JMEPEG (2004) 13:398-405
DOI: 10.1361/10599490419900

1059-9495/$19.00

Ion Implantation of Superhard Ceramic Cutting Tools

Y. Kevin Chou and Jie Liu

(*Submitted February 10, 2004*)

Despite numerous reports of tool life increase by ion implantation in machining operations, ion implantation applications of cutting tools remain limited, especially for ceramic tools. Mechanisms of tool-life improvement by implantation are not clearly established due to complexity of both implantation and tool-wear processes. In an attempt to improve performance of cubic boron nitride (CBN) tools for hard machining by ion implantation, a literature survey of ion-implanted cutting tools was carried out with a focus on mechanisms of tool-wear reduction by ion implantation. Implantation and machining experiments were then conducted to investigate implantation effects on CBN tools in hard machining. A batch of CBN tools was implanted with nitrogen ions at 150 keV and 2.5 × 10^{17} ions/cm^2 and further used to cut 61 HRc AISI 52100 steel at different conditions. Results show that ion implantation has strong effects on part-surface finish, moderate effect on cutting forces, but an insignificant impact on tool wear. Friction coefficients, estimated from measured cutting forces, are possibly reduced by ion implantation, which may improve surface finish. However, surprisingly, 2-D orthogonal cutting to evaluate tribological loading in hard machining showed no difference on contact stresses and friction coefficients between implanted and nonimplanted CBN tools.

Keywords cubic boron nitride, friction, hard machining, ion implantation, surface finish

1. Introduction

Due to increasing concerns about protecting the environment, manufacturing technologies that generate waste or cause any ecological impact have been critically evaluated in industry for process alternatives. Grinding is a traditional finishing operation for precision components; however, this process is not environmentally benign and costly in some applications. In contrast to machining that has well-defined cutting geometry, grinding employs randomly shaped/oriented grits, bonded around a wheel core, to cut materials. Thus, grinding is always associated with low material removal rate, high-energy consumption, and the need of coolant, a waste source. With development of advanced ceramics, i.e., superhard cubic boron nitride (CBN), machining hardened steel (>55 HRc), a term known as hard machining in industry, has been studied to offer an alternative to grinding.[1] With two decades of research, although hard machining using CBN tools has been used to replace some rough grinding, its use of hard machining remains limited due to short tool life and relatively high tool cost, especially in finishing. Thus, improving CBN tool performance has been one of the keys to widen adoption of hard machining. This research investigated ion implantation of CBN tools for finish hard machining. The intent was to partially transform CBN to hexagonal boron nitride (HBN), a solid lubricant, at the tool surface and thus modify tribological conditions in machining.

Ion implantation involves bombardment of high-energy ions into the workpiece surface layer to form metastable nanostructures, which usually have high hardness and properties that could not be otherwise obtained.[2] The depth profile of implanted ions usually ranges from several nanometers to a few hundred nanometers, depending primarily upon the ion species, ion energy and dose, and target materials. Implanted ions will alter chemical composition and cause violent microstructural changes in the implanted zone. Moreover, due to radiation-enhanced segregation and diffusion, the region of microstructural changes such as point defects and dislocation loops can extend far beyond the implanted area, resulting in the implantation-affected zone in the order of microns. The substantial changes of chemical, mechanical, and microstructural properties of the implanted surface in turn modify tribological characteristics. Advantages of ion implantation include such factors as no dimensional change, functional gradient properties, no adhering issue, and low process temperature. However, there are also limitations in ion implantation, e.g., shallow implanted zones, restricted peak concentration, and a line-of-sight process.

Ion implantation has been widely used in wafer fabrication in the semiconductor industry. It has also been used in wear-resistance applications, including mechanical components as well as biomedical applications such as surgical prostheses. In addition, metalworking tooling has also embraced ion implantation for tooling improvement. Beginning in the mid-1980s, researchers started to explore ion implantation as a method for improving cutting tools for machining. Numerous studies have reported significant tool-life increases. A body of literature (more than 50 references) exists on high-speed steel, cemented carbide, and coated tools, but only few on ceramic tool materials. Nevertheless, structural ceramics have recently been implanted for tribological applications. Following is a review of ion implantation of cutting tools and ceramics. The purpose is to identify mechanisms of tool-life improvement by ion im-

This paper was presented at the 2nd International Surface Engineering Congress sponsored by ASM International, on September 15-17, 2003, in Indianapolis, Indiana.

Y. Kevin Chou and **Jie Liu**, Mechanical Engineering Department, The University of Alabama, Tuscaloosa, AL 35487. Contact e-mail: Kchou@coe.eng.ua.edu.

plantation and serve as a reference for future studies of ion implantation for cutting tools.

2. Literature Review

2.1 High-Speed Steel

Different types of high-speed steel tools, mostly M2, have been investigated for ion implantation.[3-11] Typically, nitrogen ions were implanted with a few cases using carbon (C).[9,11] Implanted ion energy ranged from 5 to 200 keV, and dose from 1×10^{17} to 4×10^{18} ions/cm^2. Moreover, with advancement of implantation technology, plasma-source ion implantation has also been used for high-speed steel tools,[8] especially beneficial to complex tool geometry. Implanted high-speed steel tools have been tested in different machining operations such as turning, drilling, and sawing. Tool-life increase, evaluated by tool wear land, has been consistently reported, and in some cases a 200% increase of tool life can be achieved.[8] The mechanisms of tool-wear reduction has been attributed to two factors: (1) increased microhardness due to formation of complex hard nitride (ε-$Fe_{2+x}N$ and γ'-Fe_4N) in the implanted layer[10] (2) reduced friction due to precipitation of elementary C substance.[9] Mändl et al.[10] observed the implantation-affected zone, called hard diffusion layers, to a depth of about 25 μm, which may sustain the implantation effect. Furthermore, Woods and Lambert[8] indicated that during cutting, implanted species may migrate into a deeper zone due to thermomechanical loading and, thus, retain implantation effects even after the implanted layer has worn out. Yan et al.[9] claimed increased toughness by implantation by formation of amorphous structures embedded with nanocrystalline carbides that may also improve wear resistance. Jährling et al.[11] reported, in the carbon implantation, that formation of ε-carbides in the implanted surface may change tool-wear mechanism from adhesion to abrasion. Other than tool-wear reduction, Onikura et al.[5] also indicated that ion-implanted high-speed steel tools can improve part quality: accuracy and surface finish, probably due to lower cutting forces. On machining parameter effects, Woods and Lambert observed that implanted tools would perform better only at low or medium cutting speed;[8] however, contradictorily, Bradbury et al. reported that ion implantation effects would be more effective at high cutting speed.[6]

2.2 Cemented Carbides

Several research groups have investigated ion implantation of cemented tungsten carbide tools.[12-19] A variety of ion species have been implanted, including metallic ions [magnesium (Mg), aluminum (Al), titanium (Ti), nickel (Ni), tungsten (W), etc.] as well as nonmetallic [C, nitrogen (N), fluorine (F), chlorine (Cl), bromine (Br), etc.], and in some examples, dual ions have also been used. Ion energy used to implant cemented carbides ranged from 30 to 150 keV, and the ion dose is generally on the order of 10^{17} ions/cm^2. Reports show that ion implantation increases tool life in a wide range, from 50% to four times in machining of different work materials, primarily steel and titanium alloys. Different hypotheses have been proposed to explain tool-life increase. Radiation-induced dislocation networks and hardening (carbide grains or cobalt binder) result in a microhardness increase in the implanted layer and implantation-affected zone and enhance abrasive-wear resistance.[13,15] Moreover, microstructural changes (e.g., dislocations) due to implantation can alter residual stresses from tensile to compressive at the tool surface and, therefore, may reduce chipping wear.[12] Another hypothesis is friction reduction by implantation, especially in Cl implantation.[16]

It was argued that implanted Cl ions may diffuse into the tool-chip and tool-workpiece interface rapidly during machining and react with titanium at elevated cutting temperatures, providing a lubricating film at the interfaces. Vesnovsky[15] proposed that ion implantation may reduce diffusion wear due to implanted metastable structures and grain size modification. Kanazawa et al.[12] indicated that ion implantation may change carbide tool wear mechanisms from adhesion and chipping/breakage to uniform abrasive wear. On the other hand, Treglio et al.[17] reported no change of tool-failure mode by implantation; rather, implanted structures may favorably delay chipping onset. Vesnovsky et al.[19] reported cutting forces and indicated little change on the tangential component, but significant decrease of the radial/axial components by implantation. The authors argued that radial/axial components strongly depend upon tool surface properties that may be modified by ion implantation. Poletika et al.[14] also claimed that implantation modified chemical zone may migrate toward the bulk during cutting and extend the effective duration.

2.3 Coated Tools

Though there are several reports[17,18,20-23] of ion implantation of coated carbide tools in the literature, the majority of contributions is from A.J. Perry and his research associates. Treglio et al.[17] reported dual implantation of Ti and Ni, at 70 keV and 5×10^{16} ions/cm^2, on coated carbide cutting tools and showed a more than 200% increase of tool-life in machining of AISI 4140 steel. The authors argued that tool life improvement by ion implantation was due to formation of dislocation network structures or amorphous structures. On the other hand, compressive residual stresses caused by implantation has also been suggested for tool-life increase. Perry et al.[20] studied residual stresses of implanted TiN coating and found that ion implantation may alter residual stresses from tensile to near zero or compressive on TiN coating. However, the authors suggested that tool-life increase by ion implantation is not due to change in residual stresses, but rather that microhardness and tribological properties (cohesion) through the coating contribute to tool improvement.[21] It has also been shown that microhardness increase, mainly associated with dense dislocation by radiation, may extend to a few microns of the implantation-affected zone.

Bull et al.[23] characterized the implanted TiN coating and concluded that grain refinement and surface composition change lead to friction reduction and wear-mode changes. More interestingly, the authors discovered a large amount of C onto the TiN surface from the implanted system, which may contribute to friction and wear reduction. Manory et al.[22] studied ion implantation of TiN coatings and claimed an optimal implantation for machining requires a combination of sufficient amorphicity for good friction and a sufficient amount of unaffected TiN for a hard supporting layer.

2.4 Ceramics

Only two articles[4,12] dated in the late 1980s, about ceramic tool implantation have been identified. Krishnamurthy[4] studied nitrogen implantation of oxide ceramic tools (white alumina). The applied implantation energy was 90 keV and dose was 1×10^{16} ions/cm^2. Machining of cast iron and EN 8 steel was conducted to examine implantation effects, evaluated by tool flank wear. The results showed that implanted ceramic tools performed better than unimplanted counterparts due to, suggested by the authors, reduced adhesion between the tool and work material. Ion implantation seemed to reduce spalling at the tool rake face that consistently appeared on unimplanted tools. Kanazawa et al.[12] studied nitrogen-implanted ceramic tools, at 90 keV and 3×10^{17} or 5×10^{17} ions/cm^2, in interrupted cutting. The finding was that ion implantation reduced the probability of the cutting-edge fracture. However, ion implantation showed no effect on cutting-edge chipping or edge fracture in long cutting.

Ion implantation has also been used to modify ceramic surfaces for different applications such as wear resistance. Most studies[24-27] concluded friction reduction as the main mechanism for wear decrease. Friction reduction by ion implantation may be due to formation of thin layers of lubricious oxide [24] or amorphous structures.[26] Yu et al.[28] implanted nitrogen ions into boron carbide (B_4C, a candidate of cutting tool materials) with 25 keV at a dose of 4×10^{17} ions/cm^2 and observed HBN formed at B_4C surface, which reduces surface friction.

Ion implantation of thin CBN films has also been studied,[29,30] showing that ion implantation may transform CBN to HBN, a solid lubricant, at the surface. Despite the evidence of HBN formation at CBN surface by ion implantation, the formation mechanism of HBN is not clearly understood. Trehan et al.[29] reported that N_2^+ bombardment to CBN changes the local bonding environment of B and N from *sp*^{3}-type to *sp*^{2}-type characteristic of hexagonal phases. Using MeV He and Xe ions, Ullmann et al.,[30] however, suggested that displacement density (induced by implantation) controls the transformation of CBN to HBN network.

In summary, the literature evidently supports ion implantation effects on tool-life improvement. However, due to various implantation and cutting conditions, previous research only provides qualitative information on the effectiveness of ion implantation of cutting tools. Microhardness increase, compressive residual stresses, and lubrication seem to be the three main mechanisms for tool-life increase by ion implantation. Due to sophistication of both microstructural changes by implantation and tool-wear process, there is no straightforward relation between implantation parameters and application ranges. Furthermore, it is puzzling how a shallow modification may lead to wear reduction in such an extreme tribological contact as in machining. It has been suggested that an implantation-affected zone could be a few microns and implanted species may migrate deeper during machining, though there is no systematic proof so far. Moreover, each machining operation is uniquely characterized by loading and materials, and therefore it is necessary to tailor implantation to gain tool-life improvement in individual cases. In this research, the objective was to test ion implantation effects on CBN tools in finish hard machining.

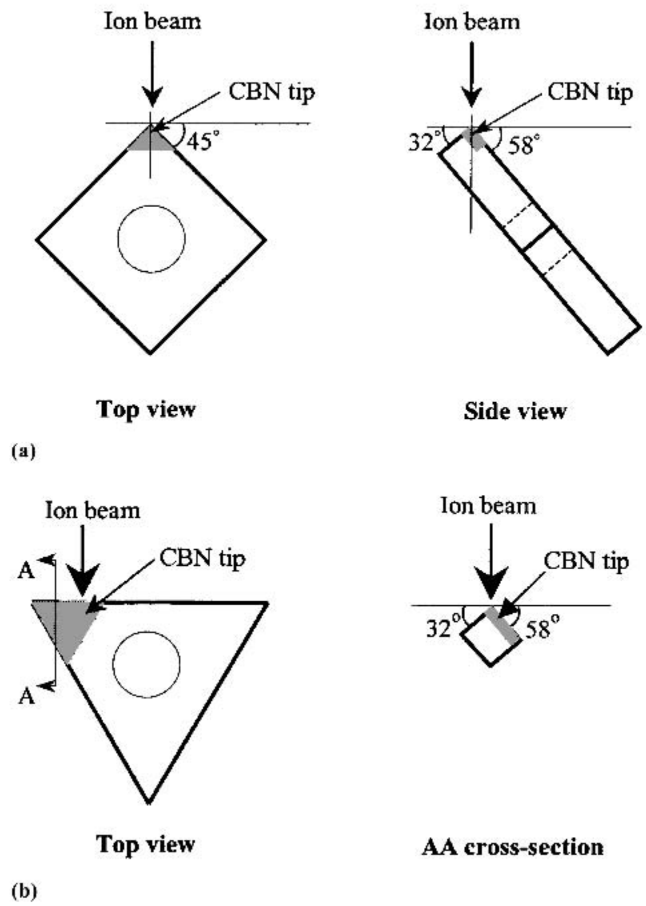

Fig. 1 Positioning and orientation of CBN inserts for ion implantation for **(a)** turning and **(b)** orthogonal cutting

3. Experimental Procedures

3.1 Cutting Tools and Ion Implantation

A CBN tool material that has 70 vol.% CBN, 0.5 μm average grain size, and titanium nitride binder was used in this study. Cutting inserts, CBN tips brazed on tungsten carbide substrates, included square and triangular types for turning and orthogonal cutting, respectively. The CBN inserts used had a chamfered cutting edge (25° × 0.1 mm), and the cutting edge radius was about 10 μm. Ion implantation of CBN cutting tools was performed using a commercial implantation provider. Ion species was N_2^+, ion energy was 150 keV, and ion dose 2.5×10^{17} ions/cm^2; the dose rate was kept below 1.4×10^{13} ions/s to avoid abrupt temperature rise at the tool surfaces. As ion implantation is a line-of-sight process, the cutting tools were positioned so that both the rake and flank surfaces were equally exposed to the ion beam (Fig. 1a and b for turning and orthogonal cutting).

Color changes on CBN inserts after implantation was observed. Implanted CBN tools were further examined by SEM

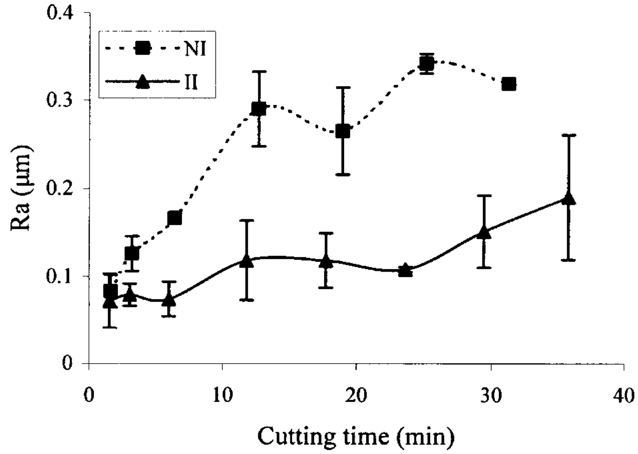

Fig. 2 Part surface finish from implanted and nonimplanted CBN tools; NI: nonimplanted and II: implanted (V = 1.5 m/s, f = 15 μm/rev)

on morphology; however, there were no noticeable changes. XPS was used to analyze the surface chemistry of implanted CBN inserts. A survey spectrum revealed peak patterns similar to those of nonimplanted CBN tools. However, a detailed multiple analysis of boron (B) 1s peak showed existence of π-plasmon loss peak, which is associated with only HBN, but not CBN, according to literature.[29] Such a minute distinction, however, is not significant enough for quantitative evaluation.

3.2 Turning Tests

Both implanted and nonimplanted CBN tools were used to turn hardened steel on a precision CNC lathe. The workpieces were round bars made of AISI 52100 steel (1 wt.% C, 1.4 wt.% Cr), hardened and tempered to 60 to 62 HRC. The tool holder and cutting inserts resulted in cutting geometry of a –30° rake angle and a 5° relief angle; the tool nose radius was 0.8 mm. Machining parameters were 1.5 and 3 m/s of cutting speed (V), 15 and 45 μm/rev of feed rate (f), and a constant depth of cut, 50 μm. No coolant was used in machining.

A combination of two speeds and two feed rates was arranged to investigate implantation effects on hard machining using CBN tools. Each test was conducted until flank wear-land width (VB) reached 0.1 mm and repeated two times. In the machining tests, part-surface finish (in R_a along the tool feed direction) and tool flank wear land width (in VB) were periodically measured by profilometery and optical microscopy, respectively. After machining tests, tool-wear conditions were also examined by scanning electron microscopy (SEM). A triaxial piezoelectric sensor with a data-acquisition system was used to measure three components of cutting forces in machining: tangential, radial, and axial in the workpiece coordinate. Cutting-force signals were then processed to calculate average cutting forces. Then R_a, VB, and cutting forces were compared to evaluate implantation effects on CBN tools in finish hard turning.

3.3 Orthogonal Cutting

Triangular CBN inserts implanted with the same parameters, but a different beam direction (Fig. 1b), were tested in

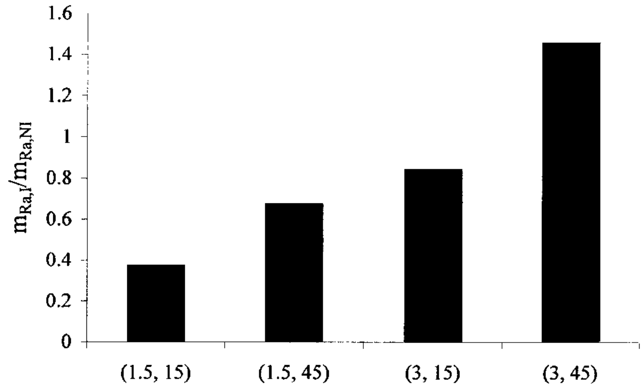

Fig. 3 Surface finish increasing rates using implanted CBN tools compared with a nonimplanted one at different cutting conditions, (a, b) = (speed, feed)

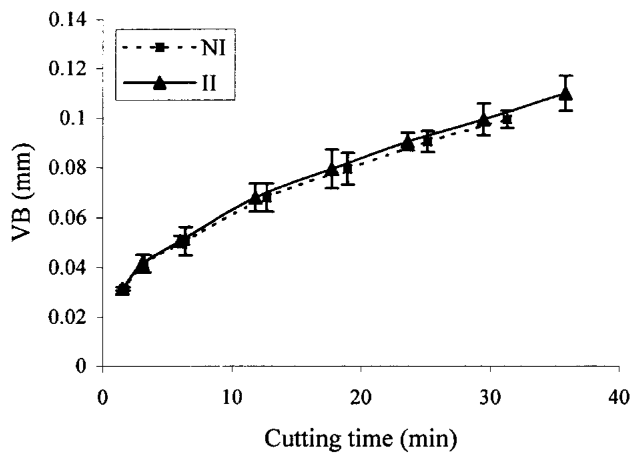

Fig. 4 Tool wear (VB) versus cutting time of implanted and nonimplanted CBN tools (V = 1.5 m/s, f = 15 μm/rev)

2-D orthogonal cutting to investigate tribological contact in hard machining. Workpieces were from a batch of 58-60 HRc AISI 52100 steel tubing, 38.1 mm outside diameter and 1.7 mm wall thickness. The tubing end was turned by CBN inserts with a straight cutting edge, normal to the cutting direction, to obtain 2-D orthogonal cutting.[31] Cutting speed (V) was 1.5 or 3 m/s, uncut chip thickness (h) ranged from 2-15 μm, and the width of cut was constant (1.7 mm as wall thickness). Very small uncut chip thickness was purposely selected to be comparable to turning tests where the uncut chip thickness is determined by feed rate, depth of cut, as well as tool-nose radius.[32] Cutting forces (cutting and thrust components) and chip-tool contact length at the rake face were also measured.

4. Results and Discussion

4.1 Turning Tests

4.1.1 Surface Finish. Figure 2 shows part surface finish, R_a, versus cutting time at low cutting speed and low feed rate. Error bars represent the ranges of two tests. It is observed that

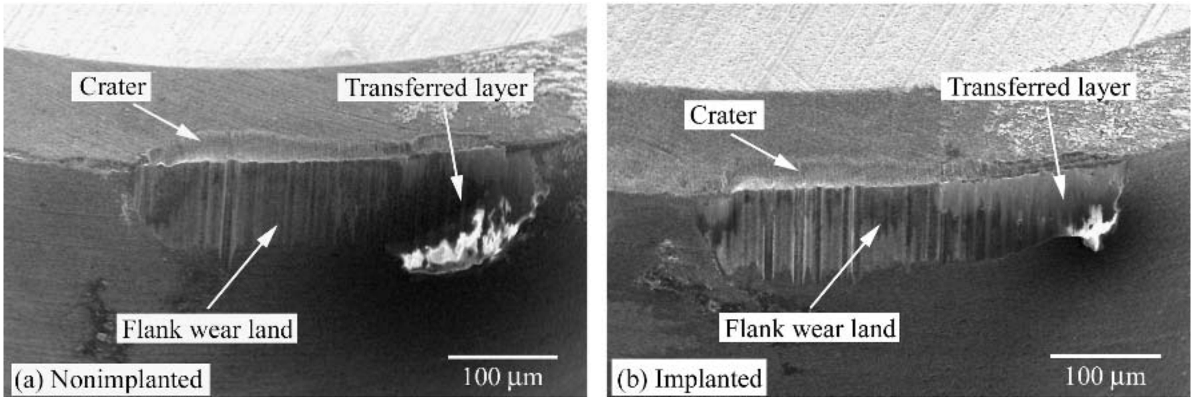

Fig. 5 Scanning electron micrographs of **(a)** nonimplanted and **(b)** implanted CBN tools at $VB = 0.1$ mm ($V = 1.5$ m/s, $f = 15$ μm/rev)

as the cutting time increased, surface finish affected by ion implantation is evident. In particular, the maintainable surface finish was significantly improved; R_a was below about 0.2 μm for over 35 min cutting time, or 0.1 mm *VB*. For other cutting conditions, surface finish was also affected by ion implantation, but less noticeably. To quantitatively correlate implantation effects on surface finish at different cutting conditions, the R_a versus cutting time results were approximated in a linear manner. The linearized R_a increasing rates ($m_{Ra,I}$) were further normalized by that of nonimplanted CBN tools ($m_{Ra,NI}$). Figure 3 compares implantation effects on surface finish increasing rates ($m_{Ra,I}/m_{Ra,NI}$) at different machining conditions. It seems that ion implantation is more effective at low cutting speed and low feed rate conditions, yet may be detrimental at high speed and high feed.

4.1.2 Tool Wear. Figure 4 shows tool flank wear land width, *VB*, increasing with cutting time at 1.5 m/s and 15 μm/rev. Ion implantation seemed not to affect tool-wear size. Tool wear at other cutting conditions was not affected by ion implantation either. Figure 5 shows scanning electron micrographs of both nonimplanted and implanted CBN tools cut at 1.5 m/s and 15 μm/rev for about 35 min. Both CBN tools show similar wear features except that the implanted tools have seemingly more transferred layers on the tool flank wear land, especially around the tail-cutting edge. Thus, current N_2^+ implantation may not be intensive enough to alter wear mechanisms of CBN tools in hard machining.

4.1.3 Cutting Forces. Measured cutting forces also showed dependency on ion implantation. Figure 6 shows both the tangential and radial components of cutting forces at 1.5 m/s and 15 μm/rev. The tangential component showed minor changes, indicating that specific cutting energy is not significantly modified by ion implantation. On the other hand, the radial cutting forces show more remarkable changes by ion implantation. Similarly, cutting forces at other machining conditions were also influenced by ion implantation; however, to less extent.

Radial cutting forces seem to be correlated with surface finish, and thus it is suggested that friction conditions at the cutting edge and rake face may be altered by ion implantation and may affect part-surface finish. Three components of cutting forces were used to estimate the nominal friction coefficients[33] at the rake face along the cutting time, assuming that the percentages of wear land contribution to all three components are the same.

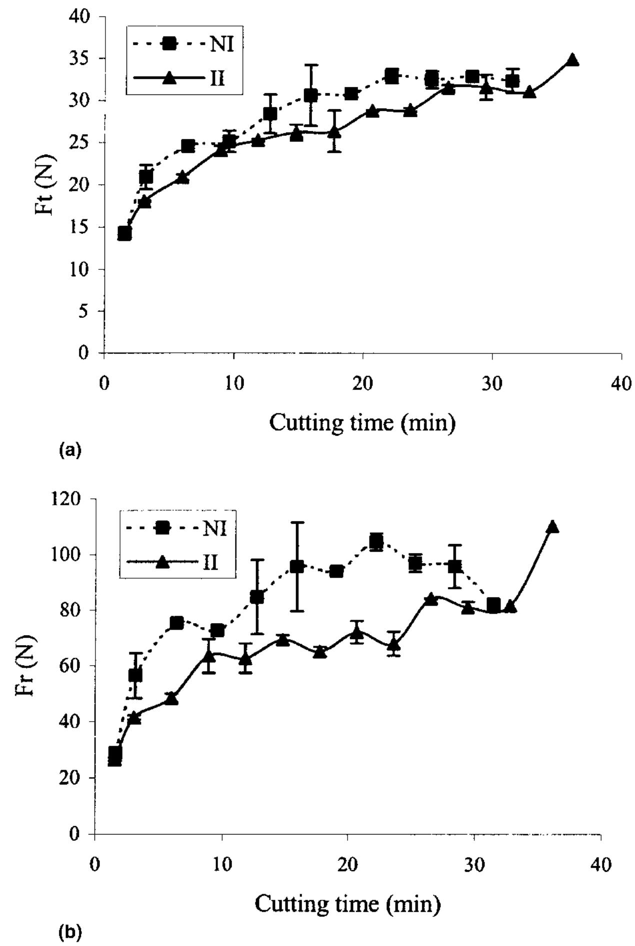

Fig. 6 **(a)** Tangential and **(b)** radial components of cutting forces of nonimplanted and implanted CBN tools ($V = 1.5$ m/s, $f = 15$ μm/rev)

Figure 7 plots friction coefficients at the rake face for 1.5 m/s cutting speed and 15 μm/rev feed rate. The friction coef-

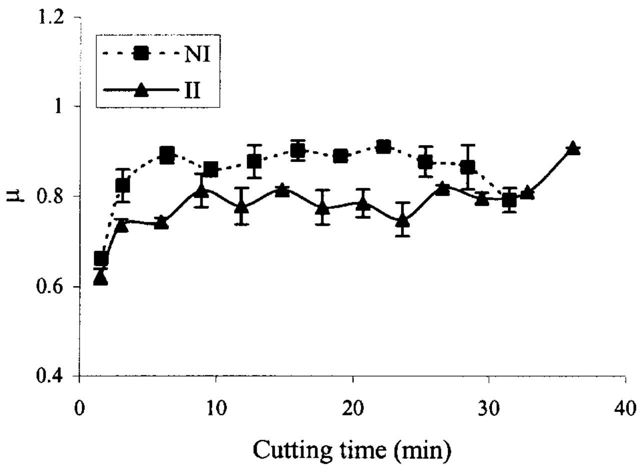

Fig. 7 Friction coefficients of nonimplanted and implanted CBN tools along cutting time (V = 1.5 m/s, f = 15 μm/rev)

ficients, in the range of 0.6-0.9, were evidently affected by ion implantation. The friction conditions at the cutting edge affect the required minimum uncut chip thickness to prevent material side flow.[34] The lower the friction coefficient, the smaller the side flow, which leads to a smoother surface. Hence, reduced friction coefficients by ion implantation may possibly improve part surface finish.

4.2 Orthogonal Cutting

Measured cutting forces were compared between nonimplanted and implanted CBN tools at different cutting conditions. Figure 8 shows both cutting and thrust components (P_c, P_t) as a function of uncut chip thickness at two cutting speeds. It is noted that ion implantation does not affect cutting forces in orthogonal cutting. Using classic cutting mechanics analysis, friction coefficient at the tool rake can be derived from measured cutting forces and the given rake angle (–30°).[33] Figure 9 plots friction coefficient versus uncut chip thickness. The friction coefficient, again not affected by implantation, was in the range of 0.4-0.6, slightly lower than estimates from turning.

Chip-tool contact length measured by optical microscopy also showed no difference from implantation. Figure 10 shows friction and normal stresses at the tool rake face (calculated from cutting mechanics). Extremely high stress levels, on order of GPa, are recognized.

Results from orthogonal cutting do not seem to support the turning results. Orthogonal cutting indicated that current ion implantation does not affect tribological loading of CBN tools in hard machining. Implantation parameters used might not be aggressive enough to impact the severe tribological loading in hard machining. However, it was evident that surface finish and cutting forces in turning were modified by ion implantation. In practical machining such as turning, the final part surface profile is generated by chip formation and material flow exclusively in the tail-cutting edge where the uncut chip thickness approaches to zero and tool wear is small. Thus, it is assumed that ion implantation may be effective in the tail-cutting edge and improve part surface finish.

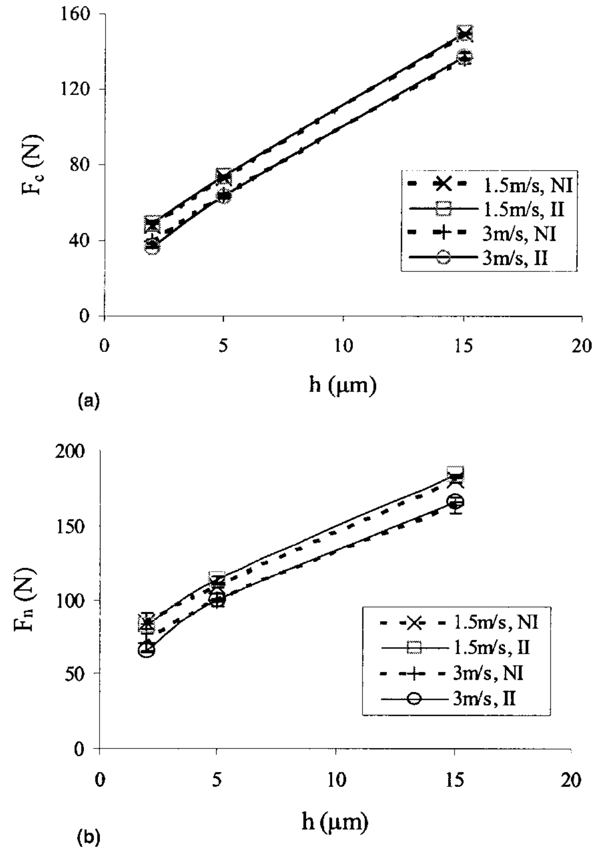

Fig. 8 **(a)** Cutting and **(b)** thrust components of forces in orthogonal cutting

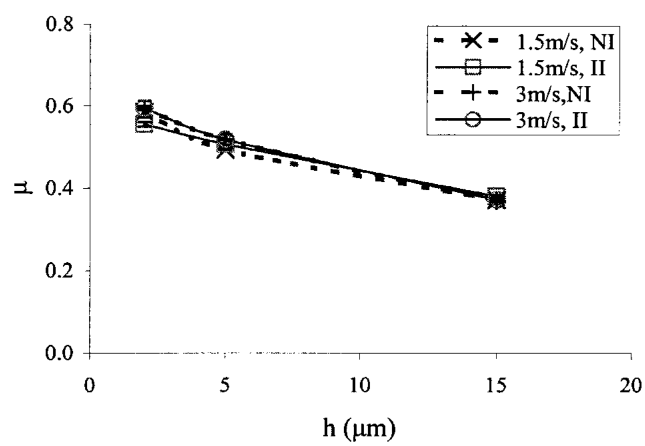

Fig. 9 Friction coefficients of implanted and nonimplanted CBN tools in orthogonal cutting at different conditions

5. Conclusions

A literature review indicated that ion implantation may improve cutting tool performance by hardness increase, compressive residual stresses, and lubrication. However, implantation applications of ceramic tools are hardly identified. In this

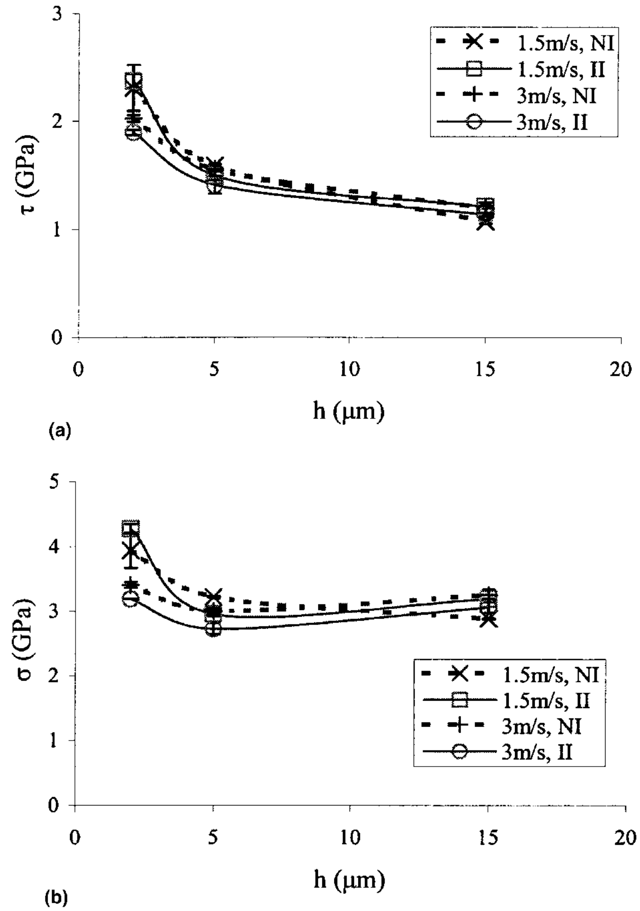

Fig. 10 **(a)** Friction and **(b)** normal stresses at CBN tool rake in orthogonal cutting

study, ion implantation of CBN tools has been experimentally investigated in both turning and orthogonal cutting. N_2^+ ion implanted CBN tools consistently improve part surface finish in finish hard machining finishing; though effects on cutting forces are moderate, yet negligible, on tool wear. Furthermore, implantation effectiveness depends upon machining conditions as well. However, in orthogonal cutting, contact stresses and friction coefficient were not affected by implantation in the test range. It is speculated that current level of implantation does not significantly affect tool-wear mechanism; however, ion implantation may reduce friction around the tail-cutting edge, which may result in improved surface finish. Comprehensive characterizations of ion-implanted CBN tool surfaces on chemistry, mechanical, and tribological properties along the depth would need to be studied to clarify possible applications of ion implantation of CBN tools.

Acknowledgments

This research has been supported by UA SOMED Faculty Research Award. H. Song and E. Ada, both with UA, conducted turning tests and provided assistance on XPS analysis, respectively. Sumitomo Electric Carbide, Inc. supplied CBN inserts for the test.

References

1. W. König, A. Berktold, and K.F. Koch: "Turning Versus Grinding—A Comparison of Surface Integrity Aspects and Attainable Accuracies," *Annals of CIRP,* 1993, *42/1.* pp. 39-43.
2. J.K. Hirvonen and B.D. Sartwell: "Ion Implantation," in *ASM Handbook,* Vol. 5, *Surface Engineering,* ASM International, Materials Park, OH, Materials Park, OH, 1994, pp. 605-10.
3. K.N. Radhakrishnan, M.K.B. Nayar, and R. Krishnamurthy: "Performance of N^{++} Plus Implanted Powder Metallurgy HSS Tools," *Proceedings of the 1986 International Powder Metallurgy Conference and Exhibition: The Future of Powder Metallurgy,* Ausschuss fuer Pulvermetallurgie, Hagen, West Germany; European Powder Metallurgy Federation Verlag Schmid Gmbh, 1986, pp. 539-42.
4. R. Krishnamurthy: "Wear Characteristics of Ion Implanted Cutting Tools," *I Mech E Conference Publications,* Mechanical Engineering Publ Ltd, London, UK, 1987, pp. 665-69.
5. H. Onikura, Y. Ishimaru, and A. Katsuki: "Cutting Characteristics of Nitrogen-Ion-Implanted Drills," *Bulletin of Japan Society of Precision Engineering,* 1989, *23,* pp. 280-85.
6. S.R. Bradbury, D.B. Lewis, and M. Sarwar: "Assessment of Enhancing the Performance and Wear Characteristics of High Speed Steel Circular Saw Blades Through Ion Implantation," *Surf. Coat. Technol.,* 1996, *82,* pp. 193-98.
7. S.R. Bradbury, D.B. Lewis, P.M. Archer, and W. Ahmed: "Impact of Surface Engineering Technologies on the Performance and Life of Multi-Point Cutting Tools," *Surf. Coat. Technol., 91* (1997) pp. 192-99.
8. R.H. Woods and B.K. Lambert: "A Performance Study of Plasma Source Ion-Implanted Tools Versus High Speed Steel Tools," Nucl. Instrum. and Methods, *Phys. Res. B,* 1997, *127/128,* pp. 1004-07.
9. S. Yan, W.J. Zhao, J.M. Xue, Y.G. Wang, and X.J. Zhang: "The Surface Microstructure of High-dose, Carbon-Implanted High-speed Steel," *Surf. Coat. Technol.,* 1998, *10-104,* pp. 343-47.
10. S. Mändl, R. Günzel, B. Rauschenbach, R. Hilke, E. Knösel, and K. Künanz: "Characterization of Drills Implanted With Nitrogen Plasma Immersion Ion Implantation," *Surf. Coat. Technol.,* 1998, *103-104,* pp. 161-67.
11. F. Jährling, D.M. Rück, and H. Fuess: "Wear and Microstructure of Carbon Implanted AISI M2 High Speed Steel," *Surf. Coat. Technol.,* 1999, *111,* pp. 111-18.
12. K. Kanazawa, K. Chijiiwa, and M. Iwaki: "Improvement on the Breakage and Chipping of Cutting Tools Using N-Ion Implantation," *Bulletin of Japan Society of Precision Engineering,* 1987, *23,* pp. 63-64.
13. L. Guzman, L. Ciaghi, F. Giacomozzi, and E. Voltolini: "Ion Implantation in WC-Co: Analysis of Treated Surfaces and Testing of Industrial Tools," *6th International Conference on Surface Modification of Metals by Ion Beams, Materials Science and Engineering A: Structural Materials: Properties, Microstructure and Processing,* 1989, Italy, pp. 183-91.
14. M.F. Poletika, O.K. Vesnovsky, and K.N. Polestchenko: "Ion Implantation for Cutting Tools," *Nucl. Instrum. Methods Phys. Res. B,* 1991, *61,* pp. 446-50.
15. O.K. Vesnovsky: "Implantation of Cutting Tools," *Surf. Coat. Technol.,* 1992, *52,* pp. 297-99.
16. J.L. Walter, D.W. Skelly, and W.P. Minnear: "Ion Implantation of Cobalt-Tungsten Carbide Tools for Machining Titanium," *Wear,* 1993, *170,* pp. 79-92.
17. J.R. Treglio, A. Tian, and A.J. Perry: "Extending Carbide Tool Lifetime by Metal Ion Implantation," *Surf. Coat. Technol.,* 1993, *62,* pp. 438-42.
18. C.G. Fountzoulas, A. Gonzales, J.K. Hirvonen, and F. Lancaster: "Corpus Christi Army Depot ion implanter: Capabilities and Capacities for Industrial Applications," *Surf. Coat. Technol.,* 1996, *84,* pp. 574-78.
19. O.K. Vesnovsky, M.F. Poletica, L.D.T. Topoleski, and V.A. Pushnykh: "Ion Implantation of Cemented Carbide Cutting Tools," *Key Eng. Mater.,* 1998, *138-140,* pp. 327-55.
20. A.J. Perry, D.E. Geist, and D. Rafaja: "Residual Stress in Cemented Carbide Following a Coating Process and After an Ion Implantation Post-Treatment of the Coating," *Surf. Coat. Technol.,* 1998, *108-109,* pp. 225-29.
21. A.J. Perry, J.R. Treglio, D.E. Geist, D.G. Bhat, S.P. Boppana, T.Z.

Kattamis, K. Schlichting, and G. Dearnaley: "Effect of Ion Implantation of the Residual Stress, Tribological and Machining Behavior of Cemented Carbide Cutting Tool Inserts Coated with TiN by CVD and PVD Methods," *Key Eng. Mater.,* 1998, *138-140,* pp. 177-94.
22. R.R. Manory, A.J. Perry, D. Rafaja, and R. Nowak: "Some Effects of Ion Beam Treatments on Titanium Nitride Coatings of Commercial Quality," *Surf. Coat. Technol.,* 1999, *114,* pp. 137-42.
23. S.J. Bull, Y.P. Sharkeev, S.V. Fortuna, I.A. Shulepov, and A.J. Perry: "Mechanism of Improvement of TiN-coated Tool Life by Nitrogen Implantation," *J. Mater. Res.,* 2001, *16,* pp. 3293-303.
24. W. Wei, J. Lankford, and R. Kossowsky: "Friction and Wear of Ion-beam-Modified Ceramics for Use in High Temperature Adiabatic Engines," *Mater. Sci. Eng.,* 1987, *90,* pp. 307-15.
25. M. Nastasi, R. Kossowsky, J.P. Hirvonen, and N. Elliott: "Friction and Wear Studies in N-implanted Al_2O_3, SiC, TiB_2, and B_4C Ceramics," *J. Mater. Res.,* 1988, *3,* pp. 1127-33.
26. F. Brenscheidt, S. Mändl, R. Günzel, E. Wieser, W. Möller, W. Fischer, and M. Herrmann: "Tribological Properties of Silicon Nitride Ceramics Modified by Titanium and Subsequent Oxygen Implantation," *Surf. Coat. Technol.,* 1997, *97,* pp. 675-79.
27. G.B. Stachowiak, G.W. Stachowiak, and P. Evans: "Characteristics of Ion-Implanted Zirconia Ceramics," *Wear,* 2000, *241,* pp. 220-27.
28. N. Yu, F. Romero-Borja, Z.H. Zhang, X.T. Cui, J.R. Liu, L.T. Wood, and W.K. Chu: "Formation of Boron Nitride and Boron Carbide Composite by Nitrogen Implantation at Elevated Temperature," *Appl. Phys. Lett.,* 1993, *63,* pp. 1643-45.
29. R. Trehan, Y. Lifshitz, and J.W. Rabalais: "Auger and X-Ray Electron Spectroscopy Studies of hBN, cBN, and N_2^+ Ion Irradiation of Boron and Boron Nitride," *J. Vac. Sci. Technol. A,* 1990, *8*(6), pp. 4026-32.
30. J. Ullmann, J.E.E. Baglin, and A.J. Kellock: "Effects of MeV Ion Irradiation of Thin Cubic Boron Nitride Films," *J. Appl. Phys.,* 1998, *83,* pp. 2980-87.
31. M.C. Shaw: *Metal Cutting Principles,* Oxford University Press, NY, 1989, pp. 18-24.
32. Y.K. Chou and H. Song: "Hard Turning With Different Nose-Radius Ceramic Tools," MR01-228, SME Technical Paper, SAE International, 2001, pp. 1-12.
33. E.J.A. Armarego and R.H. Brown: *The Machining of Metals,* Prentice-Hall, Englewood Cliffs, NJ, 1969, pp. 75-87.
34. T.I. El-Wardany and M.A. Elbestawi: "Phenomenological Analysis of Material Side Flow in Hard Turning: Causes, Modeling, and Elimination," *Mach. Sci. Technol.,* 1998, *2,* pp. 249-51.