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Investigation of a novel manufacturing technique for two-dimensional machining of Polycrystalline Cubic Boron Nitride (PCBN) tools

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**Investigation of a novel manufacturing technique for two-dimensional machining of
Polycrystalline Cubic Boron Nitride (PCBN) tools**

by

Ammar Abdulghani Melaibari

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

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Major: Mechanical Engineering

Program of Study Committee:

Palaniappa A. Molian, Major Professor

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Ames, Iowa

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TABLE OF CONTENTS

List of Tables.....	iv
List of Figures	v
Acknowledgments	vi
Abstract	vii
Chapter 1: General Introduction.....	1
Introduction	1
LWJ Technology & Process.....	2
Thesis Organization.....	5
References	6
Chapter 2: Effect of Fluid Medium on Laser Machining of Polycrystalline Cubic Boron Nitride Tool	7
Abstract	7
2.1 Introduction	8
2.2 Experimental details	10
2.3 Results and Discussion.....	12
2.3.1. Argon.....	14
2.3.2. Nitrogen.....	17
2.3.3. Air.....	19
2.3.4. Oxygen	21
2.3.5. Water-jet.....	23
2.4 Summary	25
2.5 Acknowledgments	27
2.6 References	27
Chapter 3: Two-Dimensional Contour Cutting of Polycrystalline Cubic Boron Nitride using a Novel Laser/Water-jet Hybrid Process	30
Abstract	30
3.1 Introduction	31
3.2 Experimental Details	34
3.3 Results and Discussion.....	36
3.3.1. LWJ cutting of free-standing PCBN segments.....	36

3.3.2. LWJ cutting of PCBN backed with carbide substrate	43
3.3.3. The model formulation	45
3.4 Conclusion.....	48
3.5 Acknowledgments	49
3.6 References	49
Chapter 4: General Conclusions.....	51
Conclusion.....	51
Future work	52

LIST OF TABLES

Table 1: Kerf geometry and surface roughness of laser machined PCBN	14
Table 2: Summary for the results of laser machined PCBN.....	27

LIST OF FIGURES

Figure 1: Schematic representation of the laser/water-jet system (source: reference [1]).....	4
Figure 2: Laser head description with the assist fluids inlets and outlets.....	11
Figure 3: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with argon as assist	15
Figure 4: Raman spectrum of the machined area in laser-cut PCBN with argon gas.....	16
Figure 5: Waviness in the cracked area when argon assist gas	17
Figure 6: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with nitrogen as	18
Figure 7: Raman spectrum of machined area in laser-cut PCBN with nitrogen gas.	19
Figure 8: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with air as	20
Figure 9: Raman spectrum of machined area in laser-cut PCBN with air as the assist gas....	21
Figure 10: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with oxygen assist	22
Figure 11: Raman spectrum of machined area in laser-cut PCBN with oxygen assist	23
Figure 12: (a) Top views of the LWJ cutting area at 42.3 mm/s; (b) Top views	24
Figure 13: Raman spectrum of machined area in laser-cut PCBN with water as	24
Figure 14: Raman spectrum of cracked area in laser-cut PCBN with water as	26
Figure 15: Laser head description with the assist fluid inlets and outlets.	35
Figure 16: On the left, a taper angle appeared after a 120 degree turn on	37
Figure 17: In the left, angular top view of LWJ cut of a curve with 1mm radius	37
Figure 18: An uncontrolled crack propagated at the turning	38
Figure 19: An intersection of two straight line cuts where the first line cut	39
Figure 20: Optical profilometer trace showing the change in depth of the third groove.....	39
Figure 21: Phase diagram of BN (Source: Reference 7 in chapter 4).....	41
Figure 22: Raman spectrum at point (1) in Figure 5 where different peaks of different	42
Figure 23: Raman spectrum at point (2) in Figure 5 where different peaks of different	42
Figure 24: SEM images of LWJ cuts of PCBN on thin carbide substrate.	43
Figure 25: On the left (top), top view of a 135 degree angle cut where	44
Figure 26: On the left, LWJ on PCBN blank with thick carbide	45
Figure 27: Schematic representation for LWJ machining for a The big circles... ..	46
Figure 28: Schematic representation for LWJ machining at	47
Figure 29: On the left, SEM image of the On the right, schematic top view	48

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ABSTRACT

The Laser/Water-Jet (LWJ) hybrid machining system, introduced and developed by the Iowa State University's Laboratory for Lasers, MEMS, and Nanotechnology, was applied to overcome the major deficiencies associated with current EDM and laser machining techniques for shaping Polycrystalline Cubic Boron Nitride (PCBN) cutting tools from the blanks. For PCBN, the purpose of water in LWJ is twofold: phase transformation and thermal shock. Previously LWJ was used to perform straight line cuts on various materials including PCBN. In this work, a further investigation of an understanding of the action of water and two-dimensional contour cutting of PCBN was carried out. The role played by water in LWJ was compared with that of other fluids (argon, nitrogen, oxygen, and air) to illustrate the effectiveness of water in the controlled fracture mechanism of PCBN. In addition, a two-dimensional contour cutting of PCBN using LWJ was investigated by changing the crack direction to 60, 108, 120, 135 degrees and following a curve with 1 mm radius in accordance with the standard PCBN tool shapes. The phase transition and the cut quality were investigated using Raman spectroscopy, Scanning Electron Microscopy (SEM), and optical profilometer. Results indicated that water is the best medium to control the phase transition and apply the controlled fracture mechanism for PCBN. Also, it was shown that successful cuts were made with obtuse angles in contrast to acute angles. A preliminary qualitative model was presented to explain the observed experimental results.

CHAPTER 1: GENERAL INTRODUCTION

Introduction

This work is an attempt to take the novel Laser/Water-Jet hybrid machining process (LWJ) a step further in machining Polycrystalline Cubic Boron Nitride (PCBN) cutting tools. PCBN is a super-hard tool material that has excellent mechanical, chemical, and thermal properties. However these characteristics limit the ability to shape PCBN to various tool geometries. Different machining techniques are used to shape this material such as Electric Discharge Machining (EDM) and Nd:YAG pulsed laser [1]. The Nd:YAG laser is most commonly used to machine PCBN because its efficiency depends on the workpiece material's thermal and optical properties instead of the mechanical or electrical properties. In addition, the Nd:YAG laser has better precision and machining flexibility over other methods. However, the Nd:YAG laser machining of PCBN suffers from major deficiencies such as thermal damages and long time. Harrison *et al.* reported that the cutting speed of Nd:YAG laser is only around ~ 0.6 mm/sec [2].

A solution, using a LWJ system, was proposed by our research group to overcome the Nd:YAG laser's deficiencies of machining PCBN. LWJ was able to make the straight line cuts with a cutting speed around ~ 7 mm/sec [3, 4], more than 10 times increase. However, in order to replace the existing machining processes for PCBN tool machining, the LWJ system should also be optimized with reference to thermal shock efficiency and multi-axis cutting. As a result we have undertaken efforts to identify the roles played by different fluid media to increase the efficiency and changing the crack direction in two-dimensional cutting to form the desired shape of PCBN tool.

The work reported is conveniently divided into two papers. The first paper deals with the effect of different fluid media (argon, nitrogen, oxygen, air and water-jet) on laser machining of PCBN was examined using a 500 W continuous wave CO₂ laser. Evaporation, ablation, melting, erosion, oxidation, graphitization and controlled crack fracture mechanisms were identified. The objective was to determine the most effective fluid medium for controlled fracture mechanism on PCBN samples. The study included phase transition and cut quality. The phase transformation analysis consisted of Raman spectroscopy to characterize c-BN, h-BN, w-BN and r-BN phases in the cut regions. The cut quality analysis involved in measuring surface roughness, taper angle, and recast layer. In this experiment, five triangular PCBN inserts were used; one for each fluid medium. In each case, a groove and a complete cut were performed. In the second paper, two-dimensional LWJ contour cutting was investigated by attempting to make four different angles commonly encountered in solid and tungsten carbide (WC) backed PCBN tool inserts. Four different samples were utilized: two free-standing PCBN with two different binder materials and two WC-backed PCBN with two different thicknesses. Two additional experiments were also performed to validate a proposed graphical model. The laser-cut surfaces were analyzed using scanning electron microscopy, Raman spectroscopy and optical profilometer. The effect of each sample on the cut quality (accuracy, surface roughness, and phase transformation around the corners) was determined.

LWJ Technology & Process

The LWJ technique is a hybrid process that utilizes CO₂ continuous wave laser and abrasive-free water-jet. The outlets of the laser and the water-jet were combined in one head

and used in tandem during machining. The LWJ head is able to rotate 360 degrees to allow the water-jet to follow the laser beam for the contour cutting. At the same time, the workpiece placed on XY positioning table can move in two-dimensions to change the direction of the cut. The laser beam is surrounded by a stream of air with very low pressure (5 Psi) in order to prevent the splashed water from interacting with the laser beam before it hits the material and to protect the laser lens from water, gaseous evaporated materials, and debris. Laser power, cutting speed, and water-jet pressure were controlled by power meter, CNC controller and pressure transducer respectively. A more detailed description of the LWJ system can be found in the references [5, 6] as well as presented in chapters 2 and 3.

It may be noted that LWJ uses an entirely different mechanism than conventional laser machining. The mechanism of material removal during conventional laser machining consists of three stages: melting, vaporization, and chemical degradation. When the laser beam is focused on a workpiece, the surface of the material heats up until the material starts to melt, vaporize or chemically change. During this process, a high pressure gas around the beam removes the scraps from the machining zone and accelerates the transformation process in the material. In LWJ, on the other hand, the mechanism for material separation is crack formation, propagation and fracture. The LWJ process begins with rapid laser heating which leads to localized damage and phase transformation of surface layers; this is followed by water-jet fast quenching on the surface layer which results in a stress field in the transformed material (Figure 1). This stress field contains two parts: thermal stresses produced by the temperature gradient and mechanical stresses induced by the phase change of volume in the transformed material on the sample surface. These stresses provide a controlled crack initiation and propagation through the thickness. The end result is material separation. This

controlled fracture mechanism offers a fast, cheap, and low energy method to cut difficult-to-machine materials like ceramics.

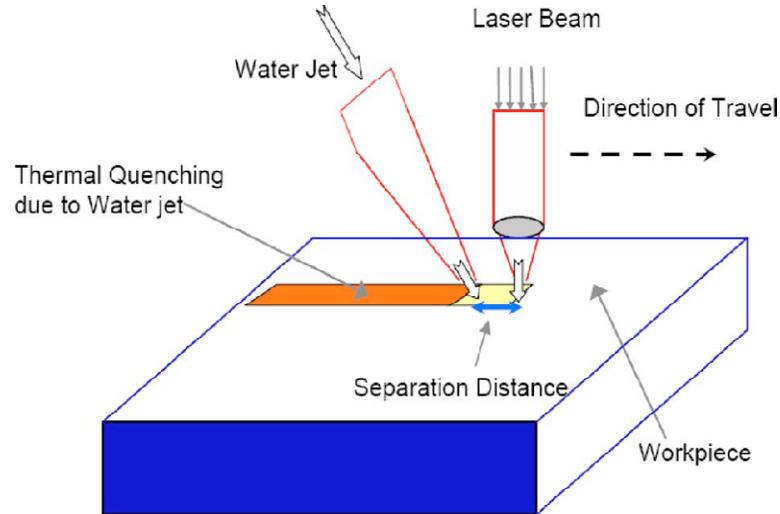


Figure 1: Schematic representation of the laser/water-jet system (source: reference [5])

The role of the fluid medium in aiding/controlling the fracturing process differs depending upon the type of material. In the case of glass and alumina, the driving forces for material separation come mainly from the thermal stresses. Wittenbecher *et al.* [7], proposed a system of gas-assisted laser to cut glass by inducing thermal stresses in the sample. Tsai *et al.* [8] used a focused/defocused laser beam technique to apply thermal stresses on alumina samples. LWJ system, on the other hand, was used to apply both stresses—thermal and mechanical—and also control the stresses to prevent catastrophic random fracture. LWJ has been successfully used with alumina and zirconia, where thermal stresses are the driving forces for material separation [9]. With PCBN and polycrystalline diamond (PCD), mechanical stresses seem to be the driving forces for material separation [4].

In the case of PCBN, the high hardness and low thermal expansion coefficient makes the thermal stresses from LWJ process low. At the same time, however, since the phase

transformation from the cubic phase to the hexagonal phase along the LWJ groove creates a large change of volume in the transformed material and thus the mechanical stresses are high. The phase transformation is the main factor for material separation in LWJ machining of PCBN [3, 4]. Since other fluids could be used instead of water to provide this phase transition without the need for additional setup or relatively high pressure (60-200 Psi) application, the role of these fluids on the laser machining of PCBN was investigated in this work to evaluate the potential of water. After finding that water is the right fluid medium for machining of PCBN, the main challenge for LWJ is to address its edge over the existing machining processes for PCBN. Changing the direction of the cut is the real challenge, since LWJ uses a fracture mechanism. Hence the two-dimensional contour cutting was performed with different angles typical of PCBN tool shapes and cut quality was determined.

Thesis Organization

This thesis is organized in the journal paper format that includes two papers (Chapters 2 and 3). Chapter 1 provides the motivation and background for the studies. Chapter 2 discusses an experimental investigation of the effect of different fluid media on continuous wave CO₂ laser machining with respect to controlled fracture mechanism. Chapter 3 addresses the difficulties encountered in the change of the crack direction in multi-axis cutting. A preliminary qualitative model is also presented to explain the observed experimental results. Chapter 4 presents general conclusions observed in the studies of chapters 2 and 3 and describes future research ideas to make the LWJ as a successful industrial process.

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CHAPTER 2: EFFECT OF FLUID MEDIUM ON LASER MACHINING OF POLYCRYSTALLINE CUBIC BORON NITRIDE TOOL

A modified version from a paper published in the conference proceedings of The 44th CIRP Conference on Manufacturing Systems June 1-3, 2011

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Abstract

Polycrystalline cubic boron nitride (PCBN) tools are currently fabricated through Nd:YAG laser machining, electric discharge machining, and water-jet, all of which suffer from thermal damage and low speed. A hybrid CO₂ laser-water-jet machining (LWJ) was able to overcome these deficiencies. In order to understand the role of water-jet and its effects in laser machining, a study was undertaken to identify the effect of various fluid media (argon, nitrogen, oxygen, air and water) on kerf geometry, surface roughness, phase transition and recast layer of PCBN tools. Scanning electron microscopy, Raman spectroscopy, and optical profilometer were used to characterize the machined regions. The effect of each fluid medium on the outcomes of the experimental investigation is discussed.

Keywords: laser, water-jet, PCBN tool

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2.1 Introduction

Polycrystalline cubic boron nitride (PCBN) is the second hardest known material, diamond being the hardest. Unlike diamond, PCBN is not found in nature, but is a man-made material. It is hailed as the best performance cutting tool material for machining hard cast iron, high chrome alloy steels, high-strength nickel super alloys and powder metal alloys because of its advantages over diamond in terms of thermal and chemical stability. PCBN is manufactured by sintering fine particles of c-BN with the aid of ceramic matrix typically TiN or AlN under high pressure and high temperature conditions. PCBN not only possesses the outstanding mechanical properties such as extreme hardness and wear resistance but also exhibits high thermal conductivity, high Young's Modulus, low coefficient of friction, and chemical inertness (less reactive to metals like titanium) [1]. In recent years, PCBN tools are increasingly used in micro-manufacturing of a variety of precision components because PCBN is able to keep its nature when scaling down the end mills from conventional to microscopic sizes. In addition, PCBN meets the high demands of form accuracy, surface quality and low subsurface damage in ductile machining of brittle materials. Thus, PCBN is currently employed in the industry for cutting 'difficult-to-machine' materials because of its superior characteristics [1]. However the same properties limit the ability to shape the PCBN tools for various geometries.

Many machining techniques have been developed to shape PCBN that ranged from water-jet to electric discharge machining (EDM), and pulsed Nd:YAG laser. Due to the shortcomings in the water-jet process such as time consumption, wide kerf, poor surface finish and taper water-jet was not acceptable. In EDM, the process has been used to fabricate all insert shapes with good quality, but the material removal rates remained low. Lasers, on

the other hand, have excellent prospects for machining PCBN. However, the central issues like formation of recast layer, phase transition, and kerf geometry require a secondary process like honing. Also, the material removal rate is low. Thus the existing processes for the fabrication of PCBN tools are inefficient with respect to cost, time, and energy consumption.

The current processes used to produce PCBN tool inserts are pulsed Nd:YAG laser and EDM, both of which suffer from thermal damages and long machining time. We have recently demonstrated a novel, hybrid continuous wave CO₂ laser/ water-jet process (LWJ) for machining hard ceramic materials that seems to eliminate many of the deficiencies associated with pulsed Nd:YAG laser and EDM [2, 3]. It may be noted that LWJ uses an entirely different mechanism than conventional laser machining where a laser beam causes the material removal by heating up and evaporating the material. In LWJ, thermal stresses induced by temperature gradient and phase transition provide controlled crack initiation and propagation that in turn offers a fast, cheap, and low energy method to cut PCBN. The LWJ process begins with rapid laser heating leading to localized damage and phase transformation of surface layers; this is followed by water-jet (fast quenching of the surface layers) resulting in a stress field in the transformed material. The stress fields propagate the localized cracks through the thickness with the end result of material separation. Small kerfs, less taper and high-speed cutting are the beneficial effects of LWJ process. Drawbacks include the presence of recast layer and chemically-induced products on the top of kerf that increase the surface roughness [4].

In this work, a study was undertaken to identify the material removal mechanisms in laser machining under different fluid media including LWJ. A 500 W continuous wave CO₂

laser was used to examine the effects of argon, nitrogen, oxygen, air and water-jet on the cutting of PCBN substrates. Evaporation, ablation, melting, erosion, oxidation, graphitization and controlled crack fracture mechanisms were elucidated. The laser-cut surfaces were analyzed using scanning electron microscopy, Raman spectroscopy and optical profilometer to determine the role of each medium on the cut quality.

2.2 Experimental details

Equilateral triangular inserts of PCBN without carbide backup, prepared by EDM, were offered by Diamond Innovations, Worthington, Ohio, USA for the experiments. The triangles have 7 mm side length and 1.6 mm thickness. The average particle size is 4 μm with a composition of 75% of c-BN and 25% of Ti based matrix containing carbon, by volume (BZN 9000 of Diamond Innovations). Surface roughness (Ra) of the top (polished) and the side (EDM machined) were 0.3 and 3 μm respectively.

Five triangular inserts were used, one for each fluid medium. Laser machining was accomplished at two different cutting speeds 42.3 and 84.6 mm/sec (100 and 200 in/min) for each insert. All fluid media pressure was kept at 140 kPa (20 psi) except for the water-jet. Since the abrasive-free water-jet was used in the work, the pressure was kept higher at 5.5 MPa (800 psi).

A continuous wave CO₂ Laser (Model 820 Spectra Physics) of 10.6 μm wavelength and 500 W power was used in all experiments. The laser beam was focused to a spot size of 0.2 mm on the sample surface using a 127 mm focal length lens. For the laser/water-jet experiment, the water-jet followed the laser beam with a spacing of 4 mm to avoid the absorption of laser power by direct contact with water. See Figure 2 for laser head

description. It may be noted that water absorbs about 70% of CO₂ laser energy. Details of laser-water-jet setup are described elsewhere [5].

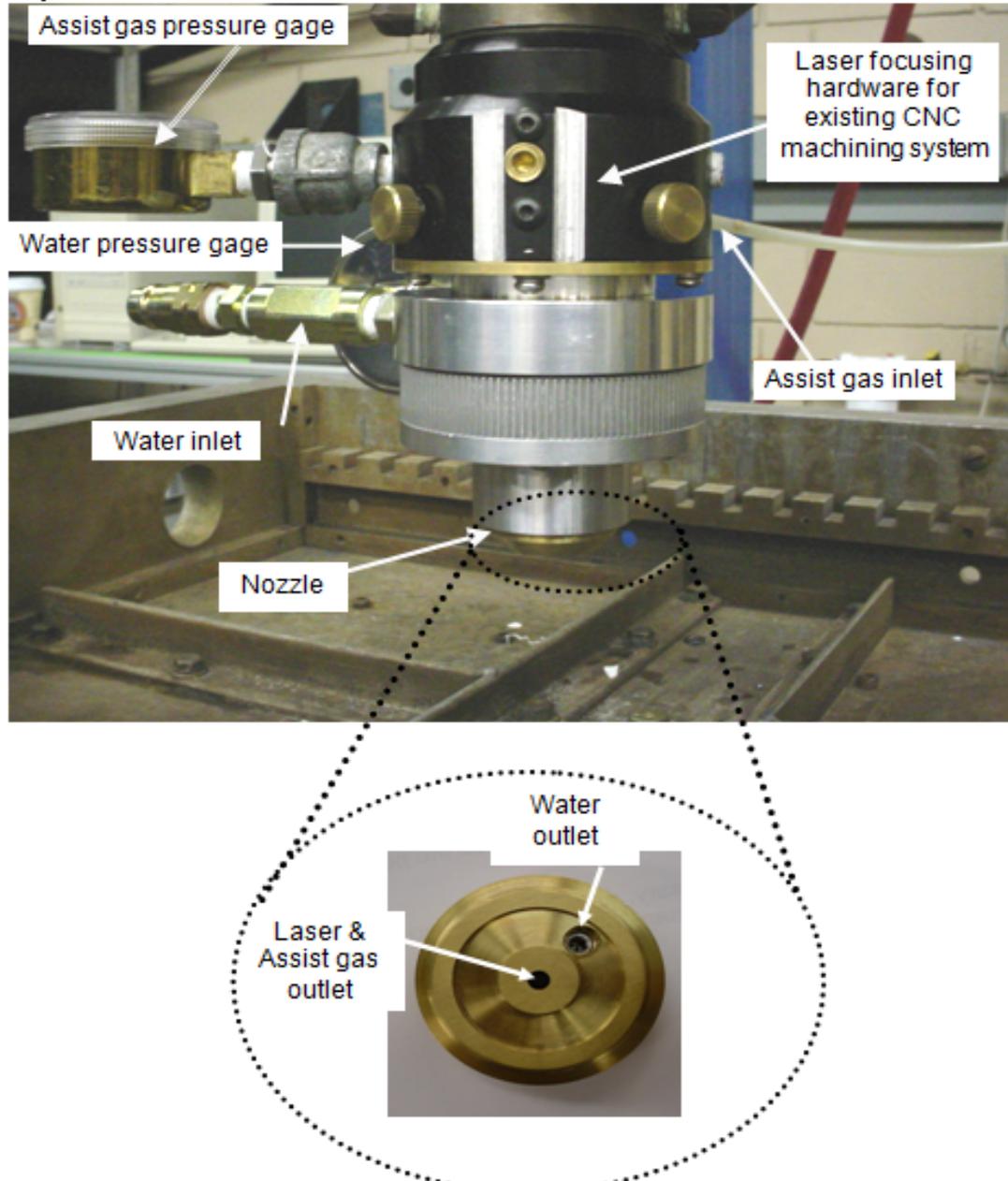


Figure 2: Laser head description with the assist fluids inlets and outlets.

Measurements of kerf geometries and surface roughness profiles were carried out using an optical profilometer (Zygo NewView 7100) with 5X and 20X magnifications. The

roughness readings were taken from the kerf side of those samples that were completely cut through. In those samples that were only scribed, roughness was measured from a region very close to the top edge of the kerf. Scanning electron microscopy (SEM Model JEOL JSM-606LV at 20 kV) was used to make secondary electron image of the machined surfaces in order to identify the growth of the recast layer and the characteristics of phase transition regions. Phase transition was determined using Dispersive Raman spectroscopy (Renishaw-inVia Raman Microscopy). Ar-ion laser at 488 nm wavelength was used for excitation.

2.3 Results and Discussion

The assist gas plays a key role in laser machining. In general, the assist gas serves four main purposes:

1. It can cause a chemical reaction depending on its reactivity and produces or absorbs heat.
2. It provides a mechanical force to eject the melt from the cut zone. However inefficient removal of the molten layer can lead to deterioration of cut surface.
3. It cools the cut zone by forced convection causing a potential loss in heat penetration.
4. It protects the lens from the contamination by evaporated species.

The efficiency and overall quality of laser machining is thus strongly dependent on the interaction of the assist gas with the sample. Table 1 summarizes the data on kerf geometry and surface roughness of laser machined PCBN with different fluid media; these are average values based on many data points. At the cutting speed of 42.3 mm/sec, complete separation was achieved when using air, O₂, N₂, and Ar. For the same speed, water-jet caused only scribing suggesting that water-jet forced significant convection and also changed the material removal mechanism to more of cracking. However mechanical snapping of the

scribed samples enabled complete separation. At a cutting speed of 84.6 mm/sec, only scribing was made possible in all samples. The effect of doubling the speed on kerf depth is quite striking with all gas media.

Direct sublimation or melting of PCBN by laser irradiation is a challenge. In order to machine PCBN, high laser intensity and phase transition from c-BN to h-BN (surface reconstruction) are required. The process begins with the conversion of sp^3 to sp^2 phase transition followed by gasification of sp^2 -bonded BN [6]. In the oxygen environment, both oxidation and phase transition govern. First, c-BN oxidizes to a protective layer of B_2O_3 , and then this layer evaporates allowing c-BN to transform to sp^2 -bonded BN phases on the surface. Then, these phases will melt and evaporate. In addition, the oxidization of the binder material and all the gaseous products will continue to yield fine particulates with different sizes. Thermal expansion mismatch between c-BN and h-BN leads to thermal stresses that in turn create crack formation. The crack growth is caused by stresses induced by thermal gradients and phase changes. The effect of each fluid medium on oxidation, and phase transition is discussed below along with the material removal mechanism.

Table 1: Kerf geometry and surface roughness of laser machined PCBN

Fluid medium	Kerf Width, μm	Kerf Depth, μm	Taper angle, degrees	Surface Roughness (R_a), μm	
				Machined area	Cracked area
Ar (42.3 mm/s)	complete separation (1600 μm)			-	2.5
Ar (84.6 mm/s)	211	60	30	6	-
N ₂ (42.3 mm/s)	complete separation (1600 μm)			5	3
N ₂ (84.6 mm/s)	177	450	11	5	-
Air (42.3 mm/s)	complete separation (1600 μm)			4	1.2
Air (84.6 mm/s)	185	100	42	6	-
O ₂ (42.3 mm/s)	complete separation (1600 μm)			5	1.8
O ₂ (84.6 mm/s)	172	360	13	4	-
Water-jet (42.3 mm/s)	200	185	14	7	-
Water-jet (84.6 mm/s)	190	85	24	4	-
Original PCBN	Side machined with EDM			3	-

2.3.1. Argon

The complete separation of PCBN at 42.3 mm/sec is illustrated by its transverse section in Figure 3(a) while the scribing at 84.6 mm/sec is shown by its top view in Figure 3(b). A thin layer is melted and evaporated followed by crack formation and propagation through the thickness (Figure 3(a)). The kerf in the complete-cut sample is characterized by two regions: machined area (melts and evaporates) and cracked area (fractured zone). Figure 3(b) shows a shallow but wider kerf compared to all other gases. The temperature-induced phase change makes a thermally insulating h-BN layer which reduces the machined depth in argon environment [6]. It may be noted that in a flow of high purity argon gas, PCBN can be heated up to about 2800°C without any oxidation although its surface blackens, possibly due to the phase change beginning at ~1600°C [7] where c-BN transforms to h-BN, and the carbon in the binder matrix to graphite, or h-BNC. Another possible reason is the oxidation of nitrogen to form NO and/or NO₂ due to air exposure after machining since no boron oxide

protective layer is formed; this led to the creation of boron carbide (B_4C) on the surface. The kerf is rough with a chipped zone at the start and end points of laser cutting that could be attributed to thermal expansion mismatch stresses between c-BN and h-BN phases at the edge and also to the pre-existing cracks from EDM machining.

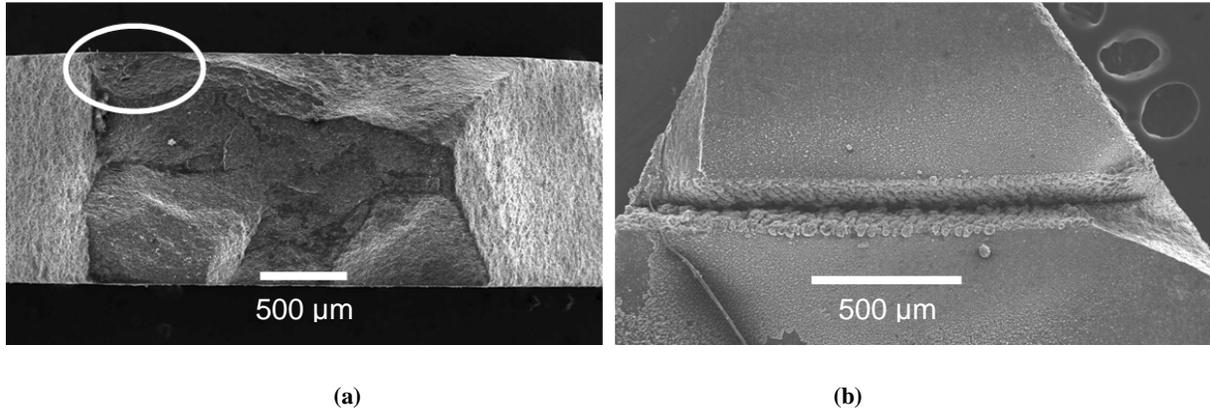


Figure 3: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with argon as assist gas, the machined area is inside the circle; (b) Top view of laser-scribed PCBN at 84.6 mm/s with argon assist gas.

The surface roughness of the machined area in Figure 3(b) was difficult to measure because the region was very small and the light from optical profilometer was completely absorbed there. Raman spectroscopy revealed the presence of h-BNC and other BN phases in the machined area (Figure 4) which could be the reason for the light absorption. The as-received PCBN has the distinct 1307 cm^{-1} peak characteristic of longitudinal optical (LO) Raman active mode for c-BN. In contrast, the machined area exhibits two peaks, one at 1377 cm^{-1} and the other at 1585 cm^{-1} . The 1377 cm^{-1} peak could belong to sp^2 bonding between N-B in the rhombohedral phase (r-BN) or in plane vibrations of the hexagonal phase (h-BN) [8]. The shift to higher frequency in h-BN Raman line –which is $\sim 1366\text{ cm}^{-1}$ – can be attributed to the effect of impurities like carbon in the matrix material on h-BN and/or to the decrease in the crystalline size of h-BN. Nemanich *et al.* [9] indicated that the Raman line for h-BN can be shifted to higher frequency, broadened, and became asymmetric as the

crystalline size decreases. The Raman features around $\sim 1585 \text{ cm}^{-1}$ can be attributed to h-BNC [10] or B_4C [11]. The formation of rhombohedral BN and/or of well-crystallized h-BN layers was observed along grain boundaries. Rapid heating and cooling associated with the process will cause the more probable c-BN transformation to h-BN, h-BNC and/or rhombohedral phase. Furthermore, the fact that phase transition takes place at the grain boundaries implies that finer grain size grades (as in the present case) would provide a large number of sites for the formation of these phases.

In contrast to the machined area, the cracked area has low surface roughness but exhibited high waviness (Figure 5). The waviness effect is explained by a stress-induced explosion mechanism caused by a) the phase change where the lattice structure changes from c-BN to r-BN and then h-BN decreasing grain size and inducing high stresses [6]; and b) thermalization of the lattice because argon has the lowest heat conduction coefficient.

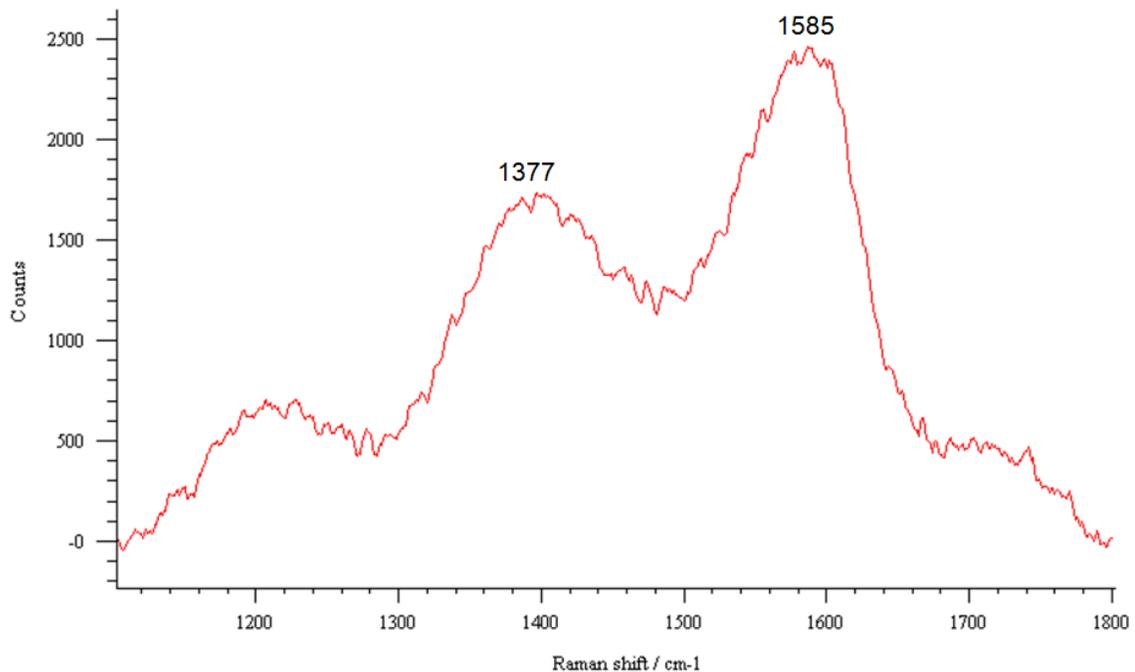


Figure 4: Raman spectrum of the machined area in laser-cut PCBN with argon gas.

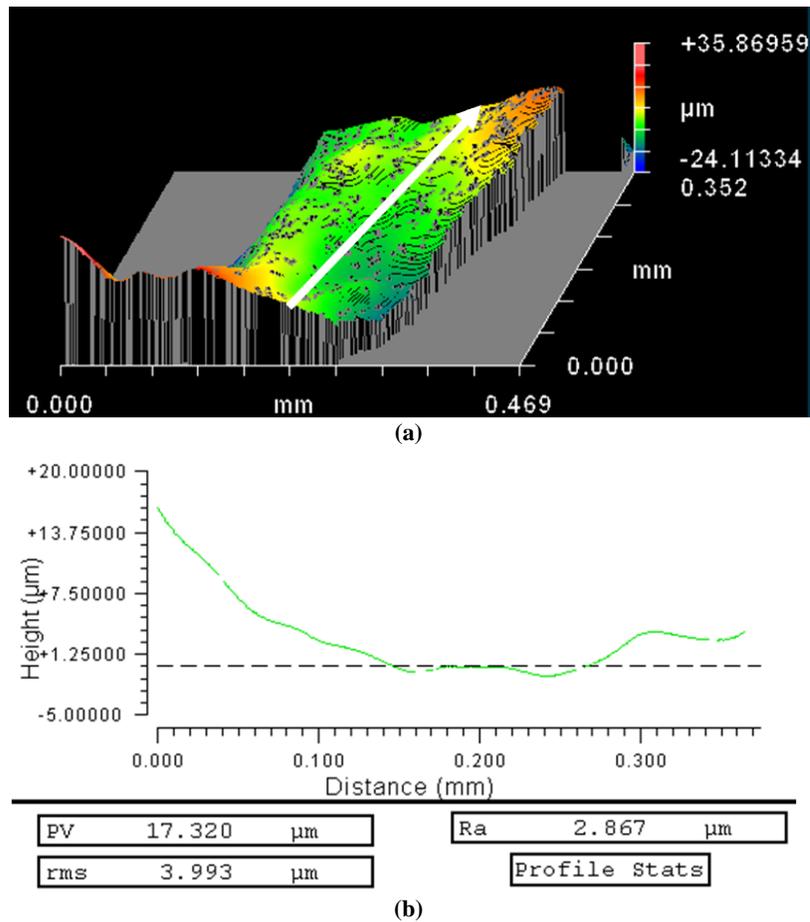


Figure 5: Waviness in the cracked area when argon assist gas was used; (a) 3D topography of the transverse section, the arrow indicate the locations of the profiles taken; (b) Surface Profile.

2.3.2. Nitrogen

Figure 6 shows the scanning electron micrographs of the transverse section of complete-cut (Figure 6(a)) and scribed (Figure 6(b)) PCBN tools. The kerf in complete-cut sample consists of two regions: a) machined area near the top showing a particulate structure ‘debris’ unlike that of argon; this structure contributed to roughness peaks in the kerf and on the edge. Collision interaction between the nitrogen molecules and the sputtered particles from ablation and evaporation modes in the PCBN which make up the recast layer may account for high degree of surface roughness. This interaction has been recorded between diamond and different gases in a research conducted by Gloor *et al.* [12]; and b) cracked

area which is rougher than those produced by other gases. The roughness is believed to result from the different depths of the machined area that in turn created sub-micro cracks with different orientations. When the crack propagates it needs space; the absence of space means roughening. For the scribed sample (Figure 6(b)), the kerf was deepest and narrowest among all assist gases. Surface roughness is same as that obtained in the machined area (Figure 6(a)). It appears that nitrogen facilitates improving laser ablation of PCBN and thereby increased the machined depth. Nitrogen gas enhances the reactivity of PCBN that is partially responsible for the improved CO₂ laser ablation.

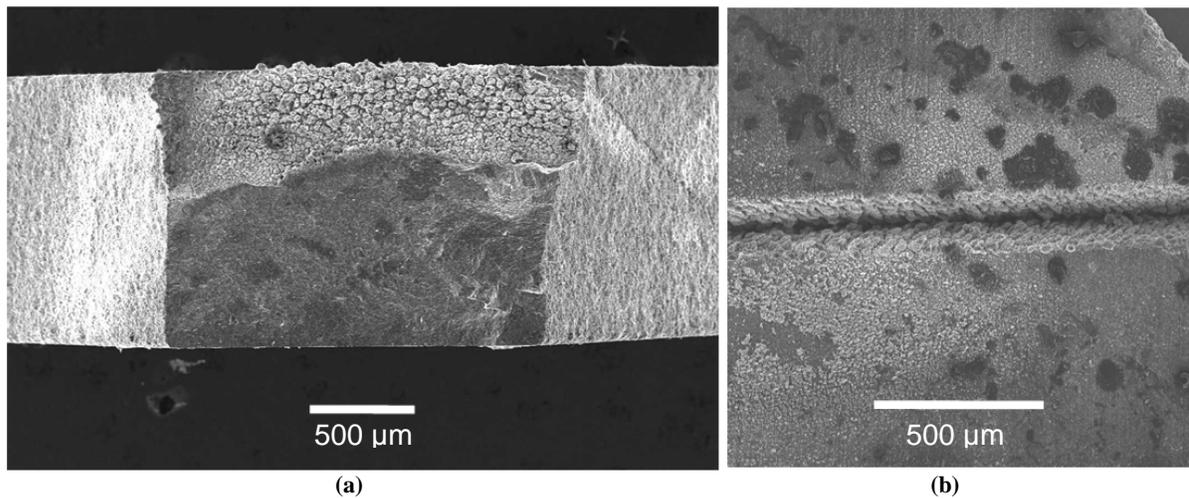


Figure 6: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with nitrogen as assist gas, the machined area is near the top; (b) Top view of laser-scribed PCBN at 84.6 mm/s with nitrogen as assist gas.

Raman spectroscopy analysis revealed many phases including the h-BNC or B₄C, h-BN and/or r-BN, as shown in Figure 7. The 1710 cm⁻¹ peak, which is close to the theoretical carbonyl peak, could be an indication for the addition of oxygen, upon air exposure, to the (C=N) band as in Aramid. Using nitrogen gas with PCBN increases the tendency for the previously stated phase transitions and creates some kind of fibers.

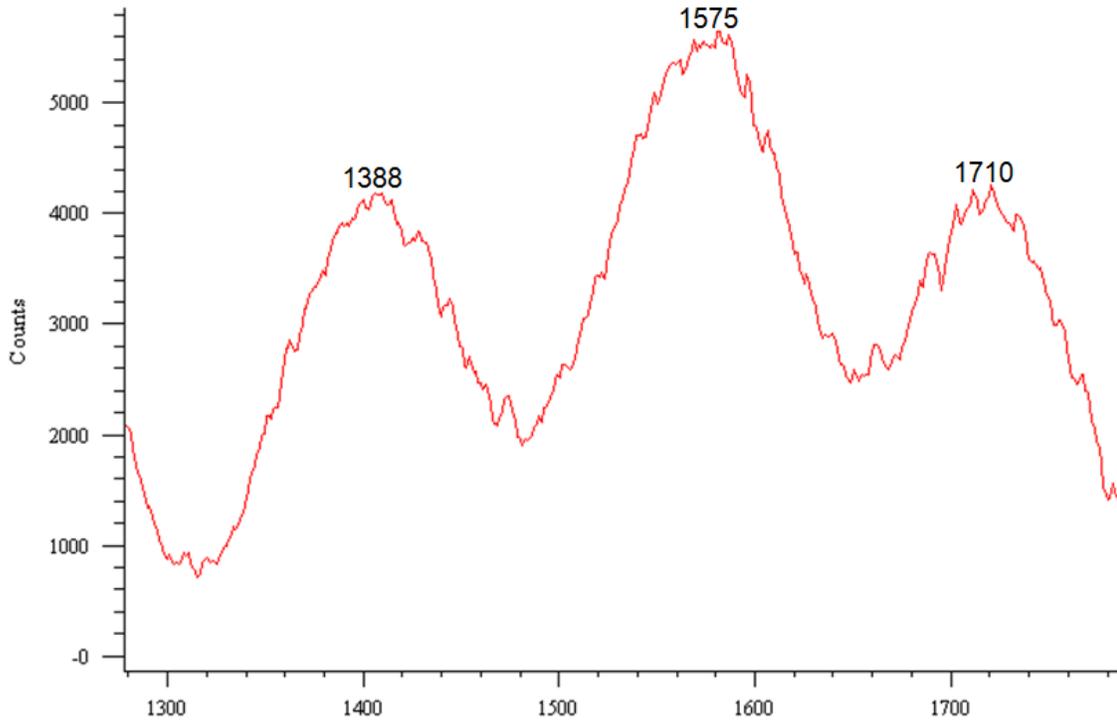


Figure 7: Raman spectrum of machined area in laser-cut PCBN with nitrogen gas.

An intriguing feature of nitrogen assist gas is the formation of particulate structures (various sizes) in both machined and scribed areas. These fine particulate matters ranging in size from nanometers to few micrometers can be attributed to the chemical reaction of nitrogen and carbon binder with oxygen right after laser machining. Thus, nitrogen assist gas in CO₂ laser cutting of PCBN promotes the initial phase change to h-BN, which creates thermal expansion mismatch stresses sufficient to fracture the sample, and improves the laser energy absorption leading to evaporation and condensation of vapour phases leading to fibres formation.

2.3.3. Air

Unlike argon and nitrogen, the air assist gas produced a heavy recast layer (Figure 8) in the laser-cut PCBN. The machined surface was rough due this layer. This recast layer also

affect the depth of the machined area as in nitrogen assist gas which roughen the cracked area too. Electron dispersive X-ray analysis indicated that the recast layer was composed of TiB_2 and TiO_2 because of the variety of chemical reactions that could occur among PCBN, binder (Ti matrix) and different impurities in air and the Oxidization temperature of materials other than PCBN are below the oxidization temperature of PCBN e.g. Ti starts to oxidize at $600^\circ C$ and carbon at $700^\circ C$. Raman spectroscopy revealed c-BN, fiber phases and unknown phases which could be attributed to stretching in the h-BN and h-BNC bonds (Figure 9).

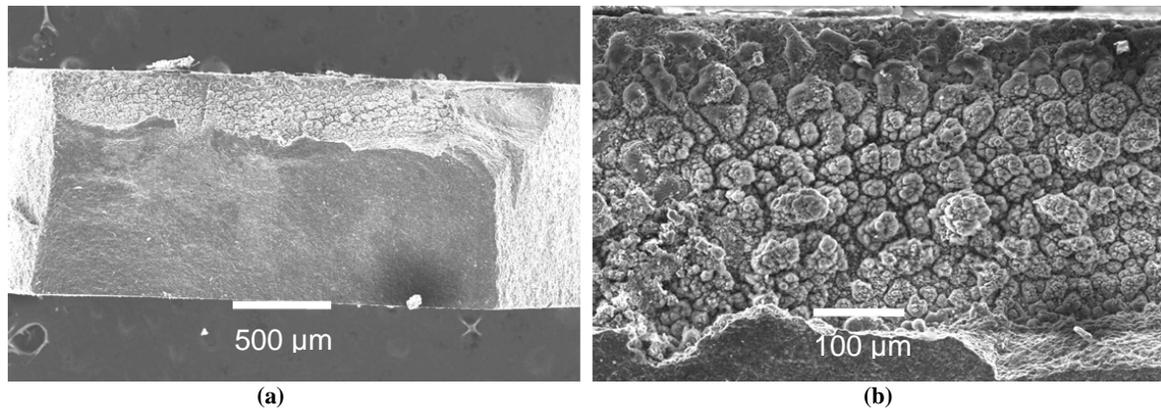


Figure 8: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with air as assist gas; (b) Structure of the machined area near the top

It is well known that a protective layer of B_2O_3 will cover c-BN when heated to $300^\circ C$, and no further oxidization will occur until heated over $1300^\circ C$ in air or oxygen; the released Nitrogen will form NO and/or NO_2 [13]. The first reaction is not likely to protect the sample in our case due to the fast elevated temperature to $\sim 3000^\circ C$. In contrast, the second reaction is more likely to happen in the heat affected zone; machined area, inside the kerf, and around the kerf. The oxidization of nitrogen will leave the oxidized area with rich boron content which is in good agreement with the black heat affected zone and black recast layer. Having more boron will blacken the area and create boron clusters [14] or boron rich phase of c-BN [6]. Therefore, the high temperature will sublimate the material in the machined

zone and oxidize the heat affected zone. Although PCBN oxidation and phase transition are connected phenomena, they are not fully understood. We propose that PCBN undergoes oxidization first which create rich phase of $c\text{-BN}_{1-x}$ and form NO_x gases. Then, a reaction/phase transition to h-BNC or B_4C , and some kind of fiber will take place. Recast layer is essentially the binder material oxidation.

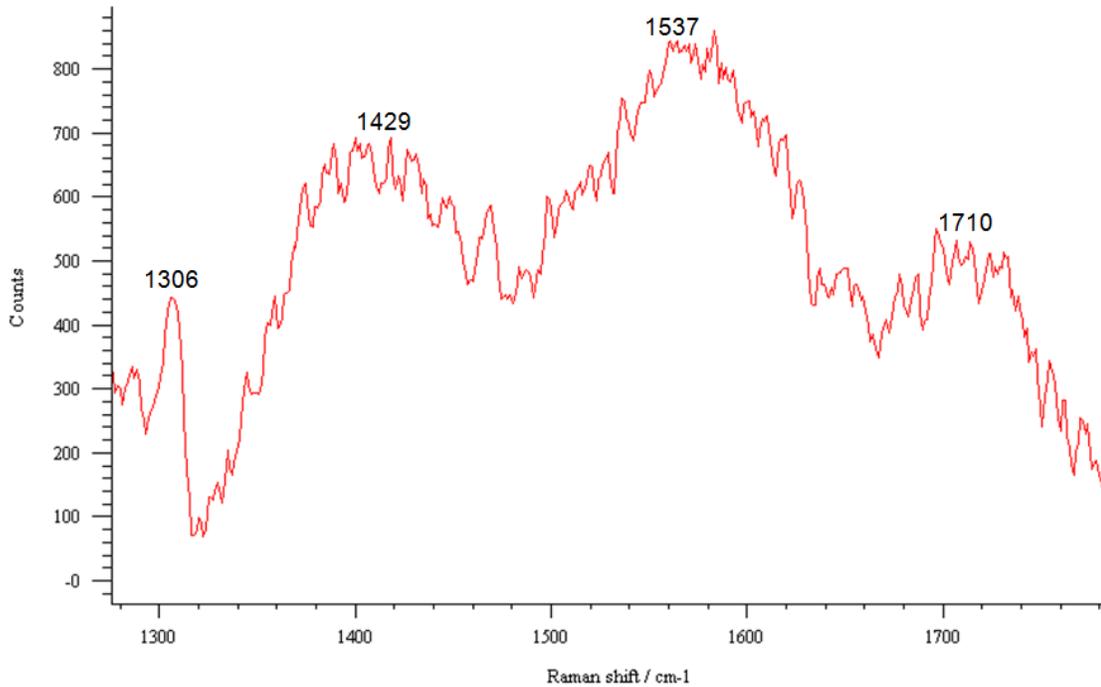


Figure 9: Raman spectrum of machined area in laser-cut PCBN with air as the assist gas.

2.3.4. Oxygen

Using oxygen as an assist gas showed a recast layer in the complete-cut similar to that of water on one side and similar to that of argon on the other side. This indicates that the cutting mechanism is more complicated and the resulting chemical reactions are also complex. The $c\text{-BN}$ starts to change to h-BN as well as h-BNC. Then a strong chemical reaction occurs between oxygen and BN phases as well as with the binder to remove the debris Figure 10(a). The cracked area, on the other hand, was similar to that of nitrogen.

Scribing with oxygen assist gas (Figure 10(b)) tends to reduce the phase change area on the sample even though the oxidized particles were sputtered all around the surface. In addition, no peaks of debris were observed along the kerf edge due to the effect of the high weight of oxygen compared to nitrogen in the collision interaction between the oxygen and the sputtered particles [12].

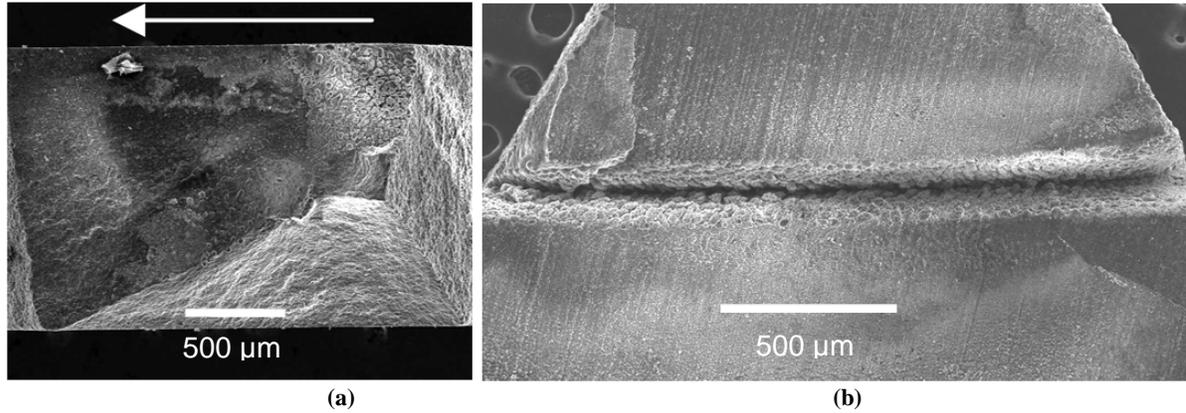


Figure 10: (a) Transverse section of laser-cut PCBN at 42.3 mm/s with oxygen assist gas. The arrow shows the machining direction; (b) Top view of laser-scribed PCBN at 84.6 mm/s with oxygen assist gas.

Raman spectrum shown in Figure 11 indicates that the peaks were similar to that of argon medium since the cutting area in that case was exposed to air very fast which resulted in binder material oxidization; however, in the case of rich oxygen environment the oxidized particles are very fine and small due to the pure oxidization effect. It should be noted that the increased shift in the Raman peak of BN is connected to the reduction in the crystal size [6]. On the other hand, cutting with 42.3 mm/sec does not show a lot of debris which is a result of further oxidization or the increased blowing effect corresponds to the lower cutting speed. The lower cutting speed allows the gas stream to force melted and evaporated material away from the machined area. It may be concluded that laser machining of PCBN samples under oxygen is more stable with respect to oxidization than phase change.

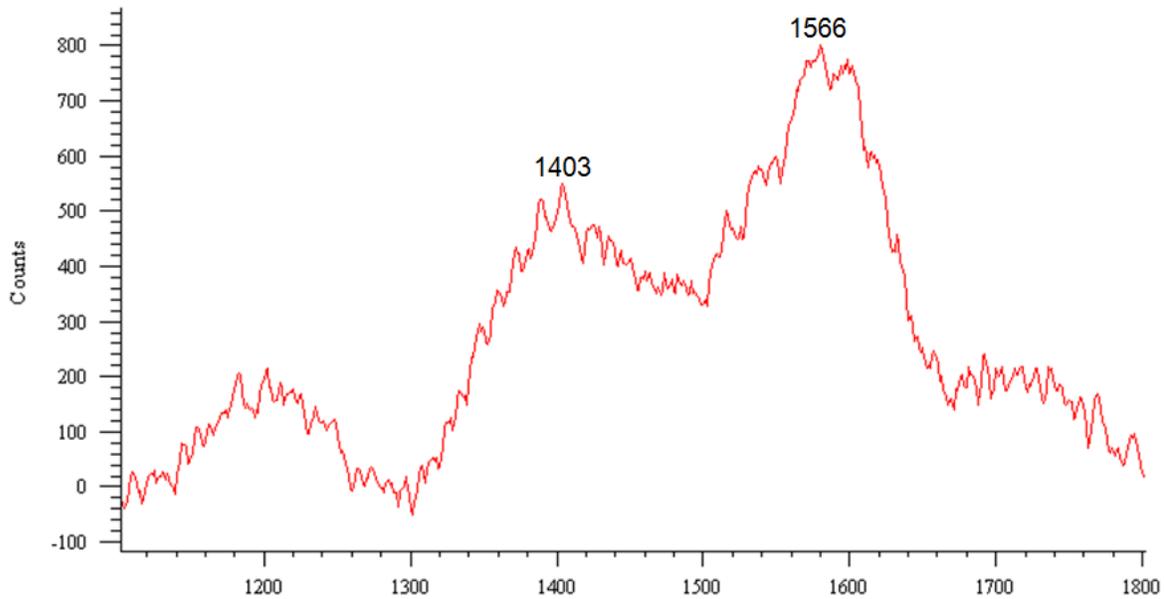


Figure 11: Raman spectrum of machined area in laser-cut PCBN with oxygen assist gas.

2.3.5. Water-jet

The coupling between the laser and water-jet produced a recast layer similar to that obtained using oxygen assist gas. At the same time, other reactions are expected to occur due to the presence of hydrogen in water. Hidaiw and Tokura [15] observed a c-BN reaction with water and steam in laser machining which produce NH_4^+ or $\text{NH}_4^+\text{-N}$ and boric acid. Products from these reactions are free to escape. However, the extent of oxidation was very severe because water reacts with sample material violently releasing gases and forming heavy recast layer (Figure 12). Even at low speed, there was an oxidized layer that resulted from high heat dissipation allowing the oxidized layer to form on the surface. The recast layer also increased the roughness. Furthermore the heat dissipation was so fast that the heat penetration (kerf depth) was quite low. Raman spectrum of the zones around laser-cut was mixture of those of oxygen and argon (Figure 13). Despite such drawbacks, easy mechanical separation after scribing was achieved. The phase transition (machined area) layer was very thin. In addition,

kerf and taper were attractive. The best candidate fluid between oxygen and water is found to be water because by virtue of its rapid quenching effect, the crack propagation was much better controlled. Furthermore, the sputtered particles below the recast layer were very insignificant.

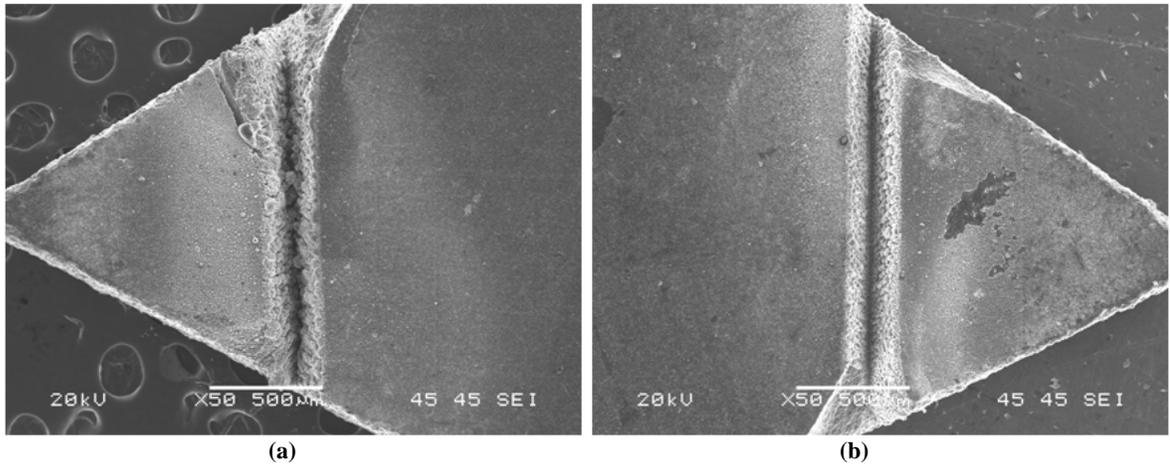


Figure 12: (a) Top views of the LWJ cutting area at 42.3 mm/s; (b) Top views of the LWJ cutting area at 84.6 mm/s.

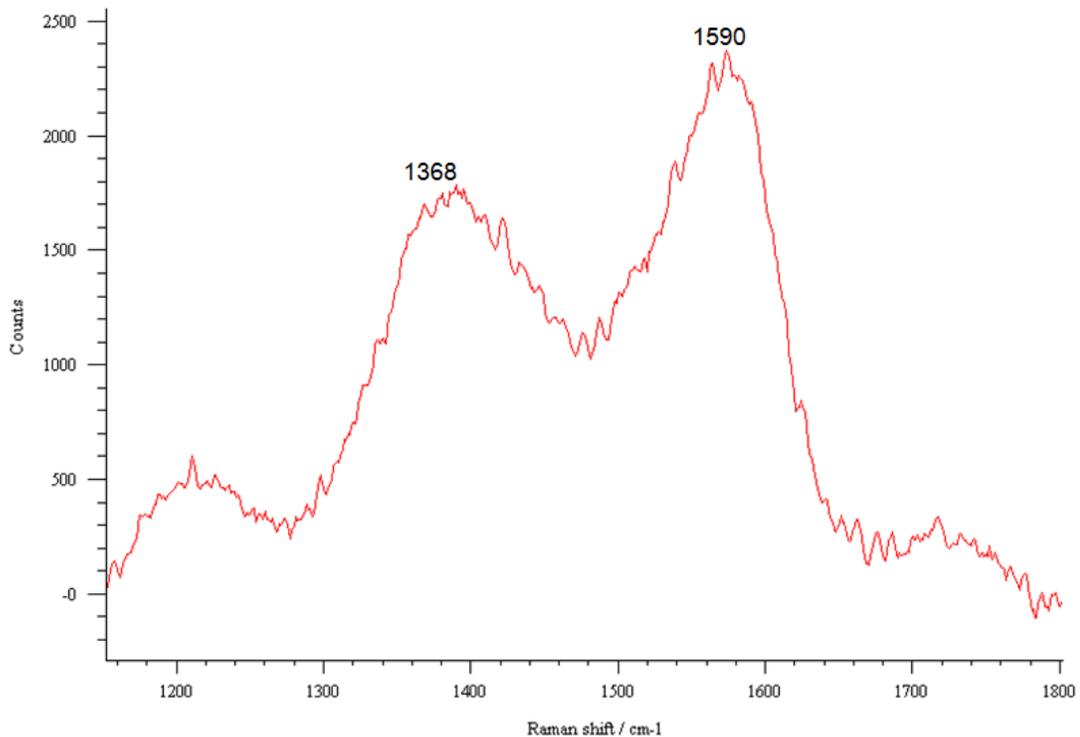


Figure 13: Raman spectrum of machined area in laser-cut PCBN with water as the assist fluid.

2.4 Summary

The effect of assist gas (Ar, N₂, air, O₂) and water in CO₂ laser machining of polycrystalline cubic boron nitride (75% c-BN and 25% Ti based matrix) was investigated. Different material removal mechanisms were observed depending on the type of fluid medium. Analysis of the observation revealed a two-step process consisting of: 1) phase transition of a thin surface layer of PCBN (melting, evaporation, oxidation (c-BN_{1-x} and B₄C) and phase change (h-BN and h-BNC)); 2) crack formation and propagation. In all cases, the cut surfaces can be characterized by two regions: machined area and cracked area (Table 2). The machined area had different phases of boron nitride while the cracked area retained the original c-BN structure (Figure 14). Argon enhanced the phase change but did not offer controlled fracture mechanism due to the explosion effects. Nitrogen, air and oxygen are more effective for removing material through ablation/evaporation. However, the surface roughness and unfavourable phase transitions do not make these assist gases suitable for the controlled crack separation mechanism. Water is an excellent candidate in producing very thin phase transition layer as well as controlled cracking. Optimization of LWJ process is in order to further improve the process.

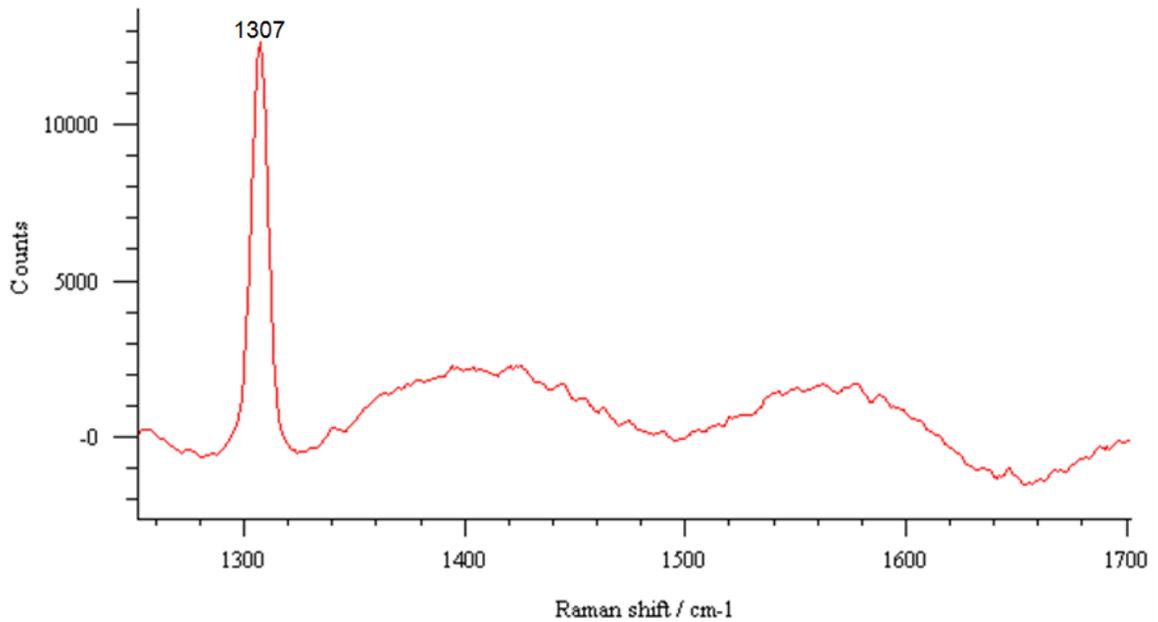


Figure 14: Raman spectrum of cracked area in laser-cut PCBN with water as the assist fluid.

Note, the broad peak around 1200 cm^{-1} , which has been detected only when using nitrogen and air, could be attributed to a new boron-doped phase [16]. Amorphous boron which has a peak around 1150 cm^{-1} , boron carbide which has a peak around 1251 cm^{-1} , or w-BN phase which has broad peaks around 1248 and 1106 cm^{-1} are the closest peaks to the unidentified peak [14]. These peaks are also under consideration to identify the broad peak around 1200 cm^{-1} since the shift in the raman peak can be affected by the presence of different impurities in the sample [14], the increase of temperature by the laser [17], the change of the crystallite size due to the phase transformation [17], and the induced stresses between the boundaries of the phases [17] which all occurred in our case. When using argon, oxygen, and water, this peak is very small and unidentifiable by the Raman program as a peak.

Table 2: Summary for the results of laser machined PCBN

Fluid	Machined area	cracked area
Argon	Shallow + Large affected zone	Rough + waviness
Nitrogen	Deep + Large affected zone	Rough
Air	Average + Large affected zone	Smooth
Oxygen	deep	Smooth + waviness
Water	shallow	Smooth

2.5 Acknowledgments

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CHAPTER 3: TWO-DIMENSIONAL CONTOUR CUTTING OF POLYCRYSTALLINE CUBIC BORON NITRIDE USING A NOVEL LASER/WATER-JET HYBRID PROCESS

A paper to be accepted by *The International Journal of Advanced Manufacturing Technology*

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Abstract

In the laser/water-jet hybrid machining (LWJ), a novel process applicable to brittle materials, the laser beam creates a groove through evaporation and causes solid-state phase transition through heating and shock waves while the water-jet performs quenching. Both laser and water-jet induce stresses and phase changes that lead to cutting via crack formation and controlled fracture mechanism through the rest of the thickness. While LWJ is very well documented by our group for one-dimensional cutting, it remains as a challenge for two-dimensional cutting because of the changing direction of the crack in relation to the laser beam path. In this paper, a focused continuous wave CO₂ laser (400 W) was combined with abrasive-free water-jet 0.4-1.4 MPa (60-200 psi) to generate and steer the controlled crack in two-directions in Polycrystalline Cubic Boron Nitride (PCBN) tool blanks. A 42.33 mm/sec (100 in/min) cutting speed was used in all the tests. The direction of the cracks generated by LWJ was changed to 60, 108, 120, 135 degrees and made to follow a curve with 1 mm radius

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in accordance with the standard tool shapes. The cut quality was investigated at the point of change in the crack direction using optical profilometer, Raman spectroscopy, and scanning electron microscopy (SEM). Results indicated that successful cuts were made with obtuse angles (120, and 135 degrees) in contrast to acute angles (60 degree). The crack propagation in the heat affected zone where the phase transition from c-BN to a new phase has occurred is responsible for the inability to obtain good quality cuts in the acute angle cases. A preliminary graphical representation that explains the observed experimental results is formulated.

Keywords: Two-dimensional cutting, cubic boron nitride, tool, laser, water-jet

3.1 Introduction

Polycrystalline cubic boron nitride (PCBN) is the second hardest material on earth with outstanding mechanical properties such as extreme hardness, high Young's Modulus, low coefficient of friction, and superior wear resistance. PCBN also offers greater thermal and chemical stability than polycrystalline diamond. These characteristics make PCBN as an ideal material for tool inserts used to machine hard cast iron, high chrome alloy steels, high-strength nickel super-alloy, and powder metal alloys. At the same time, these characteristics limit the ability to shape the PCBN tools for various geometries. PCBN is available in two forms: one is in the form of thin layer backed on tungsten carbide substrate and the other is in free form, solid cylindrical compact. Carbide backing provides the high impact resistance.

PCBN tool inserts are traditionally produced by cutting a master blank using wire-EDM and Nd:YAG, both of which suffer from deficiencies that in turn require finishing by diamond grinding, lapping, or polishing. PCBN tools having low electrical conductivity are

better cut by the laser than wire-EDM. However PCBN on WC substrate has sufficient electrical conductivity to be cut by wire EDM. The material removal rates in wire-EDM and Nd:YAG pulsed laser are low. Such processes also consume very high energy. Among these techniques, Nd:YAG laser cutting seems to be widely used because of the following benefits: high speed, precision, minimal thermal damage and flexibility. For example, a 300 W average power Nd:YAG laser is capable of cutting 1.6 mm thick PCBN 30 times faster than wire cutting [1]. The cut width was also three times narrower than achieved by wire cutting. The location error is on the order of few micrometers. The laser easily evaporates PCBN but the carbide substrate is more difficult to cut. Nitrogen gas assist was utilized to overcome this problem.

PCBN tool makers are seeking for novel material removal methods and mechanisms to overcome the deficiencies associated with traditional laser and wire-EDM cutting. Consequently hybrid machining processes were developed. Swiss Federal Institute of Technology in Lausanne, Switzerland has developed a Laser-Microjet® technology [2] that uses water to guide the Nd:YAG laser beam for machining of PCBN. Although it has a number of benefits, it still suffers from very slow cutting speeds and utilizes the same material removal mechanism as in traditional laser cutting. For example, it has been reported that it took 70 passes at the rate of 7 mm/min per pass to cut 3.25 mm thick PCBN blank [2].

Another potential approach is the use of dual laser beams that were effectively used to cut ceramics such as aluminum oxide through a controlled fracture mechanism [3]. The first laser beam is used to create a groove while the second laser beam is used to induce tensile stresses that can propagate the crack. While this mechanism offers the opportunity to solve the problems of laser cutting of PCBN, the high hardness and low thermal expansion

coefficient of PCBN limit the stresses required form the crack. Our group has recently developed a novel process of continuous wave CO₂ laser/water-jet (LWJ) to improve the machining of PCBN [4]. In this process, controlled fracture mechanism was utilized rather than energy-consuming evaporation mechanism as in laser cutting and taper-causing erosion mechanism as in water-jet cutting. LWJ process begins with rapid laser heating leading to localized damage and phase transformation of surface layers, followed by water-jet (fast quenching of the surface layers) resulting in a stress field in the transformed material. The stress fields propagate the localized cracks through the thickness where the end result is material separation. The controlled fracture mechanism led to the achievement of a complete cut through the thickness of the workpiece with less energy and time. LWJ is well proven for one-dimensional cutting of PCBN with the following benefits: very small kerf width determined by the size of crack, little taper, higher speed and minimal thermal damage.

The standard tool shape for PCBN is round. Other shapes such as rectangle, triangle, rhombus and square are less frequently used. In order to implement LWJ technique for PCBN tool blanks, it is imperative that LWJ should cut regular and irregular shapes needed for tool inserts. This implies that crack direction should be made to follow the laser beam path in contour cutting which remains as formidable challenge. In addition, PCBN backed on WC substrate poses difficulties in controlling the crack through the thickness. In this work, we have studied the effect of changing the direction of the controlled crack in LWJ process using four different angles commonly encountered in solid and WC-backed PCBN tool inserts. Accuracy, surface roughness and phase transformation around the corners were investigated.

3.2 Experimental Details

PCBN tool blanks were acquired from Diamond Innovations, Inc. (Ohio) both in solid and WC-backed forms. The thickness of solid form PCBN was 1.6 mm. The WC-backed PCBN had the following thicknesses: PCBN = 0.8 mm, WC = 0.8 mm; and PCBN = 0.8 mm, WC = 4 mm. The CBN content of the grades varied from 50% to 75% with additives and binders like TiN, AlN, Ti-matrix etc. Higher CBN content provides increased fracture toughness, resistance to abrasion and higher thermal conductivity.

Figure 15 shows the LWJ head where the nozzle at the bottom left shows two holes. The central hole is to pass the laser beam while the smaller hole is to transmit the water. The nozzle is configured such that the laser beam is ahead of the water-jet by 2 mm under focused condition and 6 mm under defocused condition to prevent the direct interaction of the laser beam with the water-jet stream. The tool blank was held on a fixture mounted on a cutting box and made to move by a positioning table in X-Y plane. The laser head can also be rotated such that the beam and water-jet are made always in tandem. A continuous wave CO₂ laser of 10.6 μm wavelength and 400 W power was used in all experiments. The laser beam was focused to a spot size of 0.2 mm on the sample surface using a 127 mm focal length lens. In one set of experiments of PCBN on thin carbide substrate, multiple passes were performed; the laser beam was focused in the first pass, and then defocused to a spot size of 0.5 mm in the other passes. The water-jet followed the laser beam in the focused mode with a spacing of 2 mm to avoid the absorption of laser power by direct contact with water. The spacing was increased to 6 mm in the last set of experiments of the defocused passes for the same reason. The water-jet pressure in the experiments was 1.4 MPa (200 psi) and 0.4 MPa (60 psi) for solid PCBN and WC-backed PCBN substrate respectively. The air

was flown with the laser beam at a pressure of 35 kPa (5 psi) to keep the lens from contamination with water. The angles used were 60, 108, 120, and 135 degrees typical of common insert angles. All the angle cuts were performed by turning the LWJ head while moving the sample. The 60 degree cut was also performed by making intersection between two straight line cuts.

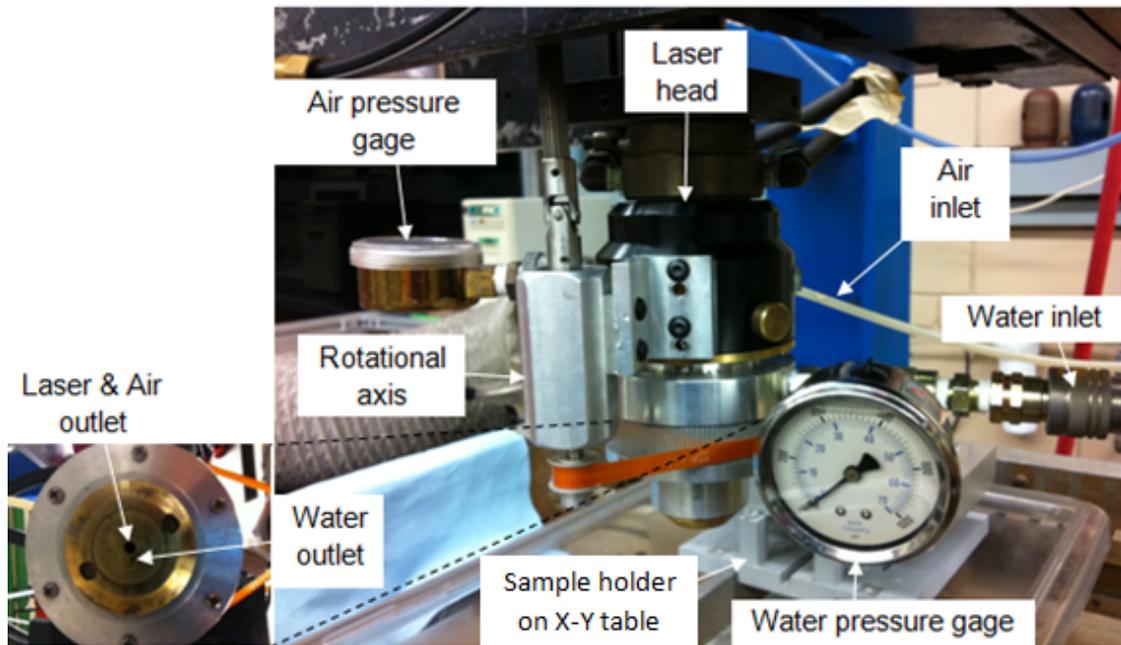


Figure 15: Laser head description with the assist fluid inlets and outlets.

Scanning electron microscopy (SEM Model JEOL JSM-606LV at 20 kV) was used to obtain secondary electron images of the cut surfaces in order to analyze the machined and cracked regions before and after the turns. The kerf geometry and the surface roughness were analyzed using optical profilometer (Zygo NewView 7100) with 5X and 20X magnifications. The extent of phase transition around the corners and intersections were examined using Dispersive Raman spectroscopy (Renishaw-inVia Raman Microscopy) with Ar-ion laser at 488 nm wavelength.

3.3 Results and Discussion

In the investigation of the two-axis cutting of PCBN, the governing factors for the successful cutting of the free-standing PCBN samples are phase change and turning point position. For PCBN samples, backed with carbide substrate, there are three additional factors: carbide substrate thickness, thermal characteristics of WC, and water-jet pressure.

3.3.1. LWJ cutting of free-standing PCBN segments

Cuts of 120 and 135 degree angles were performed successfully on free-standing PCBN segments (50% c-BN, 50% Ti matrix) with 1.6 mm thickness (Figure 16). The transverse section of LWJ cut typically contains a shallow machined region that is close to the surface, and a cracked region throughout the rest of the thickness; this is typical of what was observed in one-dimensional cutting [5, 6]. Each region has different cut qualities. The surface of the cracked area exhibited a low waviness at the bottom, and a roughness that is almost the same before and after the turn, with an average $R_a = 8 \mu\text{m}$ (Figure 16). The waviness could be attributed to the small distance between the laser path and the cracked path which cause crack instability which will be shown later in the model formulation section. The taper angle, in the machined area, was 15 degrees along the cut; before and after the turn. However, in the cracked area, the taper angle was different after the turn. It was 0 degrees before the turn, but it started as 30 degrees after the turn and then reduced to 0 degrees along the cut (Figure 16). This behavior will be explained in the model formulation section as well.

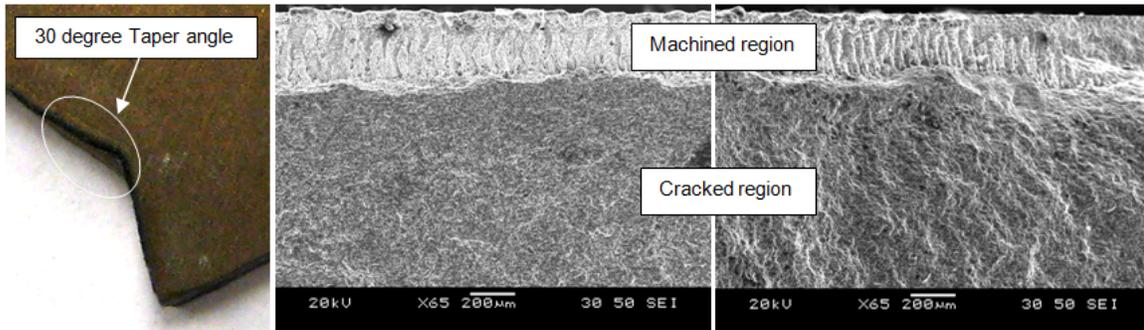


Figure 16: On the left, a taper angle appeared after a 120 degree turn on free standing PCBN sample. In the center, a SEM image of the transverse section of PCBN before the turn in LWJ cutting. On the right, a SEM image of the transverse section of PCBN after the turn in LWJ cutting.

In addition, an attempt to make a curve with a 1 mm radius was performed successfully. The cut quality was the same as those of 120 and 135 degree angles, except for the absence of a corner. Consequently, there was no taper angle in the cracked area at/around the curve; however, the taper appears after the curve (Figure 17). This taper is a result of the turning point position and not the turning itself, since the taper started to form at some distance after the curve. When the turning point position is close to the edge, the crack tends to deviate from the laser beam path and takes a shorter path to the edge.

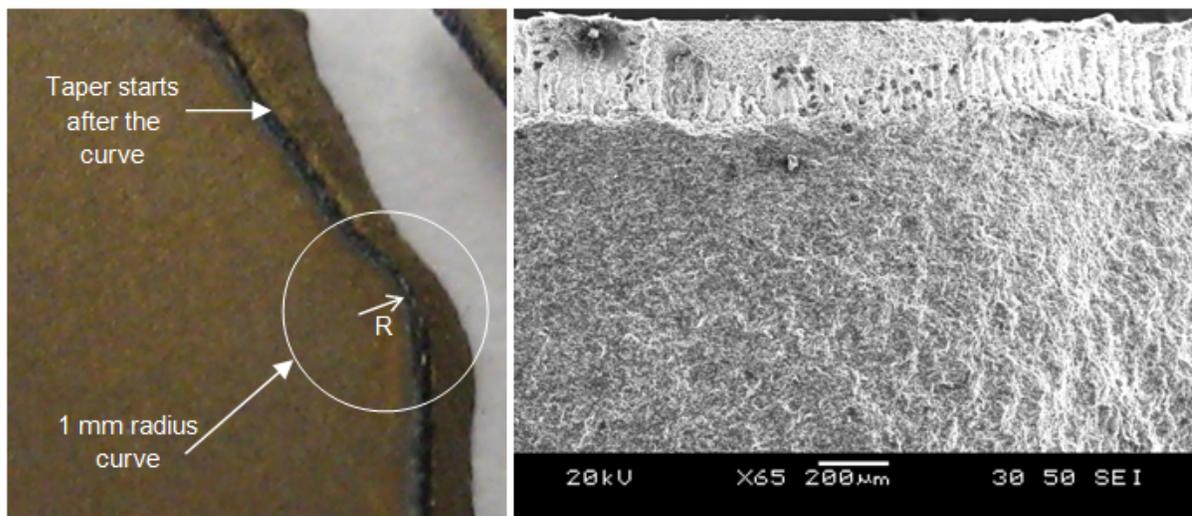


Figure 17: In the left, angular top view of LWJ cut of a curve with 1mm radius on free-standing PCBN sample showing the taper. In the right, a SEM image of the transverse view of the turn.

The attempt to cut at 108 degrees on a segment with the same composition produced a groove only. In other words, the groove was performed in two-axis, but the crack did not propagate through the third dimension, thickness. Another trail to cut a 108 degree angle with a turning point position close to the sample edge was performed. The crack propagated through the thickness before the turn and when it reached the turning point, the crack propagated in an uncontrolled fashion to the sample edge (Figure 18).

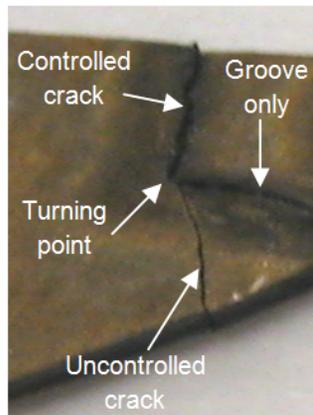


Figure 18: An uncontrolled crack propagated at the turning point when the turn is close to the edge.

The attempts to produce 60 degree cuts were also unsuccessful. Turning the cut to acute angle seems to produce a lot of heat which destroys the sample with uncontrolled fracture to small pieces. Therefore, the 60 degree angle was performed in an alternative fashion by performing an intersection between two straight line cuts. In this trail, the first line cut was all the way through as expected, but the second line did not cut all the way through because the laser beam was passed over the heat affected area from the first cut suggesting the important role played by phase transition. A groove of varying depth was created along the second cut (Figure 19). Another experiment was performed to further prove this result, in which two parallel straight grooves were made so that their heat affected zones overlap, then

a third straight groove was made perpendicular to the parallel lines. The third groove line was shallow at the overlap of heat affected zone (Figure 20).

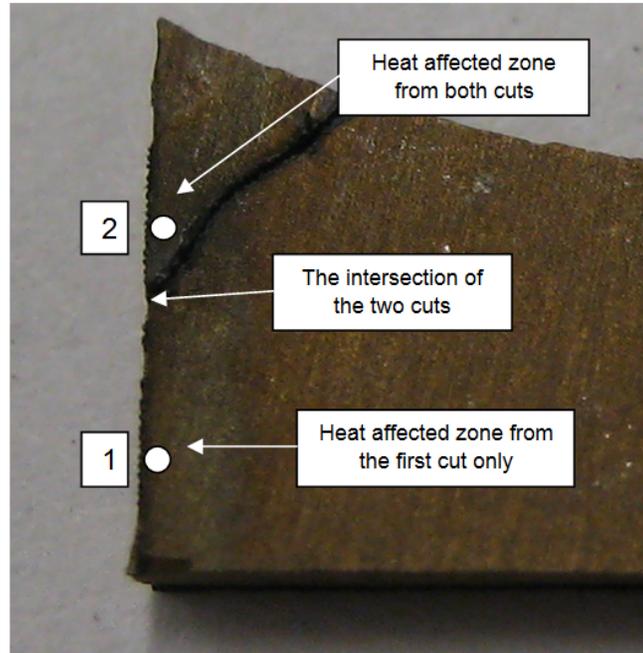


Figure 19: An intersection of two straight line cuts where the first line cut the free standing PCBN sample while the other line did not propagate through the whole thickness due to the phase change effect.

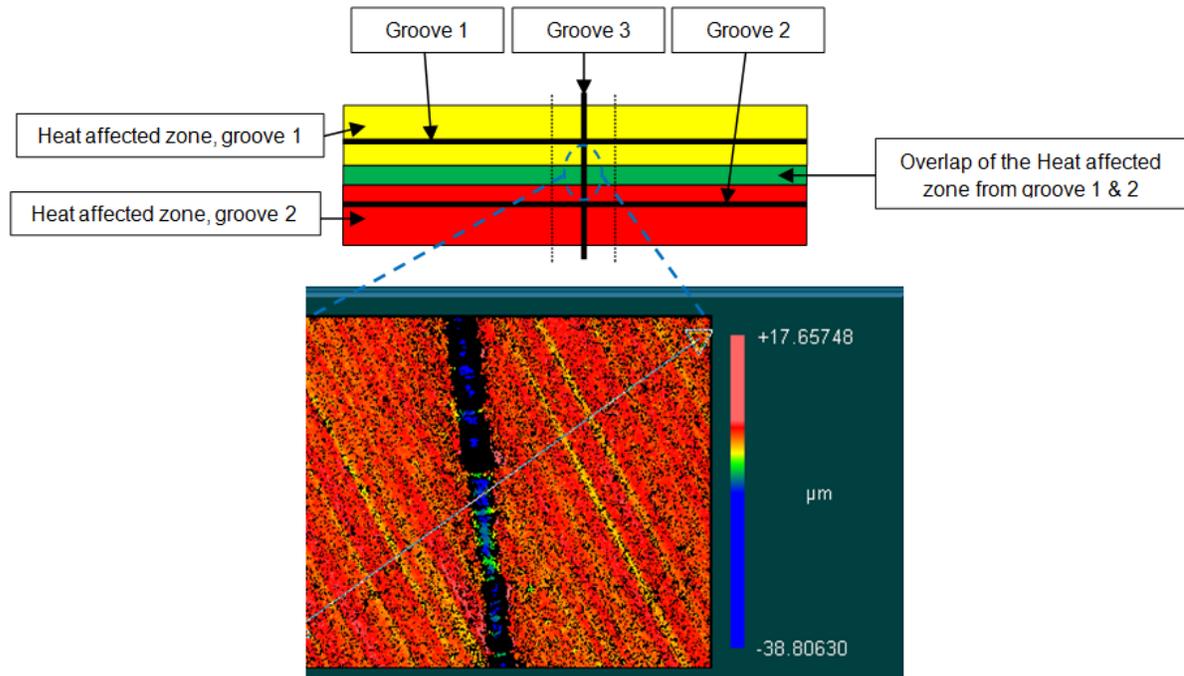


Figure 20: Optical profilometer trace showing the change in depth of the third groove.

It is clear from this experiment that the extent of phase change has a huge effect on the groove depth which in turn controls the initial crack length needed to propagate the crack through the thickness. This means the phase change plays a vital role in the ability to turn a crack in the LWJ process. Turn cuts up to 108 degrees are not possible because of the overlap between the heat affected zones of the two sides of the angle. Inside the area between these lines, the phase change is enhanced that in turn prevented the crack from taking the turn.

Let us now understand the four main different phases associated with BN: hexagonal (h-BN), rhombohedral (r-BN), cubic zinblende (c-BN), and wurtzite (w-BN) depending on the pressure and temperature (Figure 21). Both h-BN and r-BN have layer structures (sp^2 bonding) and lower densities compared to c-BN and w-BN (sp^3 bonding). Although it was accepted for a long time that h-BN is the most stable structure at ambient conditions, recent experimental investigations and *ab initio* calculations affirm that c-BN is the most stable structure at ambient conditions [7]. Using the Raman spectroscopy, we identified phase changes from c-BN to all phases in LWJ samples. An increase in a new phase (1198 cm^{-1}) is particularly noted in the acute angle area (Figure 22 and 23). This increase in the new phase at the corners can be attributed to the high pressure emerging from the transformation of c-BN to the h-BN phase before and after the turn, and the additional heat at the corner, due to the long laser exposure in that area. This new phase can be attributed to a new boron-doped phase which has a peak around 1210 cm^{-1} [8] or amorphous boron which typically has a peak around 1150 cm^{-1} since the shift of these peaks can be explained by the presence of different impurities in the sample [9], the increase of temperature by the laser [10], the change of the crystallite size due to the phase transformation [10], and the induced stresses between the boundaries of the phases [10] which all occurred in this experiment. It may be

noted the composites of c-BN and w-BN exhibit higher fracture toughness in the range of 13 to 16 MPa m^{1/2} compared to 7 MPa m^{1/2} for c-BN [11]. Consequently the critical initial crack length for propagation needs to be much longer. Hence, it can be argued that the propagation of a crack through the new phase will be much more difficult. Thus it may be concluded that increasing the cutting angle will decrease the transformation to this new phase at the corner and produce a nicer cut.

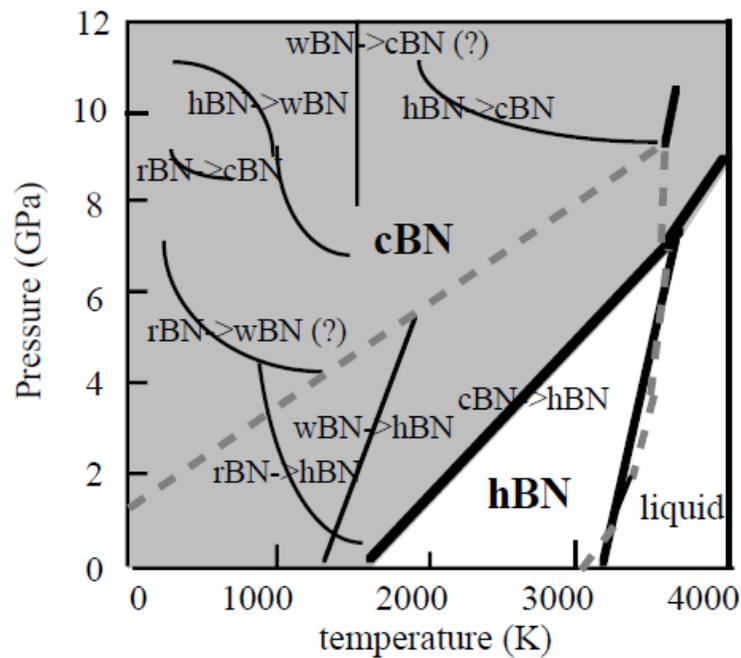


Figure 21: Phase diagram of BN (Source: Reference 7 in chapter 4)

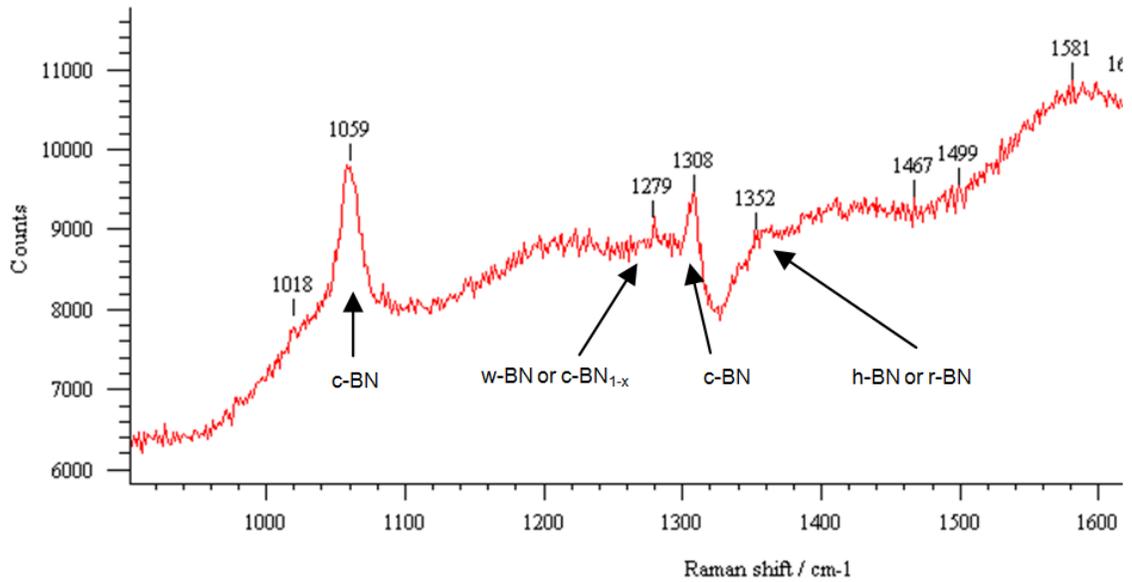


Figure 22: Raman spectrum at point (1) in Figure 5 where different peaks of different phase can be observed (c-BN_{1-x}, c-BN, h-BN, w-BN and r-BN)

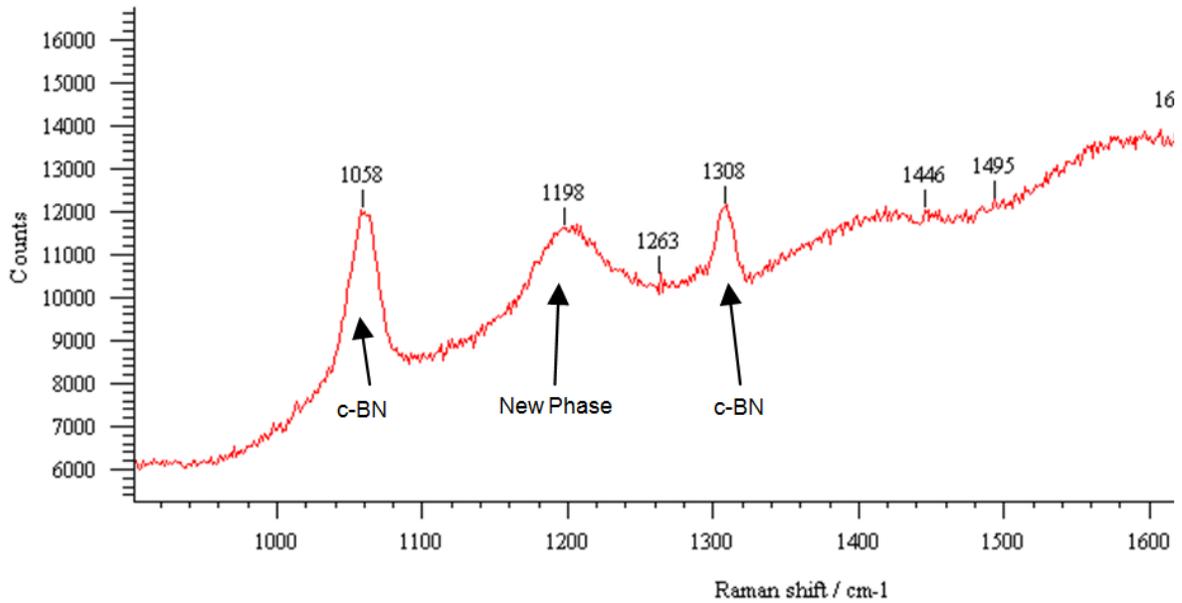


Figure 23: Raman spectrum at point (2) in Figure 5 where different peaks of different phases can be observed like in point (1); the peak at 1198 cm⁻¹ is attributed to a new phase.

3.3.2. LWJ cutting of PCBN backed with carbide substrate

In the case of two-axis cutting of PCBN on thin carbide substrate (PCBN thickness = 0.8 mm, carbide substrate thickness = 0.8 mm) with controlled fracture, the crack propagates through the whole thickness after multiple passes (4 passes) of the defocused beam followed with water-jet, and 120 degree angle cut was successfully performed (Figure 24). In this cut, the surface roughness, waviness, and taper angle were different before and after the turning point. Before the turning point, the average surface roughness in the cracked area and the carbide substrate area was $R_a = 4 \mu\text{m}$ with no taper. In the machined area before the turn, the machined surface was chipped off at the top, which added more taper to the machined area. At the turn, the whole surface was chipped off, which provides a low surface roughness ($R_a = 4 \mu\text{m}$) with no corner (Figure 24 and 25). After the turn, the machined area had an average surface roughness $R_a = 9 \mu\text{m}$ with a 15 degree taper angle. The PCBN cracked area, after the turn, had a very high waviness while the carbide substrate cracked area had low waviness (Figure 24).

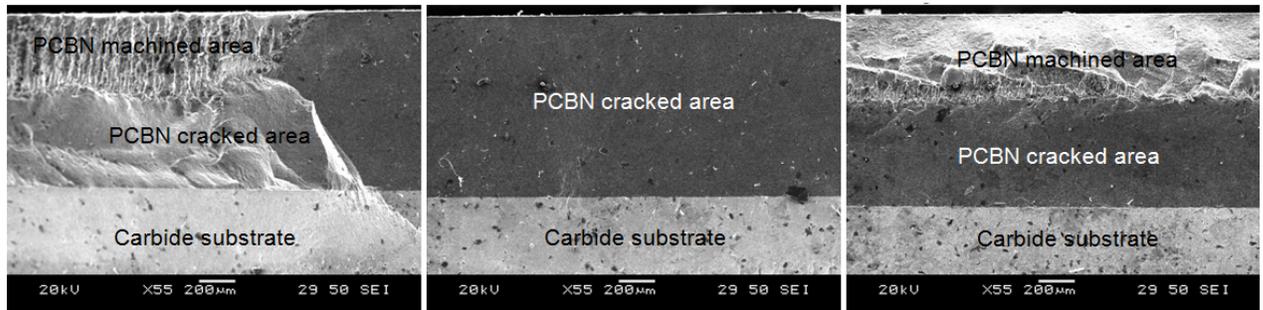


Figure 24: SEM images of LWJ cuts of PCBN on thin carbide substrate. Before the turn (right), the PCBN and the substrate cracked areas have low surface roughness values and almost no waviness while the machined area with multiple passes has high values of surface roughness. At the turning point (middle) only cracked surface with low surface roughness values. After the turn (left), high surface roughness and waviness in the cracked and machined areas.

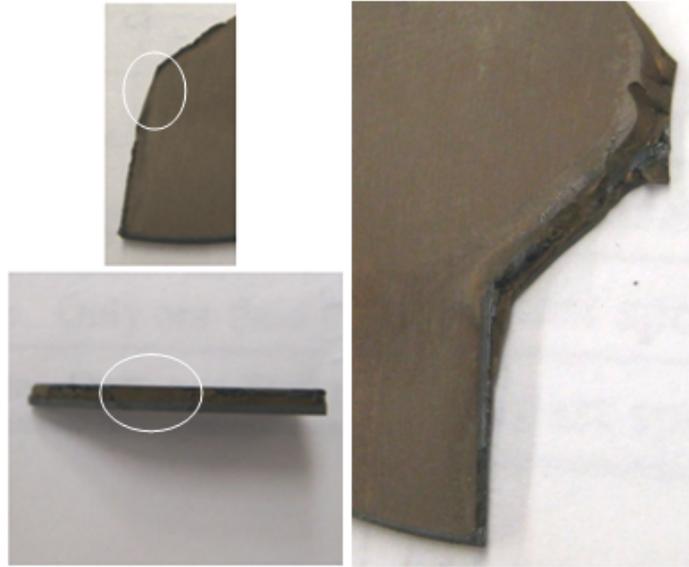


Figure 25: On the left (top), top view of a 135 degree angle cut where the crack turned before the laser beam turning point, (bottom) transverse section of the cut shows the chipped area around the turning point in the circle. On the right, a taper angle appeared after the turn on PCBN for carbide substrate sample.

The crack in the cutting of thick carbide substrate (PCBN thickness = 0.8 mm, carbide substrate thickness = 4 mm) did not propagate through the thickness. In addition, there were lateral cracks along the whole cut (Figure 26 left). Reducing the water-jet pressure from 200 psi to 60 psi (the minimum) reduced the lateral cracks, but did not eliminate them. Multiple defocused passes with the water-jet were performed until the PCBN around the cutting area was destroyed completely by lateral cracks, yet the crack did not propagate through the carbide substrate. Thus, PCBN backed with thick carbide substrate is not suited for LWJ process.

Even in the LWJ cuts of PCBN on thin carbide substrate, the cut was only attractive for about the first half inch and then the crack became uncontrolled with appearance of lateral cracks (Figure 26 right). This could be attributed to the built-up temperature in the carbide substrate and its effect on the interface between the PCBN and the carbide substrate.

The heat produced by the laser will transfer to both materials while the heat conductivity and the heat expansion coefficient of PCBN and the carbide substrate are different. This will accumulate the heat in the carbide substrate making it like a heat sink. This accumulated heat will expand the carbide more than the PCBN creating a high tension in the PCBN. This high tension creates the lateral cracks on the PCBN side.

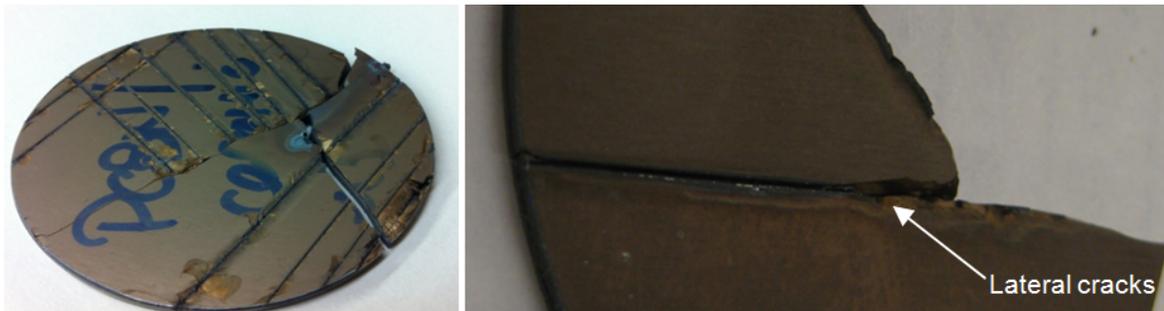


Figure 26: On the left, LWJ on PCBN blank with thick carbide substrate where extensive lateral cracks can be observed. On the right, a complete straight cut of PCBN blank with thin carbide substrate where the cut was controlled for half inch then become uncontrolled and lateral cracks start to appear from the built up temperature in the carbide substrate.

3.3.3. The model formulation

In LWJ machining, when the laser beam impinges the surface material, it starts to transform to h-BN and causes an increase in volume; this will make compressive stresses around the initial crack. When the water-jet acts on the material, the laser heated area will start to shrink due to the quenching effect around the h-BN which will change the stresses to tensile mode around the initial crack. This will allow the crack to propagate and move a distance away from the laser spot. After the crack propagates through the thickness, residual stresses will be left along the crack tip since no phase transformation occurred deep inside the material but a new surface is generated (Figure 27).

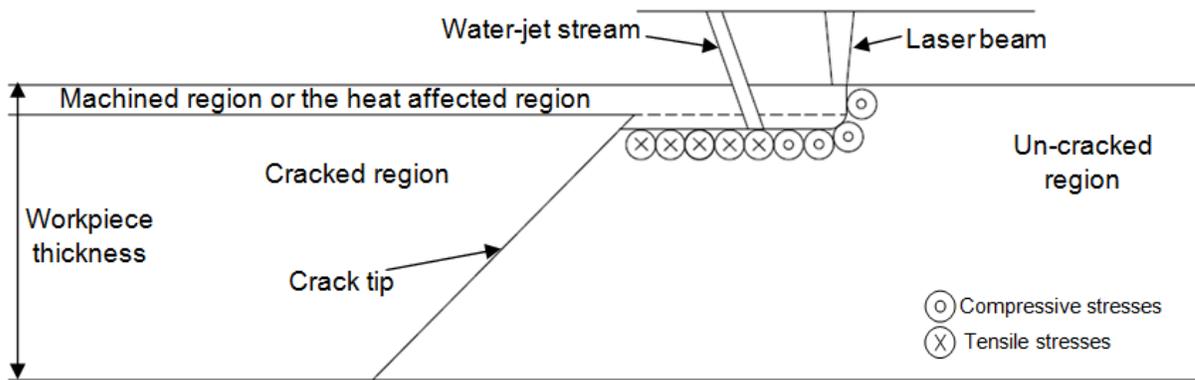


Figure 27: Schematic representation for LWJ machining for a straight line. The big circles represent the stress field inside the material; small circles (compressive) and cross (tensile).

Therefore, when making a turn with the LWJ head, the crack tip will not follow the laser beam path. It will make the turn right away, which will create the observed taper. The phase transformation to the new phase around the corner requires a longer crack size to propagate the crack through it. So, the crack tip will make a shorter path to the laser beam path and reconnect with it after it passed the new phase area (Figure 28).

In order to prove this hypothesis, we conducted the following experiment; PCBN segments (65% c-BN, 35% TiN) with 1.6 mm thickness were used to make a groove with a 135 degree angle using LWJ. In this case, the sample was snapped by applying a small bending force (by hand) to see whether the crack path follows the groove path with no taper. The crack actually propagated in a longer distance path due to the direction of the applied force. However, it did not go through the area of rich new phase, which confirms the model (Figure 28).

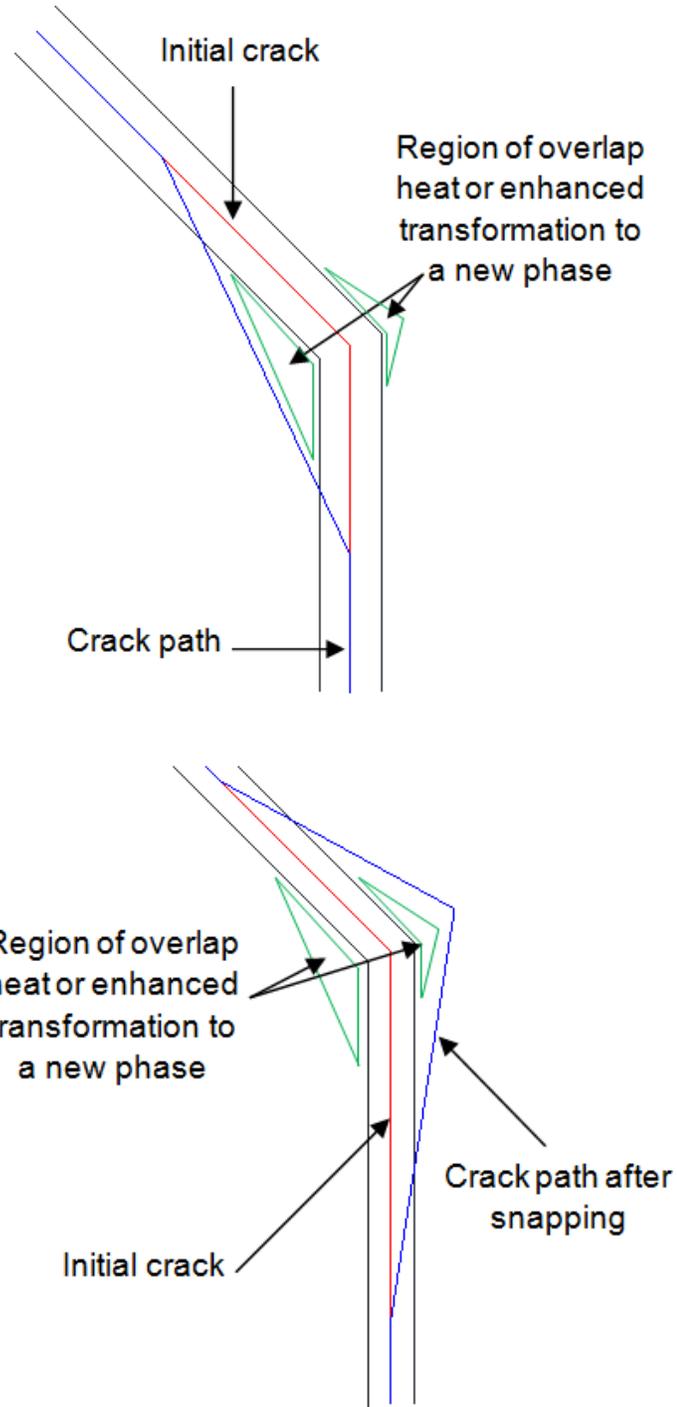


Figure 28: Schematic representation for LWJ machining at the turning point (top view). On the top, the model is for complete separation using LWJ machining on PCBN. On the bottom, the representation is for a groove made on PCBN using LWJ and a complete separation is then performed by snapping the sample.

The change of taper angle and waviness after the turn in the obtuse angle can be explained as shown in Figure 29. In the case of small thickness, the distance between the crack tip and the laser beam spot will be smaller; this will reduce the taper angle and the waviness. In other words, the sample thickness and the distance between the crack tip and the laser beam are limitations in two-dimensional LWJ cutting.

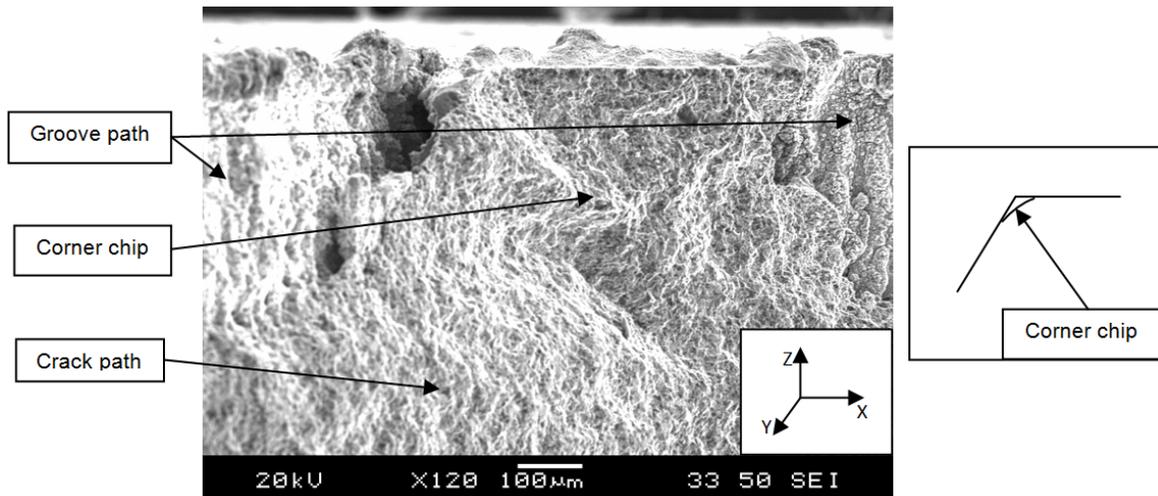


Figure 29: On the left, SEM image of the transverse section of the corner in LWJ cut which shows the crack path and groove path. On the right, schematic top view shows the corner chip due to the mismatch between the groove path and the crack path at the corner.

3.4 Conclusion

Two-dimensional cutting with 120 and 135 degrees have been successfully conducted on PCBN tool blanks using LWJ. Also, 1 mm radius cut was performed which means that the contour cutting is possible. Multiple passes of defocused laser beam can propagate the initial crack of PCBN samples on thin carbide substrate to provide a complete cut. The cut geometry and roughness are acceptable before the turn. After the turn there are some problems with taper and waviness in the cracked area. However, PCBN samples on thick

carbide substrate resulted in numerous lateral cracks making the process limited to only thin carbide substrates.

The governing parameters for the successful two-axis cutting with controlled crack propagation mechanism of PCBN using LWJ were phase change, turning point position, sample thickness, substrate thickness, substrate thermal characteristics, and water-jet pressure. A preliminary qualitative model of the two-axis cutting with controlled crack propagation mechanism confirms the observations.

3.5 Acknowledgments

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CHAPTER 4: GENERAL CONCLUSIONS

Conclusion

The development of machining technologies for shaping of PCBN cutting tools is critical to numerous industries, since tools made from PCBN are among the best performance cutting tools. Electric Discharge Machining (EDM) and Nd:YAG pulsed laser as the current machining processes for machining PCBN suffer from thermal damages and time consumption. The LWJ system is a novel machining process that can overcome these deficiencies by using controlled fracture mechanism. In the past, however, LWJ was used to cut straight lines only since directional change of the crack remained as a challenge. In addition, the potential of water as the best possible fluid medium for PCBN remained unknown. In this work, an investigation was undertaken to study: 1) the effect of different fluid media on the phase transition in the straight-line cutting of PCBN; 2) the crack propagation with different angles of cutting to shape the PCBN tools for various geometries. The primary results and conclusions are as follow.

Among all the fluid media, water has the most effect in enhancing the phase transition in PCBN. Different phases and cut qualities were observed depending on the type of fluid medium (Ar, N₂, air, O₂, and water). Argon enhanced the phase change to the h-BN phase but did not offer a controlled fracture mechanism due to the explosion effects. Nitrogen was more effective for removing material through ablation/evaporation, which creates deeper grooves. Nitrogen, however, reduced the cut quality. When using air and oxygen, surface roughness and phase transitions were unfavorable. Water, on the other hand, was an excellent candidate in producing very thin phase transition layer, as well as controlled cracking.

In the two-dimensional contour cutting, the governing factors of controlling the change in crack direction were identified as the phase change, turning point position, sample thickness, substrate thickness, substrate thermal characteristics, and water-jet pressure. Contour cutting at 120 and 135 degree angles had been successfully accomplished by a careful control of water-jet pressure and laser power on free-standing PCBN. A curve cut with 1 mm radius was also successfully performed. PCBN backed by thin carbide substrate, multiple passes of LWJ with defocused laser beam were utilized to propagate the initial crack on PCBN samples for a complete cut. The cut geometry and roughness were acceptable before the turn. However, after the turn, there were problems with taper and waviness in the cracked area. PCBN backed on thick carbide substrate resulted in numerous lateral cracks, making the process unsuitable. A preliminary qualitative model of the two-dimensional cutting with controlled crack propagation mechanism was postulated to validate the experimental observations.

The work conducted in this thesis identifies the limitations and the benefits of LWJ machining of PCBN cutting tools. Since acute angles cannot yet be cut, the useful application of LWJ system, as of now, stands limited to the cutting of round PCBN inserts.

Future work

- *Investigating Nitrogen as an assist gas in laser machining of PCBN.*

From the work conducted in Chapter 2, nitrogen seems to help the laser beam penetrating deep in the PCBN by enhancing the ablation. This shows a potential for nitrogen assist in cutting thicker PCBN tools (4.8 mm thick of free-standing PCBN)

- *Developing a rigorous mathematical model for predicting the crack changing angle in 2D cutting.*

Even though the work in chapter 3 shows potential for round inserts only, the study should be extended to verify the model mathematically since the relationship between the critical thickness and the distance between the crack tip and the laser beam should be developed. This relationship could affect the LWJ process in a number of ways. For example, the distance between the laser beam and the crack tip has a considerable effect on the taper and waviness after the turn.

- *Modeling the propagation of the initial crack due to multiple passes.*

Modeling the propagation of the initial crack due to multiple passes shows a potential to improve the cut of acute angles. In cutting PCBN with thin carbide substrate, the initial crack length from the first LWJ focused pass was extended by multiple passes of LWJ with defocused beam to the critical crack length, which made the material separation. Since the depth of the cut varied in each of the acute angles, which were made by the intersection of two cutting lines, multiple passes of defocused beam could bear the solution.

- *Extending this work to cover non-conductive PCBN and Polycrystalline Diamond (PCD) samples.*

EDM technique does not work for non-conductive PCBN and PCD. Both materials also encounter the same problems as PCBN: thermal damages and low speed cutting using the Nd:YAG conventional laser machining. Therefore, LWJ must be explored.

- *Enhancing the PCBN tool inserts by LWJ heat treatment.*

The application for LWJ system can be extended to heat treatment purposes because of the phase transition from c-BN to the new phase discussed in chapter 3. Such a phase transition will lead to improved toughness required for the interrupted machining (like milling) using PCBN tools.