continuously injected into the grinding processing area to achieve a cooling effect and to exclude burns' appearance on the specimen surface.

3.2 Analysis of grinding experiment results

Figures 10 and 11 depict the cases where the grinding wheel processed the titanium alloy specimens before

and after its dressing, respectively. The surface profiles of the ground specimens were observed with an ultra-depth-of-field microscope. By using the 3D field synthesis of the microscope, it was observed that the depth of the surface grooves of the specimen in the vertical direction was relatively uniform, indicating that abrasive particles involved in the material removal during the grinding process were highly uniform. The height of the abrasive particles of the grinding wheel showed good consistency after dressing. The distance between the trenches in the horizontal direction was small, indicating that the grinding wheel after the dressing had self-sharpening properties during the grinding process. As the grinding progressed, the number of effective abrasive particles increased. The overlap coefficient of abrasive particles increased, leading to a more uniform distribution range of abrasive particles' cutting thickness. As a result, the

Figure 10: Grinding morphology of sample before grinding wheel dressing.

Figure 11: Grinding morphology of sample after grinding wheel dressing.

distance between the ravines in the horizontal direction rendered uniform variation, reducing the grinding surface roughness in the horizontal direction. The grinding test results showed that the dressing wheel had good grinding performance.

4 Conclusion

The results obtained made it possible to draw the following conclusions.

- (1) The analysis of tracking results on particle morphology variation during the continuous dressing cycle of many CBN abrasive grains revealed that each abrasive grain's actual dressing process could have different variation patterns. This could be attributed to the difference in CBN abrasive particle morphology, the dressing tool's cutting direction relative to the cutting position of the particle edge, and the different embedding depth of the abrasive particles in the binding agent. During the dressing process, the abrasive particles at the grinding wheel's largest diameter were subjected to the largest dressing impact load, which made them prone to partial crushing. The abrasive particles' crushed shape near the abrasive particles' tip at the smallest diameter of the grinding

wheel was mostly normal micro-crushing or partial crushing.

- (2) The dressing force was effectively reduced by increasing the laser power or reducing the dressing depth, feed rate, or wheel speed. As a result, the dressing tool's wear was reduced, and abrasive particles' crushing quality was improved.
- (3) The comparative analysis of the titanium alloy block grinding by a dressed grinding wheel revealed that under the composite dressing method, the grinding wheel abrasive particles' overall protrusion height was relatively consistent, which effectively reduced the processed specimen's surface roughness and improved the grinding effect.

Acknowledgements: This work was supported by the financial supports from the National Natural Science Funds of China (U1904170), and Henan Postdoctoral Science Foundation (001701015).

Funding information: This work was supported by the financial supports from the National Natural Science Funds of China (U1904170), and Henan Postdoctoral Science Foundation (001701015).

Author contributions: Zhibo Yang: funding acquisition, investigation, formal analysis, data Cu-ratio, writing – original

draft; Wang Sun: methodology, resources, supervision, validation, writing – original draft; Dongyu He: conceptualization, investigation, supervision, resources, project administration, writing – review & editing; Daocheng Han: validation, investigation, methodology; Wei Wang: supervision, resources, validation, writing – review & editing; Qiang Guo: conceptualization, methodology, discussion; Yanru Zhang: writing-review & editing, discussion. All authors have discussed and agreed to the published version of the manuscript.

Conflict of interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement: The data used to support the findings of this study are available from the corresponding author upon request.

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