# Crystal Retention Improves ROI and Performance of Diamond Tools

Steven W. Webb, Ph.D.
MBS* Diamond Process Engineer,
GE Superabrasives

The most efficient method for cutting and drilling concrete is using saws and drill bits containing manufactured diamond. This diamond is advanced engineered to provide the specific attributes of size, shape, and impact resistance needed to achieve optimal performance for different types of materials, conditions and operations. Not only does manufactured diamond cut greater amounts of concrete in a given period than conventional abrasives, but it also provides a significantly longer tool life. Therefore, while diamond is not the cheapest abrasive, it offers the highest return on tool investment in terms of efficiency, productivity, quality and value.

**Formula for Success**

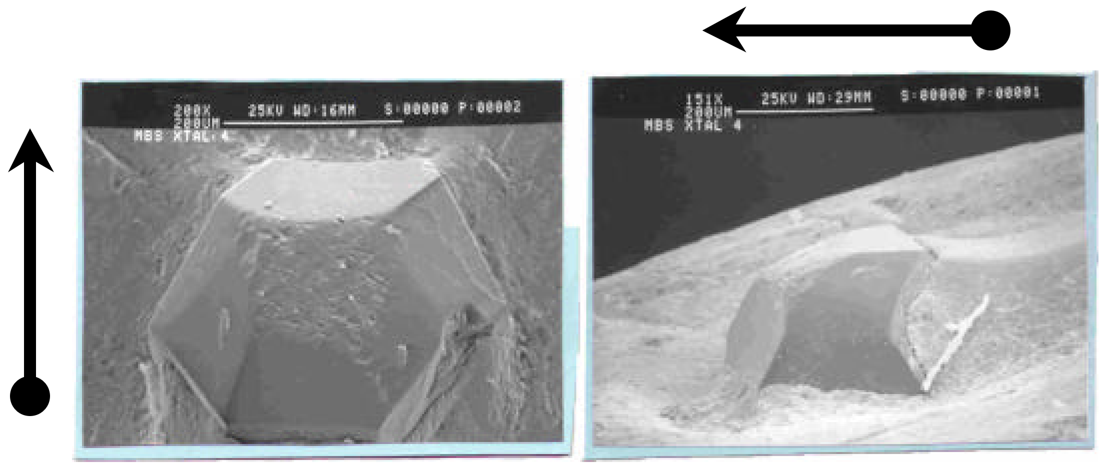
A key factor in ensuring superior diamond tool performance and maximum work life is retention of individual crystals. To create a concrete saw or drill bit, diamond is bonded in a matrix of metal powder through compression derived from sintering and contraction of the matrix under heat and pressure. The sintered metal and diamond segment is then brazed or welded onto a saw blade or drill core and then powered by a machine specified for the desired application. How well this tool performs is determined by the degree of crystal retention in the segment.

Crystal retention may be quantified as a ratio,

$$\text{retention, } R = \frac{\text{yield strength of the bond-to-crystal interface}}{\text{applied dynamic contact stress in the tool}}$$

where yield strength refers to “dynamic” hardness. If R is greater than 1, the crystal has good retention with the bond matrix. High R is achieved with a good bond exhibiting high compressive stress from sintering, as well as a high level of friction and adhesion between the diamond and the matrix. Scanning electron micrographs of working and worn crystals in a saw blade show an example of good retention.

In the figure the arrows denote the direction of stone-diamond cutting point contact at a speed of ~30m/s.

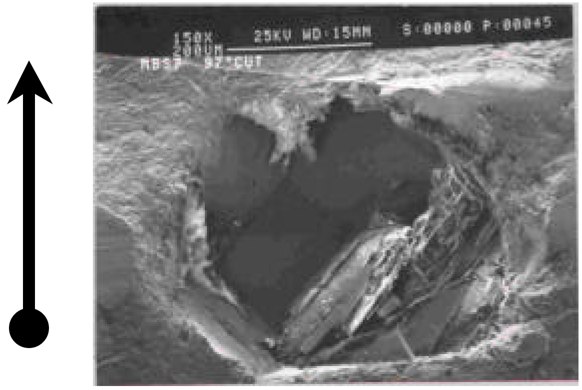



There is no gap between bond and crystal, particularly at the contact/leading edge. The bond tail at the trailing edge is smooth and un-eroded.

**Higher Grade Diamonds Require Better Bonds**

Inevitably, over time, cutting or drilling wear affects both the diamond crystal and its matrix. The rapidity and extent of tool wear depend upon many factors, including hardness, aggregate type, and abrasiveness of the concrete, cutting rate, type of metal used in the bond matrix, and density or concentration of the diamond crystals e.g., a greater number of crystals reduces contact stress per cutting point. Depending upon these variables, at some point the impact of sawing or drilling will cause detachment of the bond matrix from the diamond. When this occurs, the crystal may "pop out" of the matrix, leaving a hole. If these "pop outs" occur prematurely, before each diamond has been used for a maximum amount of work -- by breaking down at a gradual, slow rate, they impact performance by lowering cutting efficiency.

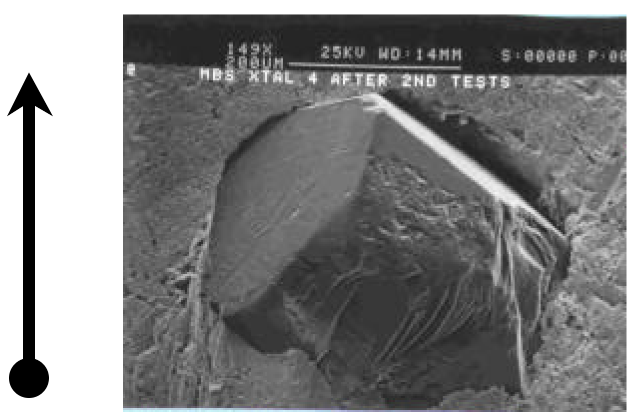
An example of a popout is shown below.




The crystal is gone, leaving an empty pocket in the bond. There is diamond wear debris in the pocket indicating that crystal failure occurs prior to, or concurrent with, popout and there is weak adhesion diamond-matrix with this bond. The bond tail is gone as well. There is no protruding crystal to protect the bond from the hard stone work piece and abrasive debris. Tool life suffers accordingly.

Crystal retention is especially crucial in "severe" applications, such as sawing and drilling reinforced concrete and hard stone, which typically demand the use of ultra-high grade (UHG) diamond. Because UHG crystals are tougher and potentially protrude higher than lower-grade diamond, they exert a stronger impact force that enables higher material removal rates. This places greater stress on the diamond to matrix bond, putting crystals at risk for early pop-outs. If crystal retention is inadequate, the bond may fatigue or fail prematurely, wasting the investment in UHG cutting points.

An example of bond fatigue, usually predicting eventual crystal crushing or popout, is shown below.



The bond is clearly deadhered from the crystal at the most critical leading edge. There is also deep erosive damage. The bond tail is also not well formed. Not surprisingly, the crystal is showing deep fracture damage at the trailing edge where reflected tensile strain is highest. Bond retention in this case is limiting tool life.

**Crystal Retention Key To Optimization**

Several factors can contribute to premature loss of diamond, including chemical attack during sintering that can damage the diamond surface and negatively affect the bonding. Diamond manufacturers and toolmakers have devoted significant research to improving crystal retention and have developed a number of options. However, each carries certain drawbacks:

- Sintering at a higher temperature or for a longer time, or adding harder alloy metals to the matrix increases yield strength of the diamond to bond interface but also changes the bond hardness and possibly its abrasion rate, altering tool behavior. While UHG crystals are more thermally stable, excessive temperatures will degrade the toughness of diamond crystals, particularly if there is specific and aggressive carbide formation e.g., Fe in the bond.
- Increasing bond density with higher press force or lubricants can increase retention but at the cost of increased die wear.
- Reducing loading on individual crystals by slowing the cutting rate, increasing the number of cutting points, or using lower-grade diamond (to reduce crystal protrusion) reduces contact stress, improving retention, but negatively impacts tool performance.
- Reducing oxide content of metal powder reduces chemical attack on the crystal and gas formation at the bond interface, but can add cost to the process.

**Advanced Coatings Strengthen Diamond-to-Bond Interface**

To address retention problems without changing the matrix composition or the sintering process, or limiting tool performance, researchers at GE Superabrasives have developed another option – thinly coating diamond crystals with metal. Through both chemical and mechanical attachment, coatings have been shown to improve the yield strength of the bond at the diamond interface.

Matrix compressive stress multiplied by diamond-to-matrix friction coefficient creates the retention force that the counters the wear-producing contact force. The compressive stress, 'hugging' the crystal cutting points, arises from differential thermal contraction of diamond vs. matrix plus contraction in sinter, limited by yield of the matrix. The interfacial shear strength reduces cyclic deformation that fatigues the crystal-matrix interface, cracking, chipping and eroding it. A coating that is durable and adherent can substantially improve that friction coefficient.

Additionally, a well-bonded, complete coating improves strain transparency at the diamond-matrix interface. To minimize wear on the crystal, it is important to transfer the contact strain energy from the cutting point leading edge through to the tool shaft, motor and frame. In essence, the diamond cutting point acts as a lens for strain much as glass acts as a lens for light. An inefficient cutting point absorbs or reflects strain internally and suffers wear; an inefficient lens, that internally reflects or absorbs light, heats up and distorts. Ideally, a diamond cutting point passes strain energy (a property termed *acoustic impedance*) to the saw blade or drill bit where it is absorbed with less cost for e.g., through frame vibration or motor heat. Strain transparency depends on the elastic stiffness and density gradient across the matrix-to-diamond interface. It also depends on the spectral content and magnitude of the strain, which depends on work piece and cutting condition. Coating the diamond, like anti-reflective coatings on glass lenses, is an effective way to decrease acoustic impedance and improve cutting point performance.

Finally, coating the diamond can impede aggressive chemical reaction between bond matrix and diamond. Coating can 'inert' the diamond permitting use of more aggressive bond matrix elements to boost matrix yield strength without adverse chemical attack on the diamond.

**Lab Tests Confirm Coating Advantages**

In a recent study, scientists at GE Superabrasives tested the retention of metal-coated versus uncoated diamond crystals. Diamond and cobalt segments were identically prepared using MBS*960 diamond 45/50 mesh crystals that were coated with 0.5 micron of titanium (denoted Ti2), 1.0 micron of chromium (denoted Cr2). To simulate wear on the segments, and prepare them for hardness measurement, the segments were machined to ~20 micron flatness using a 170/200 mesh RVG* diamond wheel.

A method, called "differential hardness", was used to evaluate crystal retention in the machined segments. This method involves locating a machined diamond, aligning a worn, $120^{o}$-diamond indentor over it and applying load to cause indentation. The deformation deadheres and pushes the bound crystal down into the bond. Alternately, the indentor is applied to the matrix adjacent to that crystal. The hardness of the matrix is subtracted from the apparent hardness of the bound diamond and becomes a measure of retention. The weaker the diamond-matrix interface the greater the difference.

Table 1 shows results. The difference hardness was most pronounced (-10 percent) in the uncoated diamond, indicating relatively weak retention. In contrast, the chromium-coated diamond demonstrated the highest retention. With chromium coating the matrix under the diamond was actually harder (+1.6 percent) than the matrix. In fact, the chromium coating was so strong that the indentor tips frequently failed before the crystal or bond. The hardness, and thus abrasion resistance, of the matrix was unaffected by crystal coating. This result is of course specific to the metal type and sintering conditions used in this work. Other bonds, with varied metallurgy, that may or may not attack the coating, will certainly produce a different response.

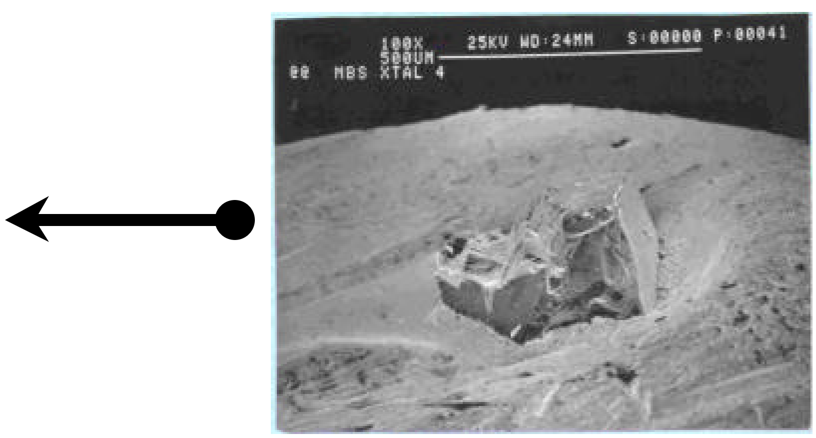
Table 1: Hardness of Matrix and Coated Diamond Crystals

| | Uncoated | | Cr2 Coated | | Ti2 Coated | | Diamond-free |
|---|---|---|---|---|---|---|---|
| | Diamond | Matrix | Diamond | Matrix | Diamond | Matrix | Segment |
| average hardness | 62.43 | 68.64 | 71.67 | 70.5 | 65.44 | 67.55 | 67.6 |
| standard deviation | 4.82 | 1.55 | 4.93 | 0.71 | 4.24 | 2 | 0.69 |
| difference | | 6.2 | | -1.16 | | 2.11 | |
| no. of indents | 18 | 18 | 3 | 2 | 15 | 23 | 10 |

The chromium coating (and to a lesser extent titanium) is an excellent carbide former. This is the heart of its efficacy in improving matrix-to-diamond friction. During coating and sintering, these metals form a new surface phase that enhances friction by increasing wetting and adhesion at the diamond-to-matrix interface. In contrast, uncoated diamond directly bonded to a cobalt matrix demonstrated a lesser degree of friction.

To verify the retention effect of the chromium coating, GE Superabrasives conducted saw tests that compared the tool performance of coated and uncoated diamond. To limit crystal retention, the researchers selected two severe applications, one with high contact load and the other with a highly abrasive work piece material that produces high bond erosive wear. The high contact load saw tests with 45/50 mesh Cr2-coated UHG crystals were performed in hard, Class V, bright-red granite at a relatively high cutting rate of $300cm^2$/min. The test results produced no observable benefit of coating mainly because crystal wear rate and crushing was limiting performance.

An example of crushing, without popout, is shown below. Retention is not limiting protrusion in this condition and coatings will not improve performance.




This is an important practical point -- if crystal retention is not limiting bit or blade performance, a coated diamond will not provide any advantage.

A second series of tests, performed with uncoated and titanium-coated diamond in abrasive granite-aggregate concrete, resulted in a 50 percent lower wear rate for the coated crystals (Table 2). In this application retention was limiting due to the high depth-of-cut and abrasive debris.

| Product | WP (m2/mm) |
|---|---|
| MBS960 Ti-coat | 39.1 |
| MBS960 | 16.6 |

Table 2: Effect of Ti Coating on Wear Performance in Concrete

**Ti2 or Cr2 a Match For The Matrix**

Coating manufactured diamond with a thin layer of chromium or titanium was shown to be effective in increasing crystal retention. A coating can add texture to the otherwise flat and smooth diamond surface, enabling better mechanical adhesion to the matrix. In addition, during the sintering process, these coatings react chemically with the matrix powder to form a hard, binding carbide or alloy phase that strengthens the bond between the diamond and the matrix. Further, they protect the diamond from chemical attack by the resulting metallic carbide. To achieve these desired results, the coating must be compatible with the matrix material.

**Turning Diamonds into Cash**

Concrete cutting and drilling must often be completed under strict time, cost and performance constraints. Selection of the most efficient, durable abrasives can make a critical difference in each of these areas. Diamond saws and drills have been widely adopted by the concrete industry because of the superior value they deliver. Enhancing these tools with thin-metal diamond coatings, in appropriate applications, can significantly increase their performance and extend their useful life. Overall, diamond coatings have proved a powerful addition to the industry's ongoing refinements to manufactured diamond resulting in more cost effective and highly productive operations.

**References**

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