Investigation of Ductile-brittle transition dynamic behavior of Tungsten carbide in Laser-assisted diamond machining based on Discrete Wavelet Transform

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Laser assisted diamond machining of binderless tungsten carbide is a promising method, which has drawn increasing attention from various fields, such as photonics and life science. This paper experimentally investigates the ductile-brittle transition dynamic behavior of tungsten carbide in laser-assisted diamond machining based on discrete wavelet transform algorithm. Groove-cutting results reveal that the ductile-brittle transition depth increases by 247.20% from 58.37 nm to 202.66 nm with the increase of laser power from 0 to 20W. Cutting force characteristics and groove profile characteristics simultaneously demonstrate the transition of the cutting mode from ductile to brittle. The detail coefficients at level 2 exhibit a distinct characteristic at the ductile-brittle transition point. The trend of the detail coefficients D2 with laser power shows good agreement with the conclusions obtained from the conventional profile data analysis. This research demonstrates the potency of discrete wavelet analysis for ductile-brittle transition dynamic behavior and provides important insights into the material removal mechanism of laser-assisted diamond machining.

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1. Introduction

Binderless tungsten carbide (BL-WC) possesses high hardness, high brittleness, superior yield strength, high-temperature thermal stability, and excellent resistance to abrasion and wear, which benefit its engineering applications but simultaneously restrict its nanometric machining strategies [1]. The ultraprecision machining of BL-WC has drawn increasing attention from various fields, such as photonics, life science, mold forming, cutting tools, and aerospace [2–4]. Conventional machining strategies for BL-WC optical components typically involve grinding and polishing to achieve the desired surface finish [3,4]. However, the geometry of the grinding wheel imposes limitations on the achievable surface forms due to the risk of interference between the workpiece and the machining tool. Single point diamond turning (SPDT) is another common method for machining BL-WC. However, the maximum undeformed chip thickness during SPDT is usually within hundreds of nanometers or even less [4,5]. This small critical depth of the ductile-brittle transformation (DBT) in hard and brittle materials (HBMs) means that brittle fracture, rather than plastic deformation, becomes the predominant material removal mechanism. As a result, the surface integrity may be compromised, and the tool's service life may be shortened [6].

Laser-assisted diamond machining (LADM) has emerged as an effective method for ultraprecision machining of HBMs. This technique has great potential to enhance the material’s machinability, as it allows for deeper DBT depth. The DBT depth of silicon was significantly increased by 364% (from 67 nm to 311 nm) with laser assistance [7]. The cross-sectional transmission electron microscope observation results indicated that In-LADM could effectively suppress the formation of subsurface damage [8]. The DBT depth of fused silica was increased by 294.9 % compared to conventional diamond cutting [9]. Compared with conventional machining without laser assistance, tool working life in LADM of nitriding mold steel has been remarkably increased by 29% [10]. The LADM method can promote the critical depth of no observed surface cracks of polycrystalline tungsten carbide from 26.6 nm to 106.3nm and the homogeneous finish quality (4.66nm in Sa) with inhibited tool wear were achieved. Although lots of scholars have studied the application of LADM in various HBMs, the ductile-brittle dynamic transition of BL-WC during LADM has not been well understood. On the one hand, the influence of laser power on DBT depth needs lucubrated investigation with convincing experimental results. On the other hand, a comprehensive analysis of the cutting force during ductile-brittle transition is required as it is an important indicator to characterize the dynamic contact performance between the tool and the material. The DBT depth is generally determined by extracting the profile data of the section perpendicular to the cutting direction at the location of the first surface defect. Due to the subjective factors of the measurement personnel, this measurement method may result in large errors. Previous studies demonstrated that the borders of BTD transition can be effectively distinguished based on the fluctuation characteristics of cutting force signals [11]. Therefore, different material removal modes can be distinguished by the dynamic change of cutting forces. Then determine the position of DBT from different aspects to ensure the accuracy of DBT depth measurement.

This paper aims to experimentally investigate the dynamic behavior of the ductile-brittle transition in tungsten carbide during laser-assisted diamond machining using the discrete wavelet transform (DWT) algorithm. Groove-cutting experiments were conducted to study the influence of laser power on DBT depth, and deep understanding of the ductile-brittle transition dynamic behavior was achieved by discrete wavelet analysis. The results show good agreement between the groove morphology (2D image and profile) and the dynamics of cutting forces (in the time and frequency domains, as well as the detail coefficients obtained from DWT) during the DBT transition. This study demonstrates the potential of discrete wavelet analysis for understanding DBT behavior and provides valuable insights into the material removal mechanism of HBMs.

2. Experimental Method

The experiment was conducted using an ultra-precision machine tool (Precitech Nanoform X, USA) with a self-developed In-LADM system, as shown in Fig. 1(a). The BL-WC materials' machinability improvement with laser assistance was studied via groove cutting experiments, as shown in Fig. 1(b). The laser used in the experiment was a Nd:YAG laser generator that emitted a continuous-wave laser with a wavelength of 1070 nm and a Gaussian beam profile. The laser beam was directed through an optical beam shaper module specially designed to focus the beam from 3 mm to approximately 80 μm in diameter. The laser spot position was precisely adjusted to align the center of the laser spot with the tip of the diamond tool. Given the short groove cutting distance and large feed rate, there is a large temperature gradient around the laser irradiation area. And cutting fluid was not used in groove cutting experiments to minimize thermal stress. A piezoelectric dynamometer (Kistler 9119AA2, Switzerland) was mounted on the cutting tool holder to measure the cutting forces for every test. The frequency of the dynamometer was set to 10 kHz for the complete recording of micro-cutting forces. In order to demonstrate the influence of the laser power on the cutting forces more intuitively, the measured thrust force Fx and cutting force Fy during the groove cutting were synthesized into a resultant force F. A single-crystal diamond tool with 35° rake angle was horizontally fed at a constant cutting speed along the X direction, while the depth of cut was continuously varied along the Z direction from 0 to 2 μm during the groove cutting process. As presented in Fig. 2, a typical microgroove showed two distinct regions along the cutting direction. In the ductile region, the material undergone shearing similar to that in metal owing to microscopic plasticity leaving behind a crack-free machined surface. As the DOC increased continuously, the pits generated by crushing initially appear, and their density increased with DOC resulting in the brittle mode cutting. The samples after the groove cutting test were observed by WLI to precisely determine the DBT position.

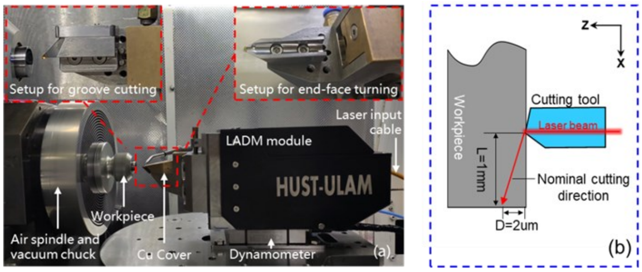

Fig. 1 (a) Experimental configuration; (b) Illustration of groove cutting.

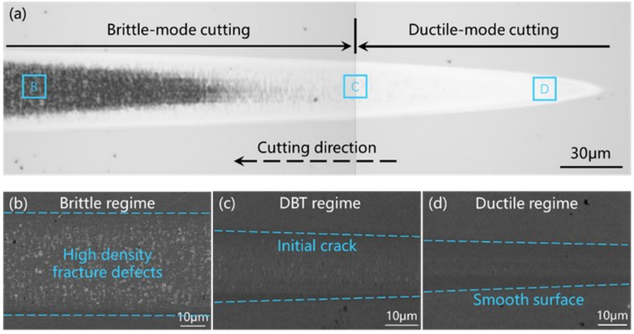

Fig. 2 Micrograph of a typical machined microgroove after groove cutting: (a) overall view; enlarged view of (b) region B, (c) region C and (d) region D.

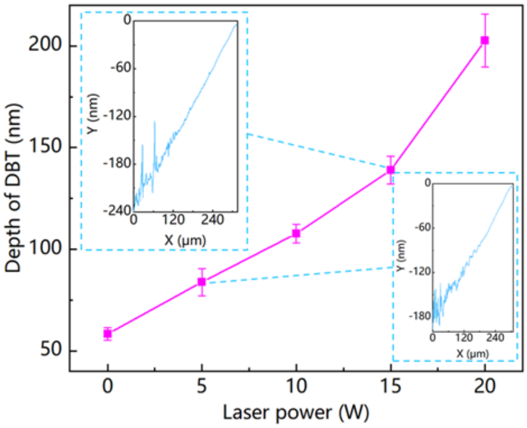

Fig. 3 Influence of laser power on the DBT depth.

3. Results and discussion

The DBT depth is a crucial parameter for evaluating the machinability of HBMs. As can be seen from Fig. 3, the DBT depth raises sharply as the laser power increases. Specifically, the DBT depth increases by 247.20% from 58.37 nm to 202.66 nm with the increase of laser power from 0 to 20W. The high temperature induced by laser radiation can decrease the material's resistance to localized plastic deformation and weaken the strength of grain boundaries, facilitating the suppression of crack propagation. The reduction in hardness and Young's modulus enhances the ductile machinability and plastic deformation of BL-WC, resulting in an increased DBT depth. Consequently, the in-LADM method effectively suppresses crack formation and significantly improves BL-WC's machinability. This allows for the application of larger critical undeformed chip thicknesses in the BL-WC turning process with laser assistance, which benefits the improvement of material removal rates.

To further reveal the dynamic characteristics of DBT, the wavelet signal denoiser based on Symlets wavelet family and Block James-Stein denoising method is used for filtering, noise reduction, and feature extraction. Fig. 4 (a) illustrates the denoised cutting force-DOC curves during the grooving of BL-WC, revealing distinct characteristics: the cutting force initially increases smoothly with minor fluctuations, then gradually increases with slightly larger fluctuations, and finally exhibits increased fluctuations. Both the groove profile morphology and the dynamic evolution of cutting forces exhibit significant fluctuations at the DBT point. The grooves can be categorized into sequential ductile regime, DBT regime, and brittle regime based on different cutting force and groove profile characteristics. The cutting force increases steadily with a small deviation amplitude due to elastic and plastic deformation of the material in the initial cutting regime with a DOC less than 193.7nm. Dynamic inspection of defect evolution demonstrates that crack initiation occurs at a DOC of 193.7nm, which corresponds to a DBT transition during cutting process. Correspondingly, the fluctuation of cutting force is significantly amplified for the DOC higher than 193.7nm, suggesting that brittle-mode cutting governs the material deformation. Fig. 4 (b) exhibits the deviation amplitude signal, calculated by subtracting the denoised signal from the original cutting forces. There is a clear correlation between the change in fluctuation amplitude and the transition of cutting mode.

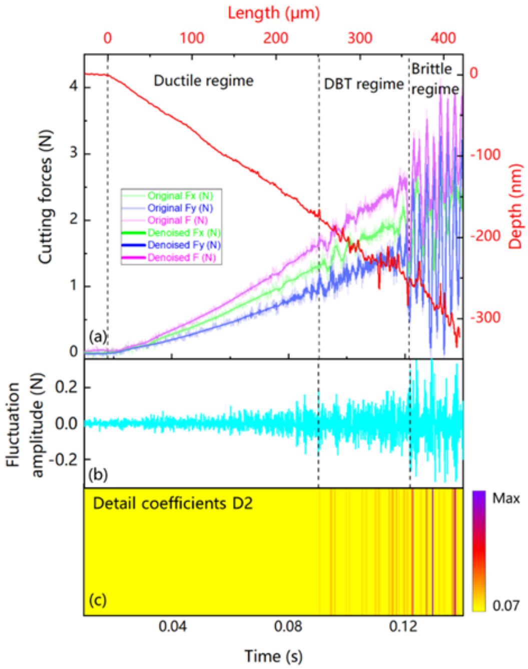

Fig. 4 (a) Variations of cutting forces and groove profile data of BL-WC during DBT with laser power 20W; (b) Deviation amplitude signal of (a); (c) Color contours of the variation of detail coefficients at level 2 with time of (a).

Although the Fourier transform has excellent frequency resolution, it fails to provide information on the timing of the sequence of events, making it challenging to associate frequency characteristics with time. In contrast, DWT has temporal resolution that transforms the time domain response to the time-frequency domain, capturing both frequency and location information (location in time). To obtain more localized high-frequency details while reducing the interference of low-frequency fluctuations, the DWT analysis was performed with 8 decomposition levels. The variation of detail coefficients at level 2 (D2) with time is extracted as feature vectors and plotted in Fig. 4(c). The minimum threshold of color mapping is set to 0.07 to highlight the initial position of DBT. In other words, when D2 is below 0.07, the corresponding color mapping appears as yellow. The color contours of D2 clearly depict the vibration characteristics of cutting forces. The detail coefficients (D2) exhibit a distinct fluctuation characteristic at the DBT transition point. Fig. 5 illustrates the variations of the detail coefficients (D2) obtained from the DWT analysis of BL-WC at different laser powers. As the laser power increases, the position of DBT gradually moves along the cutting direction, indicating an increase in DBT depth. The trend of the detail coefficients D2 with laser power is consistent with the conclusion obtained from the conventional profile analysis.

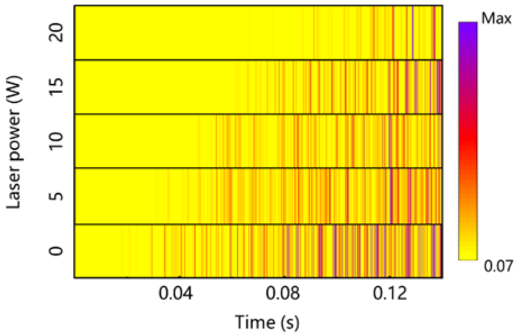

Fig. 5 Variations of the detail coefficients D2 with different laser powers.

4. Conclusions

This paper experimentally investigates the ductile-brittle transition dynamic behavior of tungsten carbide in laser-assisted diamond machining based on discrete wavelet transform algorithm. LADM can exceptionally enhance the ductility and machinability of BL-WC by reducing the material's hardness and Young's modulus. Compared to conventional groove cutting without laser assistance, the depth of the ductile-brittle transition has increased by 247.20%, from 58.37 nm to 202.66 nm. The ductile-brittle transition dynamic behavior of BL-WC in laser-assisted diamond machining is analyzed based on the discrete wavelet transform algorithm. The evolution in the time-frequency domain exhibits good agreement with the conventional analysis of groove profiles. The dynamic characteristics of cutting forces and the static characteristics of groove profiles concurrently demonstrate the transition from ductile to brittle cutting modes. In conclusion, this research highlights the effectiveness of discrete wavelet analysis in studying the dynamic behavior of the ductile-brittle transition and provides valuable insights into the material removal mechanism in laser-assisted diamond machining.

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