CRACK SEPARATION MECHANISM APPLIED IN TWO-DIMENSIONAL CO2 LASER CUTTING THICK POLYCRYSTALLINE CUBIC NITRIDE

Yixian Wang*, **Pal Molian, Pranav Shrotriya**

Laboratory for Lasers, MEMS and Nanotechnology

Department of Mechanical Engineering

Iowa State University, Ames, IA, 50011, USA

yixianw@iastate.edu

Research Program: Design and Manufacturing Innovation

An exceeded method for contour cutting thick solid-form polycrystalline cubic boron nitride (PCBN) tool blanks is called for because state-of-art techniques of pulsed Nd:YAG laser cutting and wire electric discharge machining (EDM) are restricted by low speeds, large kerf and poor surface precision. Our group developed a hybrid CO_2 laser/waterjet (LWJ) process to cut PCBN tool inserts by a crack separation mechanism. Although such method has performed some favorable cut results in thin PCBN (1.6 mm) with carbide substrate, it is still formidable to machine thick solid-form PCBN tool blanks in two dimensions.

Thus, we examined a novel progressive method in this work to cut 4.8-mm-thick PCBN tool blanks with controlled fracture both experimentally and analytically. In LWJ, the PCBN blank is locally irradiated using a high-power continuous wave CO_2 laser to cause phase transition from cubic to hexagonal and explosive BN followed by water quenching to generate thermal stresses and chemical reactions leading to increased brittleness, subsequent cracking, and material separation through the rest thickness.

Three different fluid media were applied in this experiment at varying line energy: (1) N_2-assisted laser alone; (2) Air-assisted LWJ; (3) N_2-assisted LWJ. Different critical line energy (P/v) was chosen based on previous trials. For N2-assisted laser alone process, 120˚ angle was made successful in one single pass of focused mode (spot size = 0.2 mm), however only groove left for the term of 90˚ cut. For Air-assisted LWJ process, no desirable results were obtained for both 90˚ and 120˚ cut, utilizing one focus beam following several defocused beam additionally. For N_2-assisted LWJ process, a focused beam plus 3 defocused beam passes performed a through-cut of 120˚ angle. Different fracture mechanism and cut quality are shown with several material characterizations, morphology and analysis.

Both N_2-assisted laser alone and N_2-assisted LWJ succeeded to cut through at 120˚ turn, however different fracture characterizations could be examined from cut quality. The actual cut trajectory caused from laser alone deviated from the laser beam path and attempted to make a shorter path around the corner, with a lagging distance at the turning point of approximate 2 mm. While in the N_2-assisted LWJ process, the cut path through the thickness followed the laser beam path exactly, with the beam and crack turn in the perpendicular direction. A formulated model based upon Cotterell and Rice's crack path stability theory [1] could be utilized to explain this. In our case of experiment, PCBN specimen was irradiated by laser and initiated a plane crack tip by phase transformation. The plane was assumed to be semi-infinite with a crack subject to symmetric (Mode I) loading.

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*Presenting author: Yixian Wang

The predominating terms in a series expansion of stress field very near the crack front are

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) + T$$

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$

$$\sigma_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

where r and θ are the in-plane coordinates of the plane normal to the crack front, K_I is the stress intensity factor and T refers to tensile stress T. Yang and Chandar [2] observed and demonstrated the oscillatory crack growth of a thermally quenched glass flask. For laser alone cutting, the PCBN specimen underwent merely heating up with cooling in air atmosphere, which rate of cooling in low compared to water. Thus, the T stress term is positive and acted as tensile stress which cause crack path to deviate the expected trajectory around the turning corner. For N_2-assisted LWJ cutting, water quenching followed immediately after the laser irradiation, and T stress is negative and acted as compressive stress during the crack propagation along the thickness. The 120˚ contour crack path was stable and conformed the perfection of expected trajectory for ideal Mode I loading ($\theta = 0$).

To understand the material removal mechanism of the N_2-assisted cutting in two dimensions, the transverse section along the beam path was investigate. Scanning electron image for transverse section shows two regions of different topography and microstructure with unclear boundary could be observed in this section: the shallow machined region near the top surface caused by phase transformation and chemical reaction; the bottom fracture region due to crack initiation and propagation. The depths of both regions are approximate 950 µm and 3850 µm, respectively.

The Raman spectrum is taken for the cross section of N_2-assisted laser cutting sample, including both phase transformation and fracture region. In terms of fracture zone, two peaks at 1053 and 1304 cm^{-1} was found, evolving from the cBN in TO and LO peaks. It is hypothesized that no phase transformation took place in the fracture region due to same phase signatures in as-received material. In terms of phase transformation region, two new phases with different peaks (1361 and 1562 cm^{-1}), except a TO peak of cBN at 1053 cm^{-1} are seen. The existence of cBN and eBN possibly provides the evidence of transition between sp^3 to sp^2 phase in phase transformation region.

Surface roughness and taper angle of through-cut samples were measured using an optical profilometer. The surface roughness of both transformation zone and crack zone was distinguished, with no obvious difference before and after the turning point. Average Ra of transformation region and fracture region are roughly 12 µm and 4 µm (Laser alone) and 8 µm and 4 µm (LWJ), respectively. Taper angles before and after turning point are 12 ˚ and 8 ˚ for laser alone while 1.4 ˚ and 0 for LWJ.

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*Presenting author: Yixian Wang