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The laser/water-jet (LWJ) machining of double-layer Tungsten Carbide (WC) supported Polycrystalline Cubic Boron Nitride (PCBN)

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Research Program: laser/water-jet(LWJ) machining of hard materials

Introduction

Cubic Boron Nitride (CBN) is the second hardest material on earth, and is a difficult-to-machine ceramic material due to its ultra-high hardness. PCBN has been used in industry as a substitute for diamond due to the superior thermal and chemical stability. PCBN tool blanks consists of fine crystals are sintered under the conditions of high temperature and pressure with metallic(Co) or other binders. Tool inserts are initially cut from PCBN wafer into small pieces and post processing such as grinding and polishing are needed to make them into the final products. Due to the extreme hardness, it is difficult to machine the PCBN tool blanks. Diamond sawing, electric discharge machining (EDM) and Nd:YAG laser cutting are main traditional method for cutting. None of the current machining processes perform a favorable job due to the slow speed and cost-inefficient. Given to the limitation of existing machining method of PCBN, a novel process of combining continuous wave CO2 laser and water-jet (LWJ) was developed by our group to improve the machining efficiency and quality of PCBN. The CO2-LWJ machining system implemented a high power laser heating followed by low pressure waterjet quenching that achieved fracture initiation and controlled propagation along the cutting path.

1. Cutting experiments

Cutting experiments were conducted on the 1.6mm WC supported PCBN (50% cBN with 45% TiN and 5% AlN). Only scribing was found in the single-pass cutting at laser power of 400W and speed of 43.2mm/s. Increasing energy input or reduce cutting speed or repeating focused cutting will cause severe damages of the specimen. Through-cut was achieved in one pass of focused beam plus 4 passes of defocused beam. Spalling cracks were observed in the cuttings.

2. Mechanism for material separation

Laser irradiated zone of the PCBN workpiece undergoes a phase transformation during cutting process that results in volume expansion of the transformed region. The volumetric change initiates a tensile stress field in the surrounding material that lead to propagation of the crack through thickness direction.

3. Raman spectroscopy

Raman spectroscopy was carried out on a line across the fracture region and transformation region. In the fracture region, only cBN peak at 1059cm-1 and 1302 cm-1[16] can be detected which reveals that the fracture region was original PCBN material. In the transformed region, several new phases around 1160cm-1, 1370cm-1 and 1530cm-1 was discovered and the cBN phase vanished

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completely. The Raman result validated the hypothesis that the laser irradiated zone of the PCBN workpiece undergoes a phase transformation that results in a volume expansion and helped in the material separation.

4. Estimation of transformation zone and expansion strain

In order to understand the mechanism and advantages of defocused LWJ cutting, another set of experiments was conducted on a PCBN sample with thickness of 4.8mm. The aim of this set of experiments was to replicate the laser effect produced on the thin sample for each pass without material separation. Same parameters of power and speed (400W and 100in/min) were implanted. Four cuttings were performed with different numbers of defocused passes carried out after the focus pass to study the progressive effect of the defocused beam. Number of defocused passes was 1, 2, 4 and 8 respectively for each cutting. Surface profiles around each scribing line were measured using an optical profilometer (Zygo NewView 7100). The measured surface profiles were compared with FEA results to obtain the size of phase transformed zone as well as the expansion strain associated with machining.

5. Energy release rate of vertical cracks

Fracture mechanics analysis was performed to determine the crack propagation behavior for the defocused WC-PCBN cutting. Plane strain analysis is proper to estimate the energy release rate of different crack length along the thickness direction. As the laser went further, the existing crack channeled along the laser path and achieved a through-cut that separated the specimen. Channeling energy release rate was the accumulation of plane strain cracks scaled by crack length. FEA model was developed to estimate the energy release rate for plane strain cracks. In the model the obtained transformation zone and expansion strain obtained in 4 was applied. Computed energy release rate was also compared to the weighted critical fracture energy for the double-layer specimen as to predict the fracture behavior of different defocus passes. Results of the fracture energy prediction agree well with the cutting experiment result that single-pass focus cutting was not able to cut through the material while multi-passes defocused cutting can achieve through cutting.

6. Energy release rate of spalling cracks

The spalling cracks were developed from some micro cracks during channeling crack propagation. In this work, only the initiation of spalling cracks was investigated and discussed while the propagation is not in the scope of discussion. Experimental observation suggested that two vulnerable locations were most probable for initiation of spalling cracks: the region just below the transformation zone and the interface between two layers. The spalling cracks near transformation zone were investigated for three cases: the single-pass focused cutting, multi-passes defocused cutting and a designed case aiming to reduce spalling cracks. The analytical results correspond well with the observation that the focused cutting induced more spalling cracks than the defocused cutting. In addition, the result suggested that a wider and shallower transformation shape is feasible to reduce or even eliminate the spalling cracks.

7. Conclusion

LWJ Cutting experiments are conducted on the 1.6mm tungsten carbide supported PCBN with process parameters of 100in/min and 400W. Single-pass LWJ cutting of 1.6mm WC supported PCBN resulted in just a scribing on the sample surface instead of separation of the material. In order to achieve through-cut of the double-layer specimen, a new method of combining single-pass focused beam and multi-passes defocused beam was applied that successfully achieved complete cutting. Spalling cracks were observed in both focused and defocused cutting but the amount during defocused machining were apparently reduced compared with the focused cutting. Scanning electron microscopy (SEM) and Raman spectrometry were performed on the cut surfaces to identify the mechanism governing sample separation. The results suggest that during the localized laser heating and subsequent waterjet quenching, PCBN near the top surface underwent chemical transitions from sp3-bonded phase into sp2-bonded phases that induced volumetric expansion. Surface profile was experimentally measured using profilometer and compared with analytical predictions in order to estimate the expansion strain and dimensions of transformation region. FEM model in ABAQUS was developed to determine the fracture behaviors associated with phase transformation. Fracture mechanics analysis of crack propagation is performed to validate the proposed governing mechanism. A possible method that inducing a wider and shallower transformation zone was suggested to reduce the spalling

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cracks and theoretical analysis was performed to explain the advantages and feasibility of this method.

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