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Comparative Investigation of Smooth Polycrystalline Diamond Films on Dental Burs by Chemical Vapor Deposition

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Depositions of hot filament chemical vapor-deposited diamond on cobalt-cemented tungsten carbide (WC-Co) rotary cutting dental burs are presented. Conventional dental tools made of sintered polycrystalline diamond have a number of problems associated with the heterogeneity of the crystallite, decreased cutting efficiency, and short life. A preferential (111) faceted diamond was obtained after 15 h of deposition at a growth rate of 1.1 μm/h. Diamond-coated WC-Co dental burs and conventional sintered burs are mainly used in turning, milling, and drilling operations for machining metal ceramic hard alloys such as CoCr, composite teeth, and aluminum alloy in the dental laboratory. The influence of structure, the mechanical characteristics of both diamond grains and hard alloys on the wear behavior, as well as the regimen of grinding on diamond wear are considered. Erosion wear properties are also investigated under air-sand erosion testing. After machining with excessive cutting performance, calculations can be made on flank and crater wear areas. Diamond-coated WC-Co dental burs offered significantly better erosion and wear resistance compared with uncoated WC-Co tools and sintered burs.

Keywords cutting tool, diamond, HFCVD, wear

1. Introduction

Diamond films are of interest for tribological applications due to their high hardness, low friction coefficient, high wear resistance, and chemical inertness (Ref 1). Diamond coatings are used in cutting tools and biomedical applications. At the present time, the most widely used dental diamond burs are manufactured by imbedding diamond particles into a metal matrix using a suitable binder containing nickel ions. Those burs have several limitations that are mainly due to the heterogeneity of diamond crystallites, the contamination of oral tissue, and the variation in the product performance. There is no universal specification of the diamond particle sizes imbedded into the binder matrix to ensure a repeatable and consistent cutting performance. Recently, chemical vapor deposition (CVD) has been used for the fabrication of new dental burs (Ref 2), with continuous diamond film offering improvement in cutting efficiency and a longer life. Much of the work on the CVD of diamond has been carried out on flat substrates. Although cutting tools such as drills and inserts have been successfully coated with diamond-based coatings, there have been only a few reports of diamond deposition onto rotary cutting tools, such as cylindrical abrasive pencils and small spiral drills (Ref 3). In this study, the authors report the deposition of uniform diamond films onto the cutting edges of Co-cemented WC-Co dental burs that are used in the dental laboratory and in clinical surgery using a modified hot-filament CVD (HFCVD) system. The filament is mounted in a vertical arrangement with the dental bur held concentrically in between the filament coils, as opposed to the horizontal position commonly used in the HFCVD system configurations. This new vertical filament arrangement used in the modified HFCVD system enhances the thermal distribution and ensures uniform diamond coating (Ref 4). In this article, the results are reported of the investigation on diamond films deposited on WC-Co dental burs and microtools using an HFCVD system and the subsequent machining results on extracted human teeth, CoCr hard metal alloys, borosilicate glass, and porcelain teeth. The Co-cemented dental burs operate at high cutting speeds in the range of 3,000 to 300,000 rpm (Ref 5). Such high operating speeds impose stringent demands on the cutting surfaces and the coating. The coating is required to be tough, adherent, hard, and wear-resistant to enhance the overall tool performance and extend the lifetime of the tool.

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2. Experimental

2.1 Substrate Preparation

The dental bur (WC-6wt.%Co) was 20 to 30 mm in length and 1 to 1.5 mm in diameter. Prior to diamond deposition, the dental burs were ultrasonically cleaned in acetone for 10 min to remove any surface impurities. The poor adhesion of deposited diamond films onto cemented WC surfaces can lead to catastrophic film failure in metal cutting due to the presence of the Co binder (Ref 6). The Co binder suppresses diamond nucle-

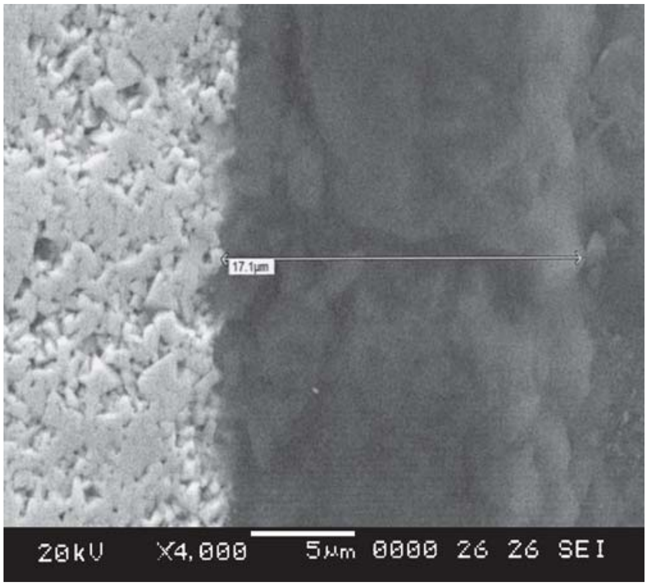


Fig. 1 Cross section of diamond film on a coated dental bur

ation and causes the deterioration of diamond film adhesion (Ref 7). To eliminate this problem, it is usual to pretreat the WC-Co dental bur surface prior to CVD diamond deposition. The WC surface has been etched with Murakami solution, and surface Co has been removed by acid etching followed by ultrasonic washing in distilled water (Ref 8).

2.2 Chemical Vapor Diamond Deposition

Diamond synthesis was performed in a stainless steel HFCVD chamber with an internal diameter of 200 mm. The gas phase mixture of H_2 (purity 99.99%) and CH_4 (purity 99.99%) with a CH_4-to-H_2 volume ratio fixed at 1.0% (1.0% CH_4 with excess H_2) was activated by Ta filament (0.5 mm in diameter) wound in a 10 mm internal diameter spiral. The dental bur was positioned centrally and coaxially within the spiral vertical filament at a 5 mm distance. The filament temperature (1800–2100 °C) was monitored by a two-color pyrometer. The substrate temperature was measured at between 800 to 950 °C. The total pressure of the gas mixture in the reactor was 2.66 kPa (20 torr), and the flow rate was 200 standard cubic centilitre/min (sccm). The diamond deposition was carried out for 15 h with a single used filament. The deposited diamond films were analyzed by scanning electron microscopy (SEM) and micro-Raman spectroscopy measurements were performed in the back-scattered mode at room temperature by using a Dilor XY (Edison, NJ) triple spectrometer equipped with a liquid nitrogen-cooled charge-coupled device detector and a modified Olympus microscope (Tokyo, Japan).

2.3 Diamond Film Erosion Test

Erosion tests were carried out in a high-velocity air-sand erosion facility that was capable of attaining impact velocities of up to 360 m/s. In the erosion rig, the abrasive was injected into an air stream and accelerated down a 10 mm diameter stainless steel tube, 0.8 m in length, into the erosion chamber, where it strikes the diamond-deposited substrate. The abrasive used was a blend of dental laboratory grade with a size distribution in the range 100 to 400 μm and an average diameter of

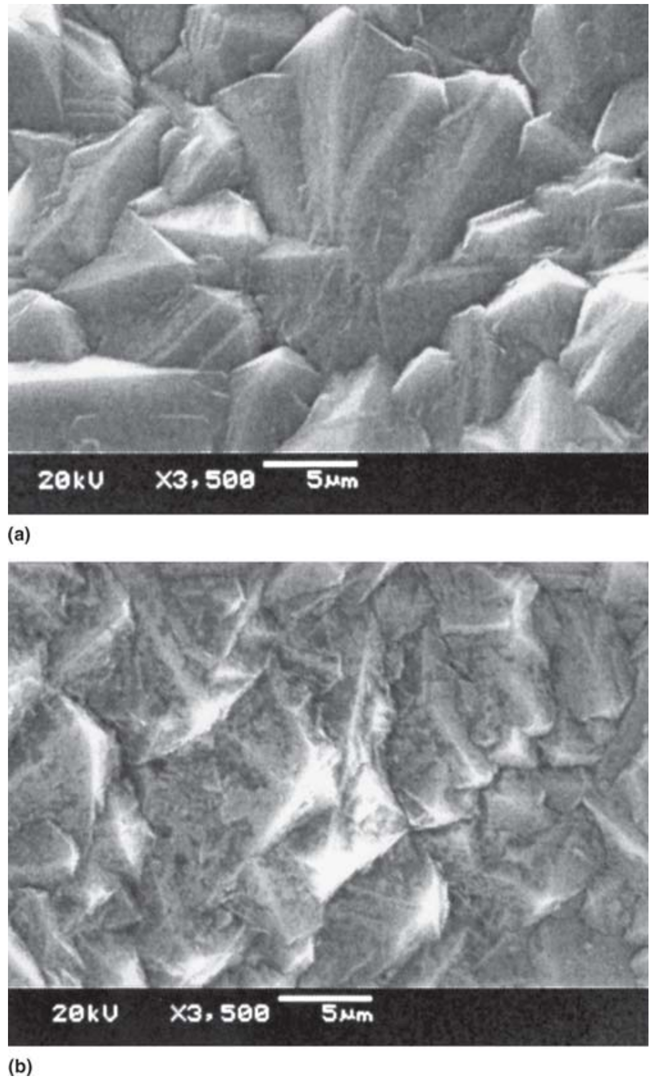


Fig. 2 (a) Diamond film before erosion test and (b) diamond film after erosion test

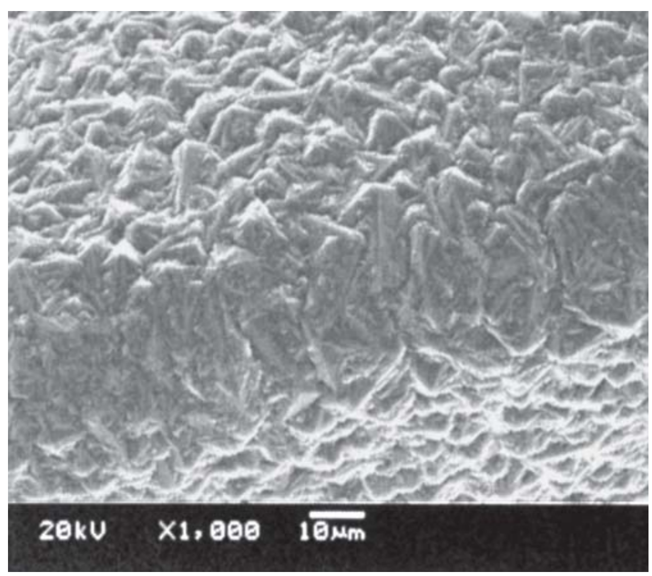
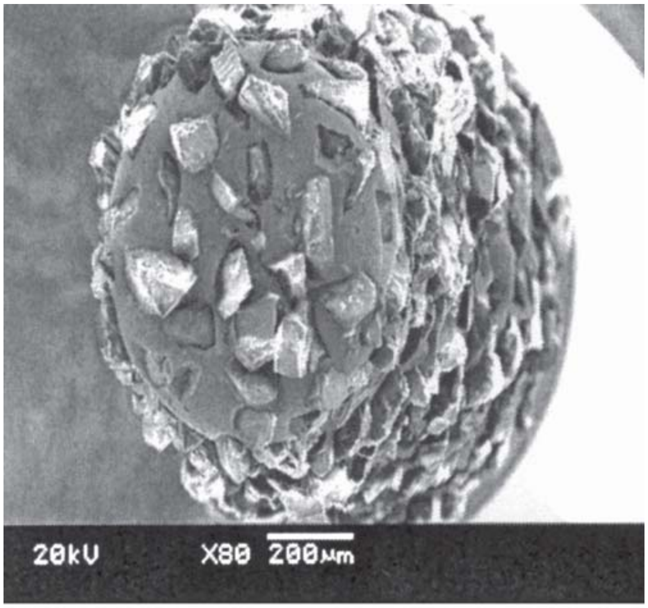
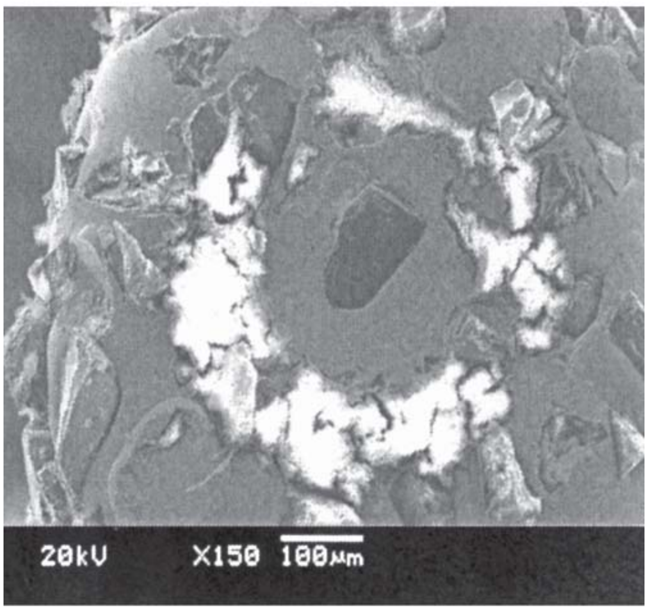


Fig. 3 Cutting edge of a diamond-coated dental bur



(a)



(b)

Fig. 4 (a) Inhomogeneous surface of a PCD-sintered bur and (b) a PCD-sintered bur after testing with glass

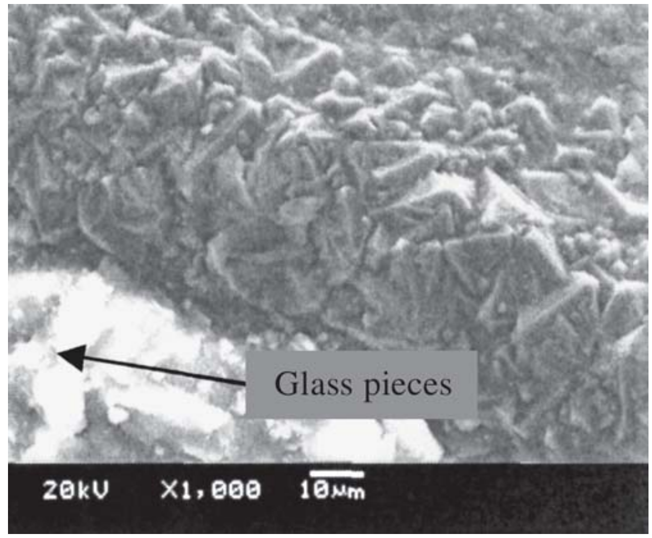


Fig. 5 Cutting edge of a diamond-coated bur after testing with glass

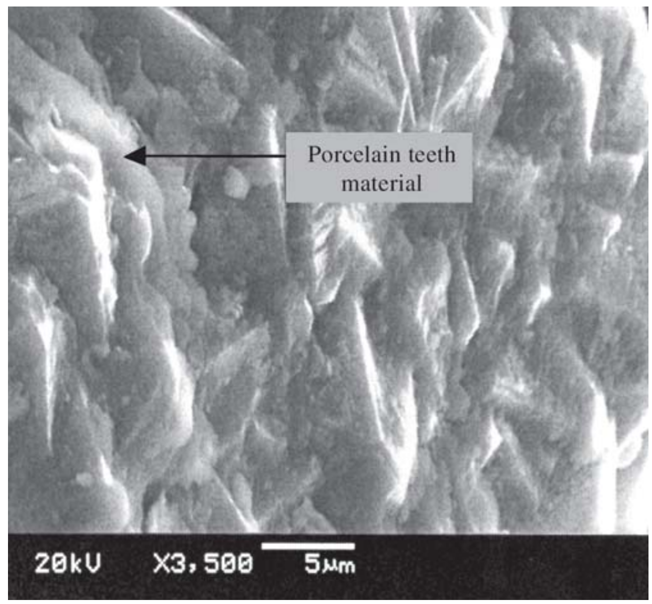


Fig. 6 Close view of a diamond-coated bur after testing with porcelain teeth

250 μm. The abrasive feed rate was 5.9 kg/m^{2}s. The nozzle standoff distance was 40 mm, and the erosion area on the substrate was 10 mm in diameter. All tests were conducted at an impact angle of 90°. The diamond-coated bur was rotated 120° in three intervals. The tests were interrupted every 10 min to monitor the diamond coating (Ref 9).

2.4 Dental Bur Machining: Drilling and Turning Tests

The machining unit was specifically constructed with a water-cooling system so that a maximum spindle speed of 250,000 rpm, feed rates of between 5 and 20 μm per revolution, and cutting speeds in the range of 100 to 200 m/min could be achieved when cutting human teeth with the clinical bur. A separate setup was used to operate at 3,000 to 30,000 rpm with a feed rate of 0.2 to 0.5 mm per revolution without water cooling. The flank wear of the burs was estimated by SEM analysis at a preselected time interval of 1 min. Prior to SEM analysis, diamond-coated burs were ultrasonically washed with 6M H_2SO_4 solutions to remove any unwanted machining material that deposited on the surface of the CVD diamond-coated bur. For comparison, conventional polycrystalline diamond (PCD)-sintered burs with a different geometry were also tested on the same substrate materials.

3. Experimental Results and Discussions

Spectra from energy-dispersive spectroscopy confirmed the removal of the Co binder from the surface for the diamond

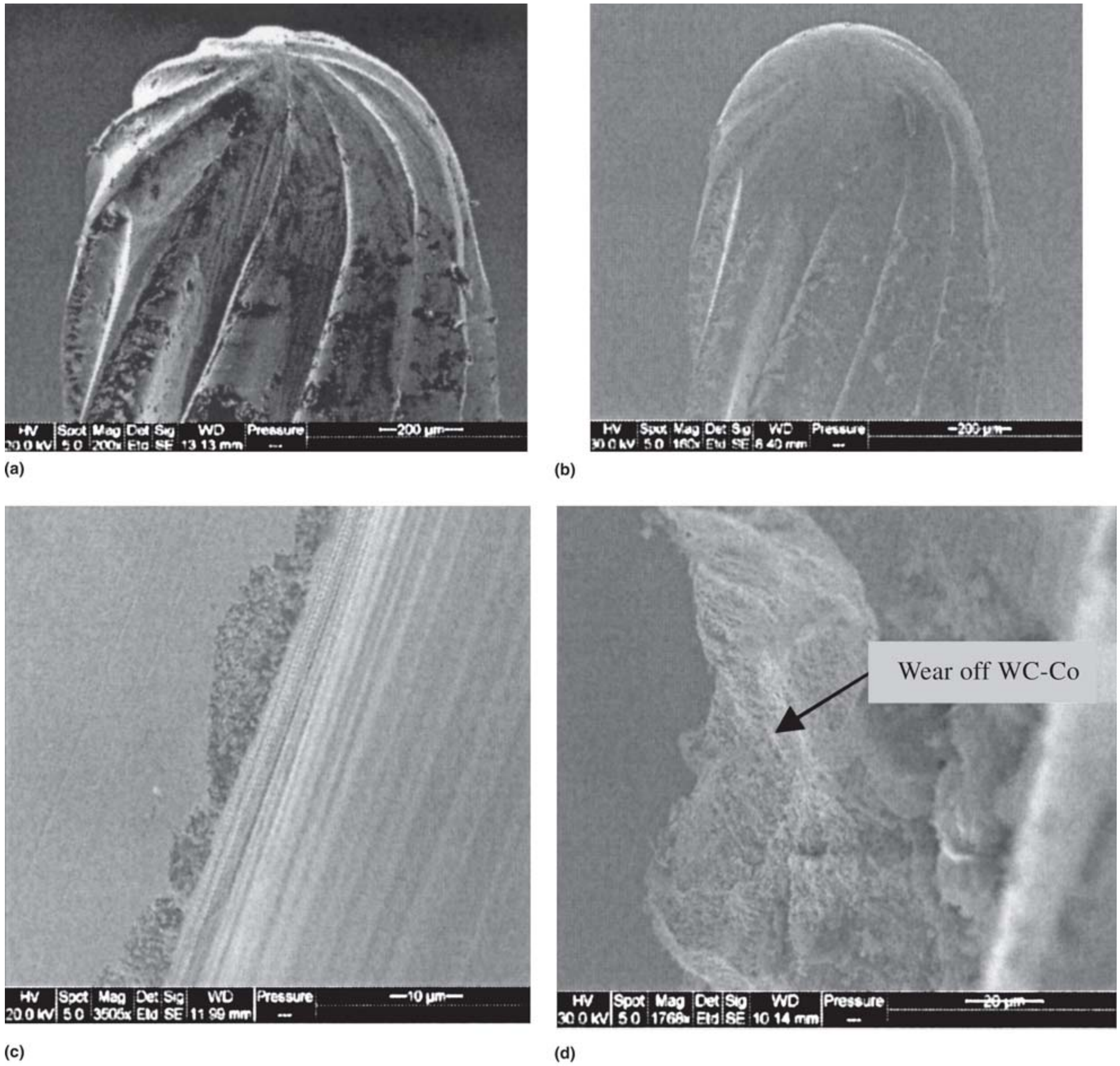


Fig. 7 (a) and (c) Uncoated WC-Co dental bur before machining with glass. (b) and (d) Uncoated WC-Co dental bur after machining with glass.

coatings deposited by HFCVD on dental burs roughened by Murakami's reagent prior to deposition. The surface morphology of the predominantly (111)-faceted, octahedral shape, diamond films was obtained after deposition for 15 h. The SEM micrograph of 17 μm thick diamond is shown in Fig. 1. The results of the erosion tests on a diamond-coated dental bur were compared with those of the untested diamond-coated bur (Fig. 2a and b). Coating failure occurred, but the only surface features observed were minor amounts of microchipping or submicrochipping of the crystal. Diamond has the greatest resistance to plastic deformation of any material, and damage is always of a wholly elastic nature, with no traces of plastic deformation (Ref 10). Figure 3 shows a SEM micrograph of a CVD diamond-coated laboratory dental bur at the cutting edge. The film is homogeneous with uniform diamond crystal sizes. Typically, the crystal sizes are in the range of 6 to 10 μm. As expected, the surface morphology is rough, making the dental burs extremely desirable for abrasive cutting applications. In contrast, Fig. 4(a) is a SEM micrograph of a conventional PCD-sintered bur. The diamond particles are imbedded in the surface with a suitable binder material such as Ni^{2+}. The surface is inhomogeneous, and particle sizes range from 50 to 200 μm, causing considerable variation in the cutting performance of the tool. Figure 4(b) shows the morphology of a sintered diamond bur after cutting borosilicate glass at a cutting speed of 3600 rpm for 5 min with an interval every 30 s. It is clearly evident that there is significant removal of diamond particles from the surface of the tool after drilling 500 holes. As expected, there is a deterioration of tool performance of the PCD-sintered diamond dental burs as a result of tool abrasive detachment. Borges et al. (Ref 2) also reported a significant loss of diamond particles during cutting with a commercially sintered diamond bur. In addition, the metallic Ni^{2+} binder shows major damage as a result of abrasive pullout. Figures 5 and 6 show a SEM image of CVD diamond-coated laboratory bur after machining tests on borosilicate glass and porcelain

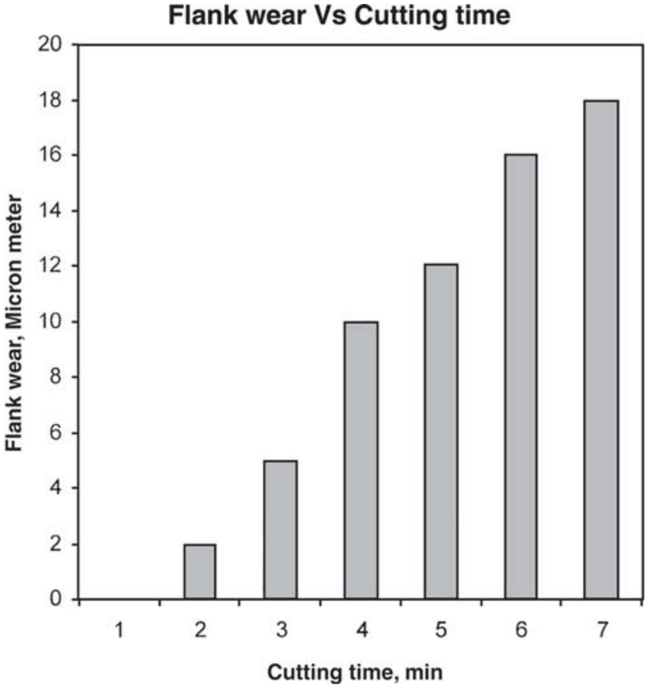


Fig. 8 Flank wear (μm) plotted against the function of time (min)

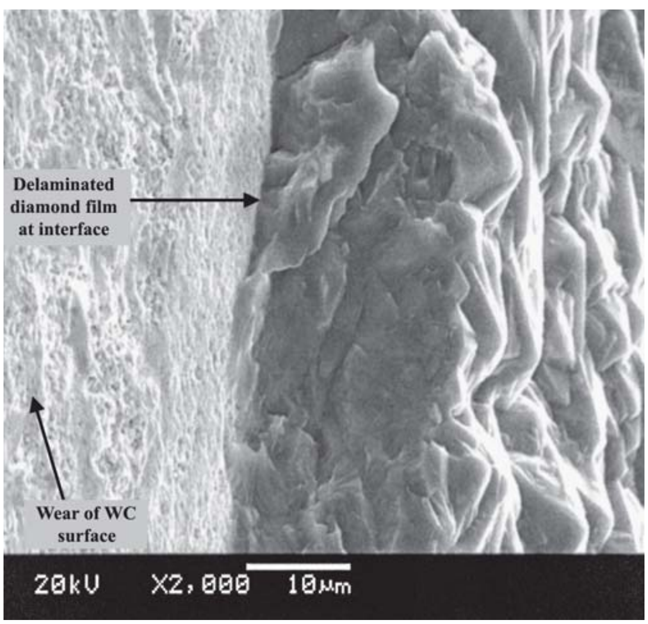


Fig. 9 Delaminated diamond film at the interface between the diamond and the wear of WC

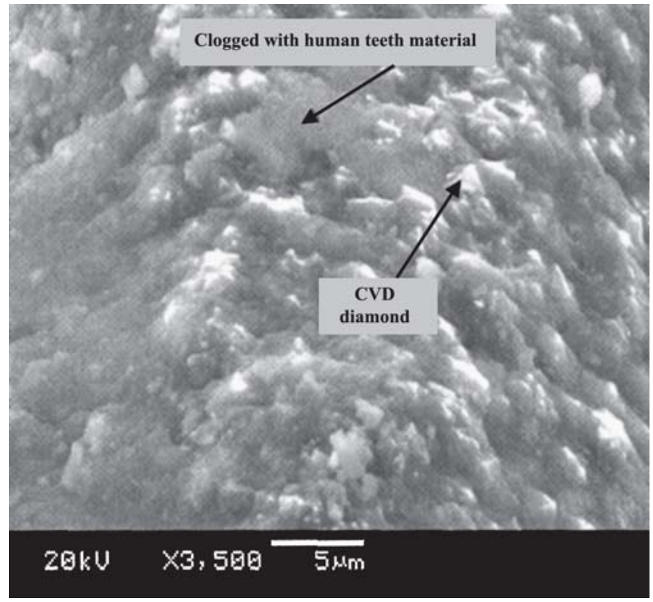


Fig. 10 A clinical bur coated with diamond by CVD after testing on human teeth

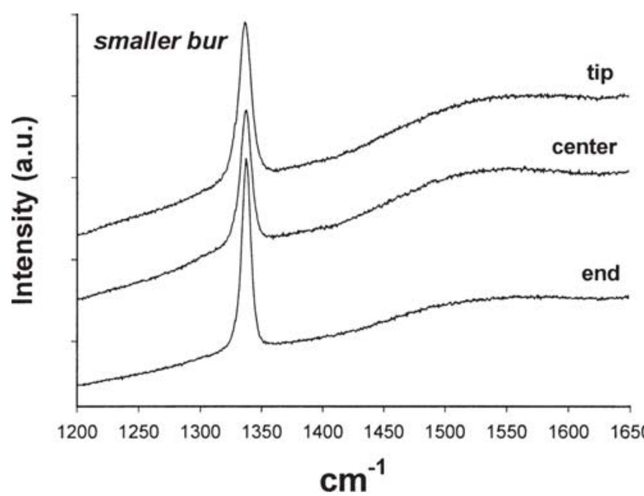


Fig. 11 Raman spectrum of diamond films

teeth, respectively, for 5 min at a cutting speed of 3600 rpm. It is clear that the diamond films are still intact on the pretreated WC substrate, and the diamond coating displayed good adhesion. There is no indication of diffusion wear after the initial test of 500 drilled holes. However, in machining materials such as glass, bits of material are deposited on the cutting edge of the diamond-coated dental bur (Fig. 5). After testing on porcelain teeth, the mechanism of wear probably involves adhesion as well as abrasion. Figure 6 shows that inorganic fillers from porcelain teeth adhered to the cutting tool surface in localized areas when increased feed rates were used (Ref 11). Figures 7(a) and (c) show SEM images of an uncoated WC-Co dental bur before testing on the borosilicate glass.

For machining tests, a material workpiece (borosilicate glass) was prepared and was aligned orthogonal to the dental cutting tool. Trench machining was the method used to generate wear on the tool with a cutting speed of 3600 rpm. After machining, Fig. 7(b) shows that the uncoated WC-Co bur has lost its cutting edges on the bur head and displays significant wear along the cutting edge of the bur (Fig. 7d). The areas of flank wear were investigated at the cutting edge of the dental bur. Figure 8 shows flank wear plotted as a function of time after testing on borosilicate glass. It is evident that a long duty cycle can cause high flank wear on the cutting edge of the tool. Therefore, the cutting edge of a WC-Co dental bur should have a significant thickness of CVD diamond, which will enhance not only the quality of cutting but will also prolong the life of the tool (Ref 12). The diamond-coated laboratory dental bur has machined over 80,000 holes on the CoCr. After excessive cutting duty, significant flank wear was observed along the cutting edge of the dental bur. Figure 9 shows that not only did delamination of the diamond occur, but wear of the WC surface occurred at the interface between the diamond and the WC.

Natural human teeth were cut using a diamond-coated clinical bur. The cuts were made in the central groove of the teeth. This permitted cutting three grooves in each tooth. Figure 10 shows an SEM image of diamond-coated clinical WC-Co dental bur after cutting. It is evident from the SEM image that tooth debris such as that with dentine clog up the bur surface, reducing its abrasive performance.

Raman analysis was performed to evaluate the quality and degree of stress in CVD diamond films. The Raman spectrum in Fig. 11 shows that at the tip, center, and end of the cutting tool a single sharp peak occurred at 1336, 1337, and 1337 cuts/cm^{-1}, respectively, for the different positions. The results of Raman analysis on WC-Co substrates performed at several different locations on the tool have shown indications of compressive stress in the coating (Ref 13).

4. Conclusions

Etching treatment of the surface of the tool to remove surface Co resulted in much better film adhesion. Erosion tests showed that adherent diamond films offer significantly better erosion resistance. Therefore, the deposition of diamond on a metal surface offers a protective coating on an uncoated substrate. The PCD-sintered diamond bur lost significant proportions of imbedded diamond particles during the abrasive machining procedure where the bur coated with diamond by CVD remained intact, thus, prolonging tool life. A thicker coating of diamond by CVD at the cutting edges is expected to give longer tool life and a better quality of machining. The performance and lifetime of CVD-coated dental burs are much superior to those of the sintered bur and the uncoated WC-Co bur. Excessive cutting performance also caused the delamination of diamond film from the WC surface. Further work is required to study the effects of diamond film adhesion related to the quality of cutting and thickness at the cutting edge based on the performance of tool.

References

1. W. Ahmed, C.A. Rego, R. Cherry, A. Afzal, N. Ali, and I.U. Hassan, CVD Diamond: Controlling Structure and Morphology, *Vacuum*, 2000, **56,** p 153-159
2. C.M. Borges, P. Mange, M. Dent, E. Pfender, D. Ring, and J. Heberlein, Dental Diamond Burs Made with a New Technology, *J. Prosthet. Dent.*, 1999, p 73-79
3. J. Gabler, L. Schafer, and H. Westermann, Chemical Vapor Deposition Diamond Coated Mine Tools for Grinding, Milling, and Drilling, *Diamond Relat. Mater.,* 2000, **9,** p 921-924
4. H. Sein, W. Ahmed, and C.A. Rego, Application of Diamond Coatings on Small Dental Tools, *Diamond Relat. Mater.,* 2002, **11,** p 731-735
5. M.S. Pines and A. Schulman, Characterization of Wear of Tungsten Carbide Burs, *JADA*, 1979, **99,** p 831-833
6. M.B. Gusev, V.G. Babaev, V.V. Khvostov, G.M. Lopez Ludena, A.Y. Brebadze, I.Y. Koyashin, and A.E. Alexenko, High Quality Diamond Film on WC-CO Surfaces, *Diamond Relat. Mater.*, 1997, **6,** p 89-94
7. I. Endler, K. Bartsch, A. Leonhardt, H.J. Scheibe, H. Ziegele, I. Fuchs, and Ch. Raatz, Preparation and Wear Behavior of Woodworking Tools Coated with Hard Layers, *Diamond Relat. Mater.,* 1999, **8,** p 834-839
8. S. Kamiya, H. Takahashi, R. Polini, and E. Traversa, Quantitative Comparison of Adhesive Toughness for Diamond Films on Co-Cemented WC, *Diamond Relat. Mater.*, 2000, 9, p 191-194
9. S. Amirhaghi, H.S. Reehal, R.J.K. Wood, and D.W. Wheeler, Growth and Erosive Wear Performance of Diamond Coatings on WC Substrates, *Surf. Coat. Technol.,* 2001, **135,** p 126-138
10. S. Amirhaghi, H.S. Reehal, E. Plappert, Z. Bajic, R.J.K. Wood, and D.W. Wheeler, Diamond Coatings on Tungsten Carbide and Their Erosive Wear Properties, *Diamond Relat. Mater.,* 1999, **8,** p 845-849
11. A. Inspector, E.J. Oles, and C.E. Bauer, Theory and Practice of Diamond Coated Metal Cutting Tools, *Int. J. Refract. Met. Hard Mater.,* 1997, **15,** p 49-56
12. H. Sein, W. Ahmed, M. Jackson, N. Ali, and J. Gracio, Stress Distribution in Diamond Films Grown on Cemented WC-CO Dental Burs Using Modified HFCVD, *Surf. Coat. Technol.,* 2003, **163-164,** p 196-203
13. W. Tang, Q. Wang, S. Wang, and F. Lu, Adherent Diamond Coatings on Cemented Carbide Substrates with Different Cobalt Contents, *Diamond Relat. Mater.,* 2001, **10,** p 1700-1704