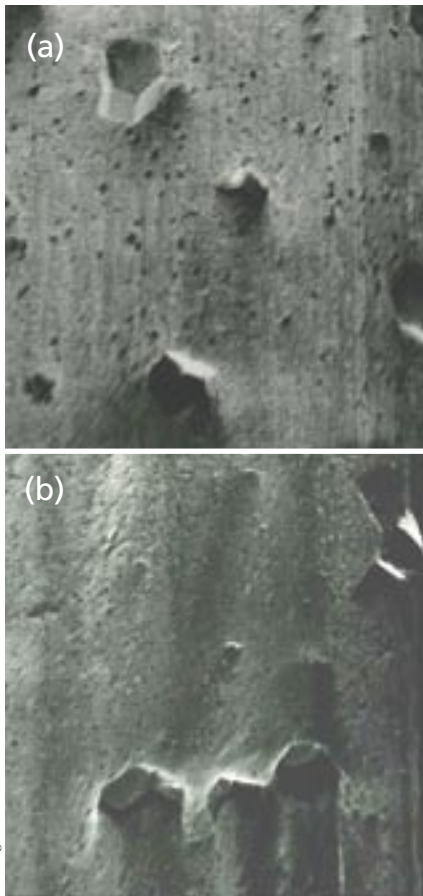


Getting the Most from Superabrasive Coatings

Good process control is critical when coating superabrasives.

Figure 1: Scanning electron microscope images show deep sockets on the wear surface. 1a: These indicate crystal pullout to be the dominant failure mode. 1b: Wear surface having well-exposed, active crystals.



All images: Diamond Innovations

Superabrasive grinding wheel performance can be demonstrably improved by use of coated crystals. Coatings enhance grain retention and protect the crystals from degradation.

However, to maximize performance, it is essential to match the coated superabrasive to the specific application.

Diamond Innovations conducted a study on the chemical nature of commercially available coatings and found that poor coating-process control can result in substantial loss of a diamond's toughness before it is subjected to the elevated temperature encountered during the wheel fabrication procedure. The researchers also studied the characteristics of coatings applied by different vapor-deposition processes and their suitability for material-removal applications.

This article summarizes the results of the study.

Crystal Pullout and Crushing

The high hardness and abrasion resistance of synthetic diamond and CBN allow wheels made from them to run at significantly higher material-removal rates and outlast conventional-abrasive wheels. The economics of operating a superabrasive wheel, however, require that the crystals be applied optimally to the end of their useful life while avoiding any premature crystal pullout or inordinate crystal crushing. Analysis of used wheels can help optimize wheel composition—the bond and crystal—around the needs of a specific application.

In a normally wearing wheel, the ratio of lost-crystal sites to active and crushed crystals should be within an acceptable range for the application. A large percentage of crushed or polished crystals indicates either the unsuitability of the abrasive grade or an inappropriate combination of crystal mesh size and abrasive concentration.

Assuming the abrasive grade and concentration are appropriate for the application, poor interaction between the crystal and the bond is most noticeable when a large number of deep pullout sites are present, such as in Figure 1a. The absence of any chemical alloying between a resin or metal bond and the superabrasive can result in premature crystal pullout. Mechanical anchoring of the crystal by the encapsulating resin or metal bond alone, without a beneficial chemical wetting of the bond and crystal, might be insufficient to retain the crystal as it engages the workpiece. Wetting of the coated abrasive by the bond components can be inferred by visual examination of the fracture surfaces of a segment. Experimental confirmation is achieved by generating X-ray maps of the bond elements using energy-dispersive spectroscopy. Figure 1b shows a worn surface with well-exposed whole crystals that are likely engaged in material removal.

Finally, in metal-bond wheels, the use of less-expensive but chemically reactive or catalyzing metals can aid in the degradation of abrasive toughness during wheel processing. Such weakened crystals can result in an undesirable distribution of crushed sites, which results in poor grinding performance.

Thus, there is a well-recognized need for maintaining the toughness of the crystals in a bond while retaining the working crystals for as long as possible. Properly coated superabrasives help ensure this occurs.

Double Protection

The benefits of superabrasive coatings are twofold. Under the appropriate processing conditions, they can aid in crystal retention and provide chemical and thermal protection to the abrasive crystals.

Coated diamond crystals were initially identified as improving the retention of working crystals. Resin-bond grinding wheels, processed at a low temperature and made with a friable diamond, were observed to suffer from premature crystal loss. The introduction of nickel-clad diamond in the 1960s significantly extended wheel

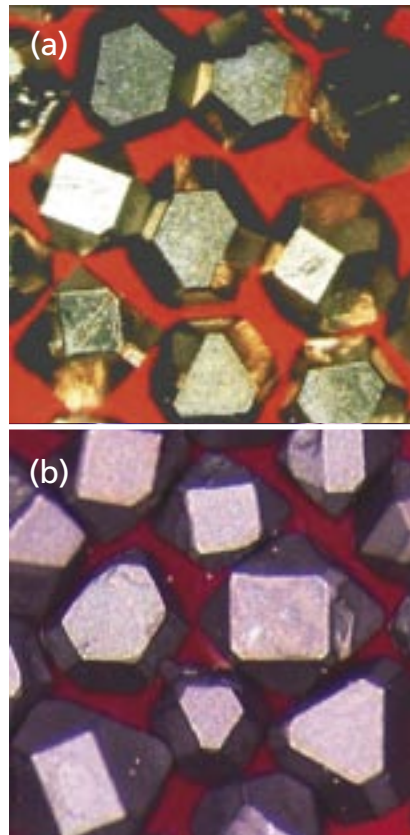


Figure 2: High-temperature CVD coatings on diamond. 2a: chromium carbide. 2b: silicon carbide.

life. A crystal that remains in the bond for the length of its useful life enables the wheel maker to rationally determine the appropriate diamond content required.

In metal bonds, the advent of coated diamond allowed the use of inexpensive but reactive bond materials, like iron. Such materials can react chemically with the carbon (diamond), causing a loss of crystal toughness. The coating's protective layer, which prevents a direct interaction between the bond and

the diamond, inhibits the oxidation of crystals at the elevated temperatures reached during wheel manufacturing. If diamond surfaces are exposed to oxidation during the manufacturing process, typically because of limited atmospheric control, the result can be poorly performing wheels.

In a wheel requiring high processing temperatures, the use of uncoated diamond is associated with degradation of its surface properties. This degradation manifests itself as pitting on the crystal facets and loss of sharpness at the edges, owing to a temperature-driven reaction between the diamond and the matrix the diamond is embedded in. Coatings can protect the crystal surface from such thermal damage.

Low-Temperature Coatings

The processes used to deposit coatings on diamond and CBN can be broadly classified into two groups: low temperature and high temperature.

The temperature at which a coating is deposited is indicative, approximately, of the processing temperature of the targeted bond. Low-temperature coatings are usually quite thick and comprise a substantial portion of the abrasive mass. These coatings are applied at temperatures lower than 100° C.

Electroless coatings involve deposition of nickel, copper or silver alloys on crystals without means of an external power source. These uniform-thickness coatings are achieved using reducing agents in a metal alloy solution, where the substrate material, or crystal, is immersed.

Electrolytic coatings employ a suit-

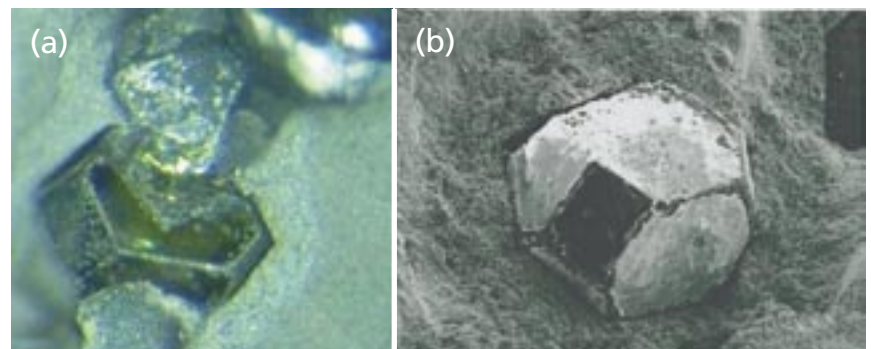


Figure 3: Micrographs show fracture surface of a titanium-tungsten PVD coating on a diamond in a 100 percent cobalt bond, sintered at 825° C for 5 minutes.

3a: Fracture surface shows evidence of crystal degradation in the form of pitted facets. 3b: loss of edge sharpness.

able solvent bath in which the substrate to be coated acts as the cathode, or negative terminal, while the metal to be deposited comprises the anode, or positive terminal. Under appropriate power settings, the electrolytic reaction preferentially deposits metal ions on the cathode.

Diamond coated by the electroless and electrolytic nickel processes are most common in phenolic and polyimide resin-bond wheels used to grind tungsten carbide and cermet.

High-Temperature Coatings

Diamond and CBN crystals that show a negligible drop in toughness when heated to 1,100° C are said to be thermally stable. Coating processes requiring high temperatures are most suitable for crystals possessing a high degree of thermal stability. These coatings are typically quite thin, on the order of 2µm to 10µm, and find application in metal-bond wheels processed at temperatures from 600° to 1,100° C.

Primarily, there are two kinds of high-temperature coatings: physical vapor deposition and chemical vapor deposition.

PVD is used to deposit elemental metal coatings on superabrasives. The typical coating temperature is about 500° C. The coating cycle times are long—lasting up to several hours, depending on the required coating thickness. Owing to the nature of the process, the coating normally comprises properties akin to that of a peanut shell, wherein the coating encases the crystal and has no chemical attachment to the abrasive substrate.

Compared to CVD processes, PVD is not as good for coating complex shapes, such as highly textured crystals. Commercial examples of such coatings on diamond crystals include elemental titanium, tungsten and combinations thereof.

CVD is used to deposit carbides of transition metals on diamonds (Figures 2a, 2b) and metal nitride and borides on CBN crystals. The typical peak coating temperature is from 600° to 800° C, and the cycle time is generally about an hour. Unlike PVD coatings, the chemical attachment to the abra-

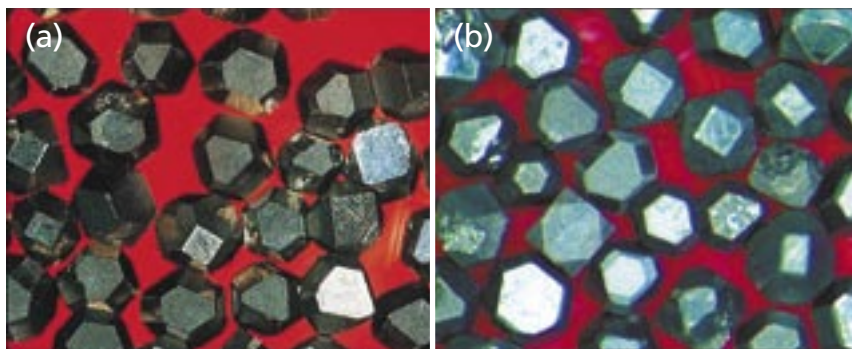


Figure 4: Visual comparison of two commercially available TiC CVD coatings. 4a: Diamond Innovative's Ti2. 4b: a competitor's product. Under an optical microscope, the coatings are similar in color and texture.

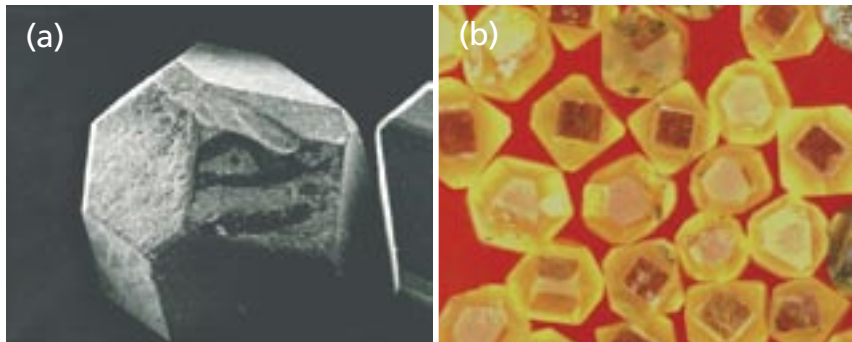


Figure 5: Commercially available, competitive TiC CVD coatings. 5a: Image shows apparent nonuniformity in the thickness. 5b: Widespread etching visible on the underlying crystal after the coating was stripped, indicating process-associated damage.

sive substrate via the carbide or nitride formation enables a firm attachment of the CVD coating to the crystal.

High-temperature coatings on diamond and CBN are prone, by the nature of the process, to cause the mechanical properties of superabrasives to deteriorate. Therefore, it is essential to confirm, by stripping the coating and evaluating the underlying crystal, that the coating process has not degraded the crystal by differential expansion of metallic inclusions embedded in the crystals or introduction of crystal surface defects. Expanded metallic inclusions in diamond reduce a crystal's fracture toughness by providing an initiation and propagation path for cracks.

Coating Evaluation

It is possible to gauge the usefulness of coated crystals in a particular bond system before it is subjected to elaborate material-removal trials. Optical and scanning electron microscopy of fracture surfaces of wheel segments

provide ample indication of the compatibility of the coating with the bond. In addition, energy-dispersive X-ray spectra of these fracture surfaces enable evaluation of the extent to which the bond constituents can wet the coating. This, in turn, is a reliable indicator of the potential improvement in crystal retention compared to an uncoated crystal.

For example, a PVD coating comprised of titanium and tungsten was tested in a 100 percent cobalt bond sintered at 825° C for 5 minutes. Micrographs of the fracture surface (Figure 3) show that the coating provided no crystal protection. This is seen in the pitted crystal facets and loss of edge sharpness, which, in turn, are likely to degrade wheel performance.

CVD coatings are, by their very nature, associated with a high processing temperature. It is essential to protect the integrity of the crystal during the coating process. High-temperature or reactive environments can drastically degrade toughness and, therefore, the

material-removal capability of the diamond or CBN crystals.

Figures 4a and 4b depict two commercially available TiC CVD coatings on diamond. Externally, they possess similar dark and shiny visual attributes. However, a closer look at the characteristics of the crystals, from another vendor, reveals the problems with the coating (Figure 4b).

An evaluation under a scanning electron microscope shows the nonuniform deposition (Figure 5a) of one of the coatings (Figure 5a) of one of the coatings (Figure 4b) on the crystal. Furthermore, when the coating is removed from these crystals, the underlying diamond shows widespread etching (Figure 5b).

Etched diamond surfaces correspond to areas where the carbon has been eroded, giving it a frosted appearance. The integrity of the crystal appears compromised even before it is subjected to the thermal cycle during wheel fabrication. Such nonuniformly coated crystals are likely to display little of the retentive benefits expected from the coatings and are likely to be crushed prematurely under material-removal loads.

Titanium-carbide coatings are deposited at high temperatures. In the absence of due process control, the coating temperature cycle can expand the metallic inclusions commonly found in synthetic diamond. These inclusions, which expand and contract at a different rate than diamond during the coating cycle, act as failure-initiation points.

Figures 6a and 6b show stripped crystals that were coated with TiC. The poor process control and the resulting expanded inclusions are prominently visible (Figure 6a). In contrast, in crystals subjected to a rigorous process control, inclusions grew minimally (Figure 6b).

The toughness-index drop of these stripped crystals (Figure 7) suggests a correlation with the visible inclusion expansion. In Figure 7, sample A, which corresponds to Figure 6a, shows a much larger decrease in crystal toughness compared to sample B, which was coated with Diamond Innovations

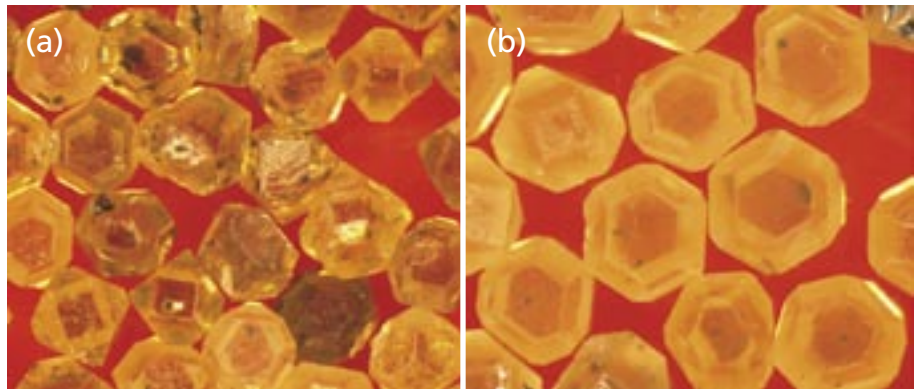


Figure 6: Comparison of two commercially available CVD TiC-coated diamonds after stripping. 6a: Poor coating processes result in uncontrolled growth of metallic inclusions, which act as diamond failure sites. 6b: In the Ti2 coating, the process has minimal negative impact on a diamond's strength. Note the barely visible inclusions.

Ti2 coating (Figure 6b). This effect on crystal integrity arises purely from differences in the extent of control over the respective coating processes.

Coatings are expected to act as a barrier, protecting the crystal from chemical attack by reactive components in the matrix. Nonuniform coatings or coatings having a suboptimal thickness provide only marginal protection compared to an uncoated abrasive.

Two commercially available CVD

TiC coatings, on diamond of comparable grade, were exposed to identical 1,000° C segment fabrication cycles to produce segments of bronze-infiltrated tungsten. The fracture surfaces of the segments were analyzed. The red circles in Figure 8a indicate substantial weakening of the coated crystal, resulting in a catastrophic cleavage of diamond crystals at segment fracture. After the crystals were reclaimed and stripped of their coating, the underlying-

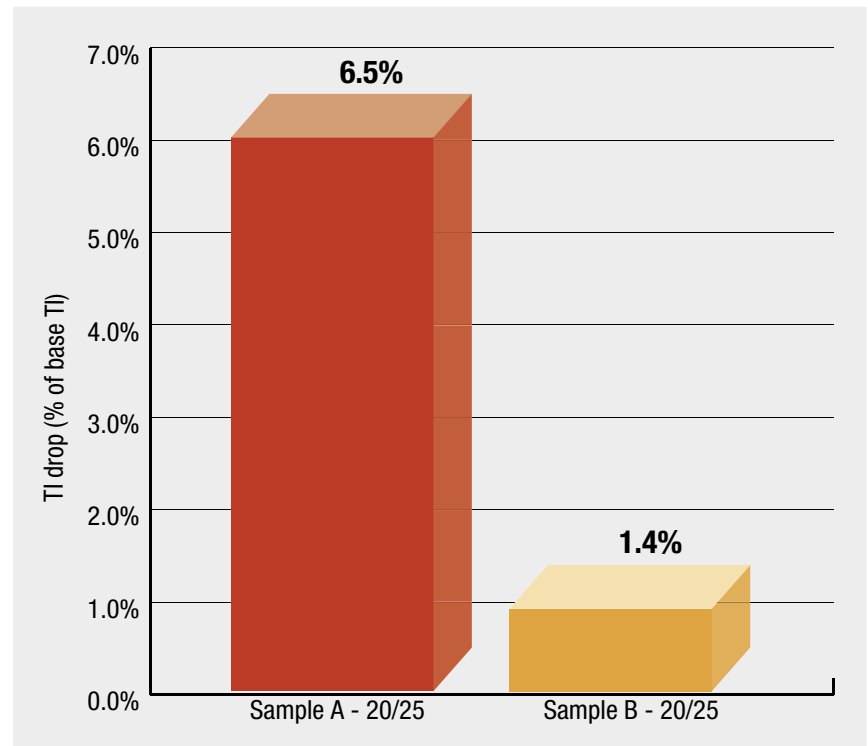


Figure 7: Toughness index (TI) of stripped and reclaimed TiC-coated diamond. Sample A (Figure 6a) from one vendor has a bigger drop in TI, which is related to the large growth of metallic inclusions in the diamond. The Ti2-coated sample B (Figure 6b), coated under controlled conditions, has a negligible TI drop.

ing crystals were found to be severely graphitized, as shown in Figure 8b. This is due to the minimal protection offered by the coating, leaving the diamond vulnerable to a deleterious conversion back to graphite.

In contrast, the fracture surface of the segment made with Ti₂-coated diamond showed little evidence of crystal cleavage, indicating that the crystals retained their inherent toughness (Figure 9a). After the crystals were reclaimed and the coating stripped (Figure 9b), there was no evidence of back-conversion to graphite. The crystals do, however, display some signs of expanded metal inclusions, which are unavoidable at the 1,000° C processing temperature and the long cycle time.

Help or Hinder?

The potential benefits of coating superabrasives are enormous. However, it is critical to distinguish between coatings that are likely to provide measurable grinding improvement and those that inflict damage and reduce the utility of the substrate superabrasive crystal.

Electroless and electrolytic coatings are suited for bonds processed at low temperatures. The thick and textured coatings—when deposited properly—provide the benefit of crystal retention with little coating-associated crystal degradation.

Of the high-temperature coating processes, PVD coatings with their shell-like structure are seen to be incompatible with traditional metal-bond wheels. It is likely that the long deposition times induce unwanted damage in the crystals.

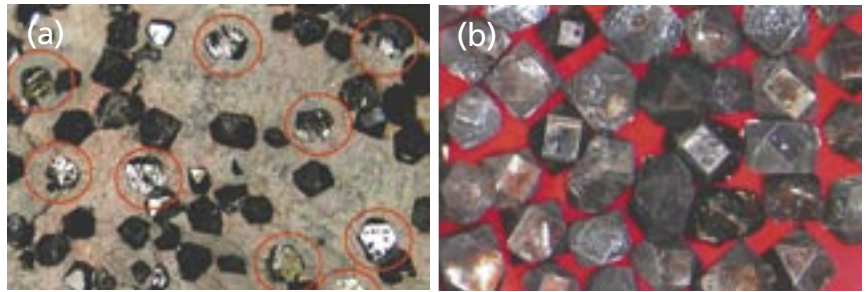


Figure 8: A commercially available TiC CVD coating in a matrix primarily comprised of tungsten and infiltrated with bronze at 1,000° C. 8a: The red circles show diamond crystals catastrophically cleaved during segment fracture, which indicates severe crystal weakening. 8b: The reclaimed crystals when stripped of their coating display graphitization, which shows the poor crystal protection of the coating.

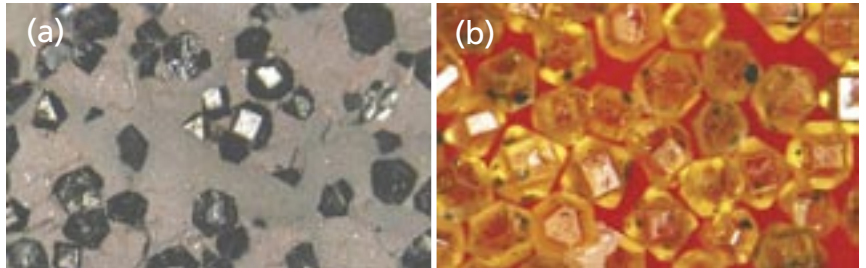


Figure 9: Ti₂-coated diamond in tungsten matrix infiltrated with bronze at 1,000° C. 9a: The fracture surface shows few cleaved crystals. 9b: The reclaimed and stripped crystals show no surface damage. Note the expanded metallic inclusions in the interior, though, which is the effect of the elevated segment processing temperature.

CVD coatings can provide demonstrable advantages in grinding performance. However, not all CVD coatings are alike. Coatings from different vendors may possess similar chemical compositions but behave differently in identically processed bond systems. Differences in the coating processes, including inappropriate process control, at different vendors are shown to leave the crystals vulnerable to severe degradation.

Fortunately, by utilizing methods to assess compatibility, wetting, adhesion and crystal degradation, the potential usefulness of various coatings can be

evaluated relatively quickly before investing in field trials. Δ

This article was adapted from a paper the author presented at the Industrial Diamond Association's Intertech 2006 conference.

About the Author

Sridhar Kompella, Ph.D., is an applications development engineer for Diamond Innovations Inc., Worthington, Ohio. For more information about the company's superabrasive products, call (614) 438-2000, or visit www.diamondinnovations.com.