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A theoretical and experimental study on the pulsed laser dressing of bronze-bonded diamond grinding wheels

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ABSTRACT

A series of theoretical analyses and experimental investigations were performed to examine a pulsed fiber-laser tangential profiling and radial sharpening technique for bronze-bonded diamond grinding wheels. The mechanisms for the pulsed laser tangential profiling and radial sharpening of grinding wheels were theoretically analyzed, and the four key processing parameters that determine the quality, accuracy, and efficiency of pulsed laser dressing, namely, the laser power density, laser spot overlap ratio, laser scanning track line overlap ratio, and number of laser scanning cycles, were proposed. Further, by utilizing cylindrical bronze wheels (without diamond grains) and bronze-bonded diamond grinding wheels as the experimental subjects, the effects of these four processing parameters on the removal efficiency and the surface smoothness of the bond material after pulsed laser ablation, as well as the effects on the contour accuracy of the grinding wheels, the protrusion height of the diamond grains, the sharpness of the grain cutting edges, and the graphitization degree of the diamond grains after pulsed laser dressing, were explored. The optimal values of the four key processing parameters were identified.

1. Introduction

Grinding wheels fabricated through a sintering method using metallic materials as the bond and superhard materials as the abrasive are called metal-bonded superabrasive grinding wheels. Presently, the most commonly used superabrasives are diamond and cubic boron nitride (CBN). Compared with conventional abrasives, e.g., aluminum oxide and silicon carbides, superabrasives have significant merits, including high hardness, high strength, good performance at high temperature, and good grain shape [1]. Currently, the most widely used metal-bonded superabrasive grinding wheels are bronze-bonded diamond grinding wheels. Compared with resin-bonded or vitrified superabrasive grinding wheels, a bronze-bonded diamond wheel has numerous advantages, such as higher hardness and strength, superior dimensional accuracy and shape retention, more favorable wear resistance, and the ability to withstand higher loading [2]. However, a bronze-bonded diamond wheel also has disadvantages, including poor self-sharpening character and proneness to clogging. Therefore, periodic dressing is necessary for this type of wheel to restore the grinding performance. However, because the bronze bond can strongly retain the diamond grains, and diamond is the hardest material known, the traditional “hard-on-hard” mechanical dressing methods for conditioning the blunted bronze-bonded diamond wheels (particularly already form grinding wheels) have shortcomings, including the excessive wear of dressing tools, low dressing efficiency, and unsatisfactory dressing accuracy [3,4]. To address the difficulties in the dressing of superabrasive grinding wheels, international researchers have not only improved the traditional mechanical dressing methods but are also continuing to explore new dressing methods, e.g., pulsed laser dressing [5–7]. As a technology based on the thermal effect of laser ablation, pulsed laser dressing completely avoids the “hard-on-hard” mechanical contact; hence, there is no wear of the dressing tools [8,9]. Moreover, theoretically, pulsed laser dressing is suitable for the precise dressing of all types of superabrasive grinding tools, including parallel grinding wheels, form grinding wheels with complex curved surfaces, and ultra-thin cutting grinding wheels. Thus, pulsed laser dressing is an advanced dressing technique with significant developmental potential and broad application prospects [10].

Because of the advantages discussed above, scholars around the world have conducted a wide range of studies and published more than 100 papers concerning laser dressing techniques in recent years. Here, we examine several representative examples.

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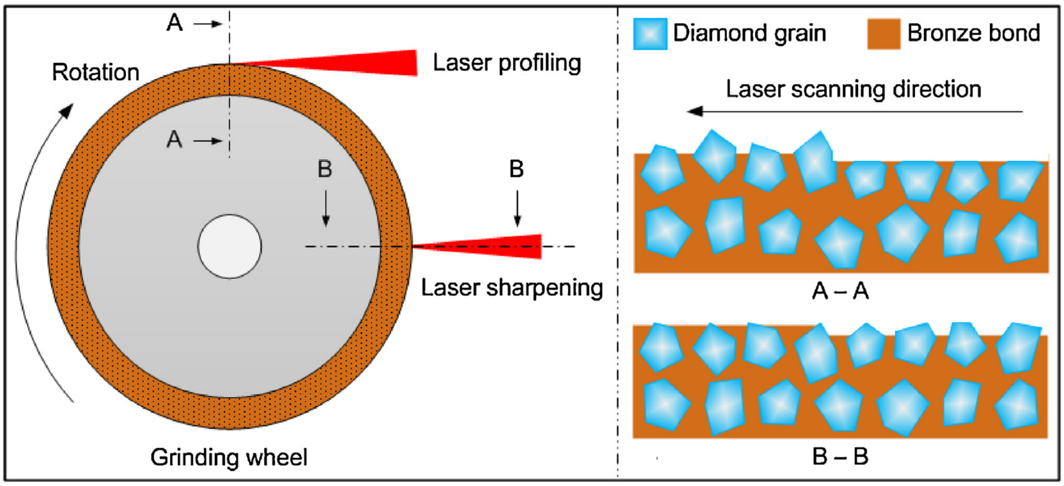

Fig. 1. A schematic of pulsed laser dressing.

Our research group [11,12] carried out various experimental studies on the radial sharpening of superabrasive grinding wheels using an acoustic-modulated Q Nd:YAG laser. We investigated the impact of processing parameters, including the average laser power, pulse frequency, defocusing amount, and wheel revolution, on the sharpened grinding wheel contour accuracy and surface topography, and we measured the normal, tangential, and axial grinding forces of the grinding wheels after sharpening. Walter et al. [13–15], from the Swiss Federal Institute of Technology in Zurich, used a pulsed fiber-laser to tangentially profile a hybrid bonded CBN form grinding tool and summarized the effects of processing parameters, such as the average laser power, pulse overlap ratio, and ablation line overlap ratio, on the material removal efficiency. Additionally, the authors measured the normal, tangential, and axial grinding forces. von Witzendorff et al. [16,17] from the Hanover Laser Machining Center performed experiments on the radial sharpening of metal-bonded diamond blades using nanosecond and picosecond pulsed lasers and further analyzed the impacts of processing parameters, including the laser wavelength, laser power density, and pulse width, on the protrusion height of the diamond grains on the blade surface after sharpening. Researchers from various countries have focused on the effects of only one or a few processing parameters on laser profiling/sharpening but have not identified or evaluated the key processing parameters that affect pulsed laser dressing and the relationships among them. Therefore, to some extent, the conclusions from existing studies are one-sided and subjective. Additionally, the key issues during the dressing process have not been sufficiently addressed, e.g., the graphitized layer of grains caused by the thermal effect of laser ablation, as well as the unsatisfactory contour accuracy and surface topography of the radial dressing as a result of the lack of a definite laser beam “tip”. These problems have become the bottleneck limiting the actual application of laser dressing techniques.

In this paper, key processing parameters that determine the quality, accuracy, and efficiency of pulsed laser dressing were proposed based on the mechanisms of tangential profiling and radial sharpening. We used a laser to ablate cylindrical bronze wheels and to tangentially profile and radially sharpen bronze-bonded diamond grinding wheels. After, a three-dimensional (3D) microscope with an ultra-large depth-of-field (ULDF) and a charge-coupled device (CCD) laser displacement sensor were used to measure the removal efficiency and surface smoothness of the bond material after laser ablation. Additionally, the circular runouts and surface topography of the dressed grinding wheel, and thus the impacts of the key processing parameters on the pulsed laser dressing of bronze-bonded diamond wheels, were investigated.

2. Principle of laser dressing

The objective of dressing is to produce, or restore, a wheel geometry and/or topography appropriate to a grinding task. Dressing involves two different sub-processes: profiling and sharpening [18]. For conventional abrasive grinding wheels, profiling and sharpening can be done simultaneously. However, for superabrasive grinding wheels, especially metal-bonded superabrasive grinding wheels, profiling and sharpening are usually performed in two distinct steps. Fig. 1 is a schematic of using a pulsed laser to tangentially profile and radially sharpen a bronze-bonded diamond grinding wheel. During laser profiling, the incident laser beam is sent in the tangential direction of the working surface of the grinding wheel; next, the grinding wheel is moved up to an appropriate distance (a_r cutting depth). Eventually, a multi-axis numerical control (NC) system is applied to precisely control the laser beam while it scans along the contour of the grinding wheel. Consequently, the diamond grains and bronze bond in the eccentric portion of the grinding wheel that interact with the laser beam will be removed (Fig. 1(A-A)). When the efficiency of laser ablation becomes low, indicating that most of the laser energy is passing through the wheel surface without cutting the wheel materials, the grinding wheel is moved up the same distance (a_r), and the profiling continues. The process is repeated until the desired contour accuracy is reached. The mechanism of laser tangential profiling is to heat, melt, and vaporize the material in the eccentric part of the wheel through laser cutting to create a high-accuracy and high-quality grinding wheel circumferential surface. In contrast to the cutting process of traditional tools, laser cutting does not generate a cutting force, tool wear, or tool wear-related or cutting force-related errors. However, if the laser power density is too high when cutting, a thick metamorphic layer will form on the surface of the grinding wheel, affecting the performance of the grinding wheel; alternatively, if the laser power density is too low, the laser beam cannot effectively cut and remove the bronze bond or the diamond grains. Therefore, the contour accuracy and grinding performance of the grinding wheel after laser tangential profiling rely mainly on this key processing parameter, laser power density (I_p). Other processing parameters, such as the laser scanning speed (v), wheel revolution (n), and cutting depth (a_r), have less impact on profiling accuracy and grinding performance but do impact on the laser profiling efficiency, to a certain extent.

Laser radial sharpening focuses the incident pulsed laser beam onto the wheel working surface along the radial direction and then scans in cycles along the wheel contour under the control of a multi-axis NC system to evenly remove the bronze bond around