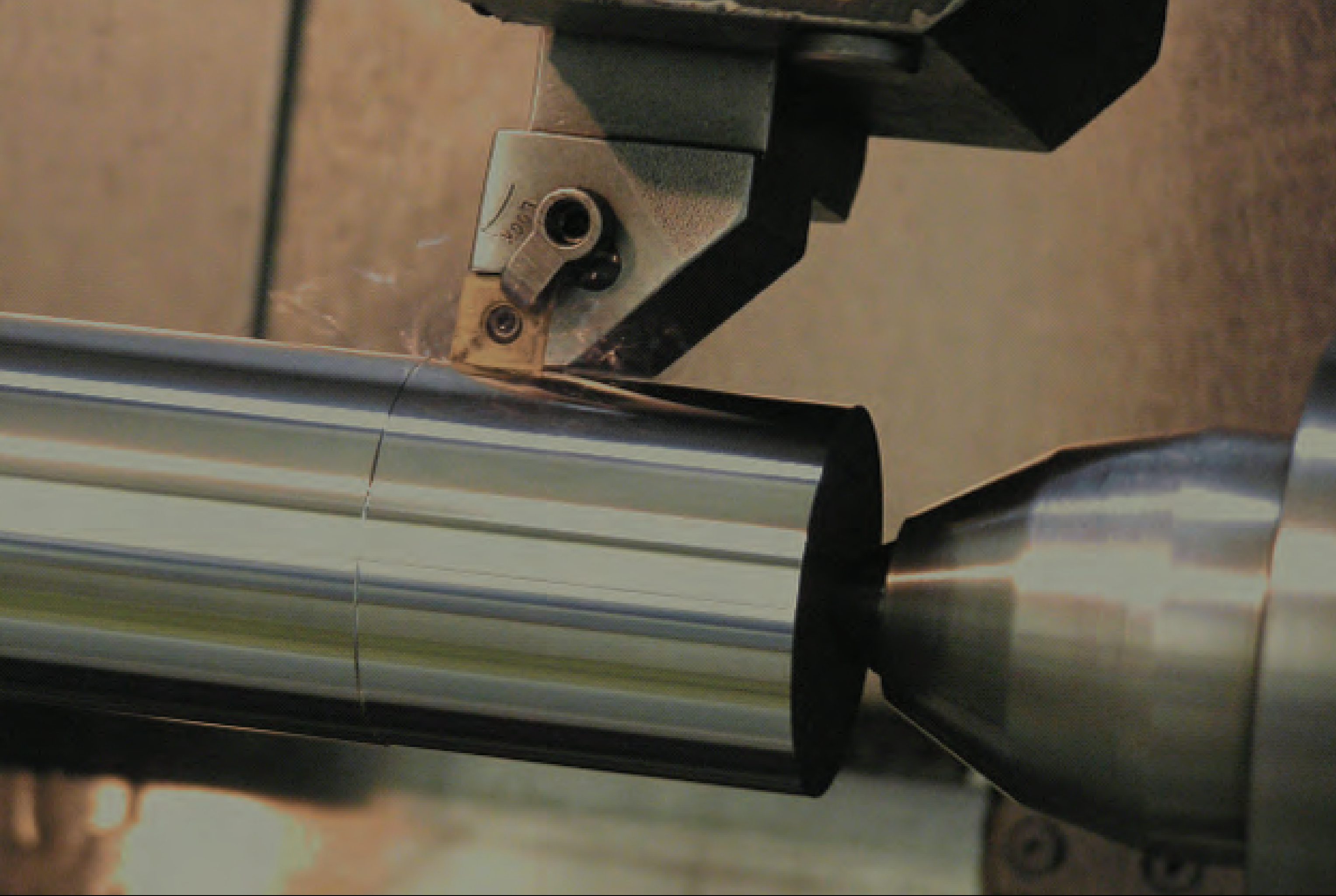


***A nano and micro composite coating series based on cubic born nitride (cBN) particulates and choice of applications specific binders was developed for machining engineering materials. The coating series were produced via two-step sequential processes: electrostatic spray coating (ESC) of nano and micro sized cBN particles (<2 μm) for a conformal porous coating green preform of designed thickness followed by chemical vapor infiltration (CVI) of ceramic binder phase(s) at a temperature of around 1000oC for a dense and well adherent composite coating. This article shares application cases where the new coating was tested for its performance in turning AISI 4340 hardened steels, AISI 4140 pre-hardened steel, and ductile cast iron at representative application conditions, and compared to correspondingly industrial benchmarks. Testing results showed that the new cBN coating outperforms its industrial counterparts, such as polycrystalline cubic nitride (PCBN) brazed inserts, titanium aluminum nitride (TiAlN) deposited by physical vapor deposition (PVD), multi-layer coating by chemical vapor deposition (CVD), and aluminum oxide ($Al_2O_3$) bulk tools, in respective applications.***

# Cubic Boron Nitride (cBN) Coated Cutting Tools for Advanced Machining

*By: Wenping Jiang, Bob Reed, Henry Renegar, Calvin Goforth and Ajay P. Malshe*
*Duralor LLC, Springdale,* Arkansas 72764

## *Introduction*

Diamond is the hardest material known and has been used as a cutting tool for long time. However, because of its aggressive reaction with iron, it cannot be used for cutting ferrous alloys. Boron nitride based tool, on the other hand, has an outstanding thermal stability and chemical inertness to iron and lists as a second known hardest material. Diamond and boron nitride (BN) based tools compliment each other - diamond can cut only non-ferrous materials (volume of 75-80% of the total machining market) and boron nitride can cut all ferrous alloys (volume of 20-25% of the total machining market). Currently, sintered cBN ceramic brazed tools have been used in sawing, cutting and crushing applications whereas thin film cBN is the best candidate for the coating on cutting chip-breaker tool inserts, rotary tools and wear parts. The polycrystalline boron nitride

**FIGURE 1: Image showing examples of turning inserts coated with the new cBN coating.**

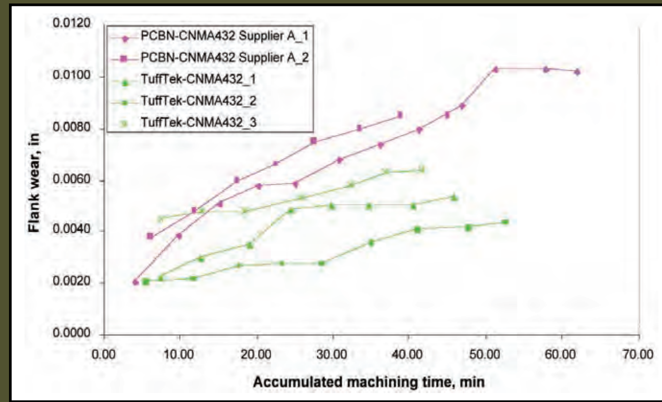



**FIGURE 2: A comparison of tool performance between cBN coated and PCBN tipped inserts.**

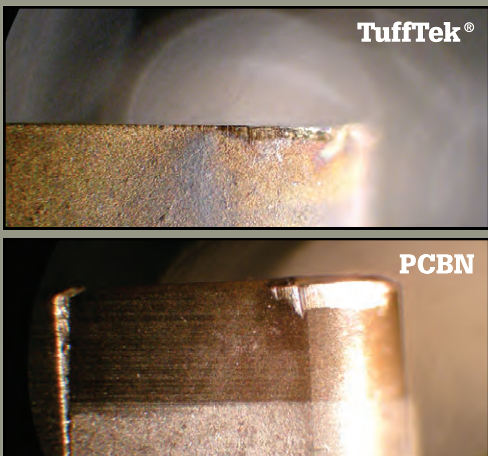



**FIGURE 3: Typical flank wear on cBN-coated insert and PCBN tipped insert.**

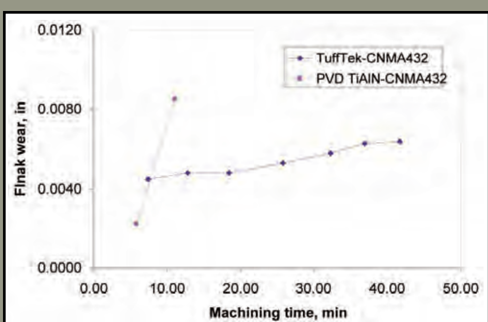



**FIGURE 4: Graph showing the tool performance of cBN coated insert and PVD TiAIN coated insert in continuous turning of AISI 4340 hardened steel.**

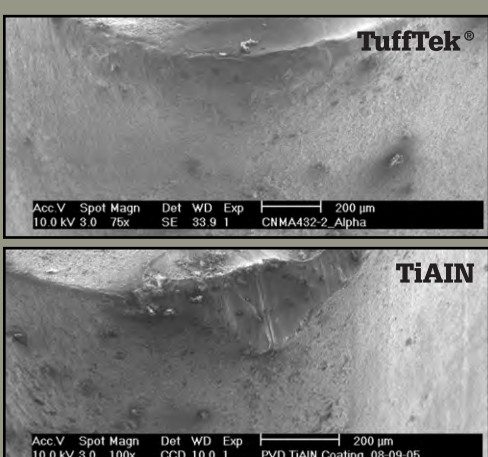



**FIGURE 5: SEM images showing the wear of cutting edge for cBN coated inserts and PVD TiAlN coated inserts.**

(PCBN) tools, synthesized using HPHT cBN crystals, have been proved to perform well in the machining of hardened steels and creep resistant alloy. The cBN tools possess all the required properties of a best-suited cutting tool. Despite the increased use of aluminum-silicon and other non-ferrous alloys, steel and cast iron are still the most abundant material in the heavy and automotive industries. For example, machinability of cast iron depends primarily on its microstructure but also on the amount of sand in casting, the distribution of chills and on the dimensional variations due to casting swell. PCBN tools are extremely successful in machining gray cast iron, particularly in machining homogenous pearlitic castings. In spite of its superior chemical stability, cBN hard coating was far from realization due to the poor success achieved in cBN thin film synthesis, with the state-of-the-art vapor deposition techniques, which includes physical and chemical vapor depositions, and hybrid techniques - those involving the mixture of the previous two techniques. Thus, the event of realizing cBN-coated tools was waiting for a major breakthrough in integrating cBN phase with thickness higher than about 500 - 800 nm. Machining hardened steel and cast iron is poised to become a major application of new cBN-coated tools. In fact the manufacturing process flexibility and cost of these tools allow them to complete with not only PCBN but also TiAlN, multilayer and other ceramic tools. In the major award winning and patented breakthrough Duralor and NanoMech in partnership with the University of Arkansas have developed 3D coating chemistry, unlike layered counterparts, and commercialized a hybrid coating process technology for realization of cBN composite coatings on carbide cutting tools of various designs (Figure 1). This hybrid technology combined electrostatic coating of cBN preform followed by chemical vapor infiltration (CVI) of a binder such as TiN, TiC, TiCN, HfN, etc. allowing desired application specific chemistries, thicknesses, conformability, manufacturability and cost. Following is an overview of the application notes comparing the superior performance of the new cBN coating with state of the art, PCBN brazed and PVD TiAlN coated inserts, as well as ceramic inserts.

## *Application Cases for cBN Coating in Turning Engineering Materials*

In the following application notes, the cBN coated tool performance was evaluated in turning engineering materials including hardened steels, pre-hardened steels, and ductile irons, and compared to its corresponding industrial benchmarks in terms of tool life and tool wear.

### TURNING AISI 4340 HARDENED STEEL

The workpiece was AISI4340 hardened steel with hardness of 50~52 HRC (L=125mm, D=62.5mm). The turning process was continuous with water-based cutting fluid. The cBN (Grade TTH-500) coated inserts were CNMA432. The benchmark inserts were all CNMA 432 for polycrystalline cubic boron nitride (PCBN), PVD TiAlN coated inserts, CVD multi-layer coated (TiN-TiCN-$Al_2O_3$-TiN) inserts, and bulk $Al_2O_3$ inserts. The machining condition applied are typically recommended for semi-finish and finish turning alloy hardened steel using polycrystalline cubic boron nitride (PCBN) tipped or bulk inserts. The conditions were also within the range recommended for the other benchmark inserts. The specific machining condition was: surface speed, V=150 m/min, feed rate, F=0.15 mm/rev, depth of cut=0.25 mm.

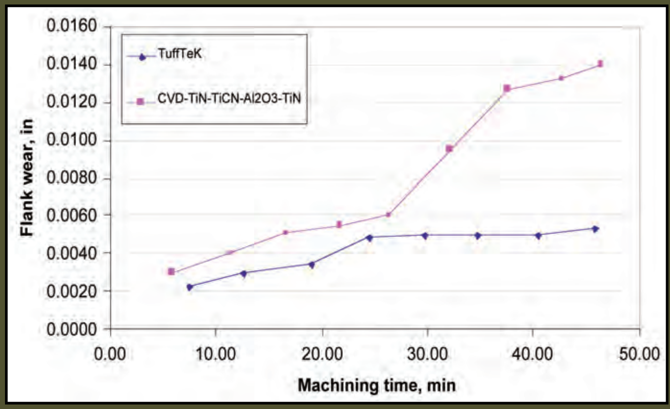



**FIGURE 6: Graph showing the tool performance of cBN coated and CVD multi-layer coating in continuous turning of AISI 4340 hardened steel.**

### *The cBN Coating vs. PCBN*

Figure 2 shows a comparison of tool performance between cBN-coated inserts and PCBN tipped inserts. In an important finding, cBN coated carbide inserts produced same or better tool life as compared to the PCBN chip brazed inserts, with much lower flank wear. Additionally, cBN coated carbide inserts provides various designs for chip breaker geometries, which facilitated the chip control specially for turning alloy steel with medium to high hardness. In terms of cost, cBN coated inserts cost only about 50~70% of the PCBN tools. The extended tool life and reduced cost from cBN coated inserts directly contributed to the gain higher productivity and significant cost saving. The typical flank wear of the tested cBN coated inserts and PCBN tipped inserts are shown in Figure 3. After more than 40 minutes of turning, cBN coated insert showed slight and uniform flank wear, while PCBN insert showed a notch at its trailing edge, in addition to more distinguishable flank wear compared to cBN coated inserts.

### *The cBN coated vs. PVD TiAlN coated inserts*

PVD TiAlN coating is widely used in turning alloy steels. It is also recommended for machining alloy-hardened steel. At the aforesaid machining conditions, the tool performance of cBN coated inserts and PVD TiAlN coated inserts is shown in Figure 4. The cBN coated inserts demonstrated more than 300% of tool life extension over PVD TiAlN coated inserts. SEM examination on the tested inserts demonstrated an even flank wear and moderate crater wear of cBN coated insert, while severe flank wear and crater wear of the PVD TiAlN coated insert, as revealed in Figure 5. Additionally, the cutting edge of the PVD TiAlN coated insert was severely damaged, leading to the loss of dimensional accuracy of the workpieces.

### *The cBN coated vs. CVD multi-layer coated inserts*

CVD multi-layer coated carbide insert is another candidate typically used for turning of hardened steels, especially rough turning of hardened steel. At the identical turning conditions, as described above, cutting performance comparison of cBN coated and CVD multi-layer coated inserts were carried out and the results are shown in Figure 6. Based on the wear criteria specified in ISO 3685, cBN coated outperformed CVD multi-layer coating by about 50%. Tool wear analysis indicated that cBN coated inserts had slight flank wear and crater wear being characteristic of abrasive wear; while CVD multi-layer coated inserts experienced severe crater wear leading to the damage of the insert substrate, in addition to non-even flank wear, as shown in Figure 7.

### *The cBN coated vs. bulk alumina ($Al_2O_3$) inserts*

As recommended by tool manufacturers for turning hardened steel with medium and high hardness like AISI 4340, bulk $Al_2O_3$ inserts (CNMA432) were also tested as a benchmark. Figure 8 shows a comparison of the cutting tool performance between cBN coated and bulk $Al_2O_3$ inserts. Apparently, cBN coated produced 100% more tool life than bulk $Al_2O_3$ inserts based on the tool wear criteria specified in ISO 3685. Analysis of the tested inserts for tool wear indicated that cBN coating has good resistance to abrasion, while bulk $Al_2O_3$ inserts show deep grooves on the flank resulted from the abrasion of the workpiece materials, as revealed in Figure 9.

## TURNING OF AISI 4140 PRE-HARDENED STEEL

The workpiece, AISI 4140 pre-hardened steel, had hardness of 25~32 HRC (D=62.5 mm, L=125mm). The turning process was continuous with water

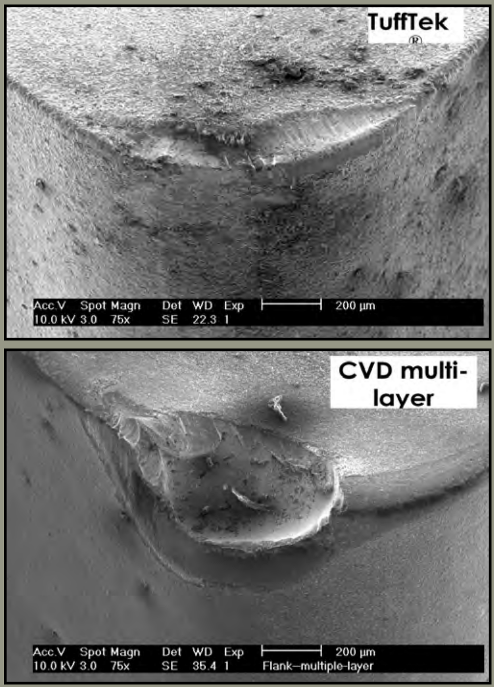



**FIGURE 7: SEM images showing the wear of cBN coated and CVD multi-layer coated inserts.**

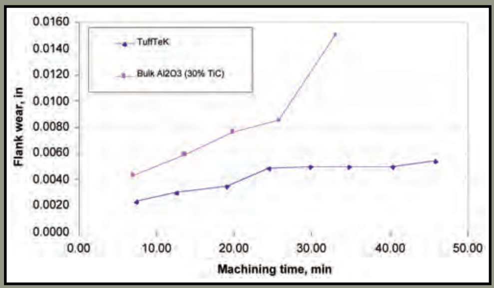



**FIGURE 8: A comparison of tool performance between cBN coated and bulk Al2O3 inserts.**

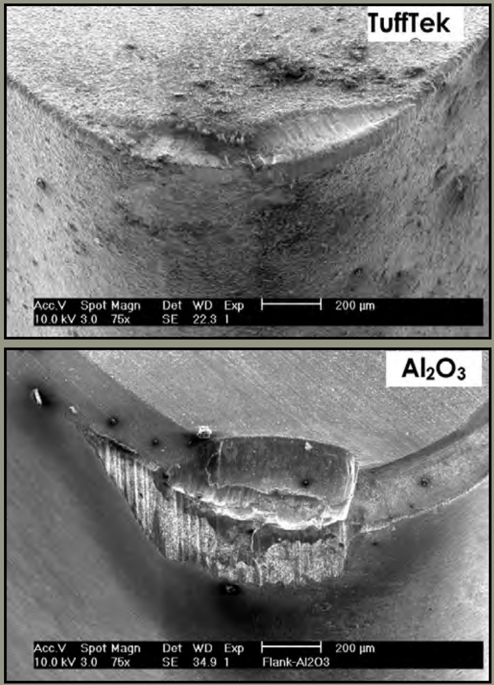



**FIGURE 9: Flank and crater wear of cBN coated and bulk Al2O3 inserts.**

based cutting fluids. The inserts were CNMG432 coated with cBN (Grade TTPH-300). Benchmark inserts used for comparison were CVD multi-layer coated CNMG432 from different sources. The machining conditions were V=183 m/min, F=0.41 mm/rev and DoC=1.78mm, which are typically recommended for rough turning. At identical machine setting and machining conditions, cBN coated (Grade TT-300) coated inserts outperform CVD multi-layer coated inserts from different vendors by at least 50%, as shown in the Figure 10 and cBN coated inserts are equivalent to CVD multi-layer coating in cost.

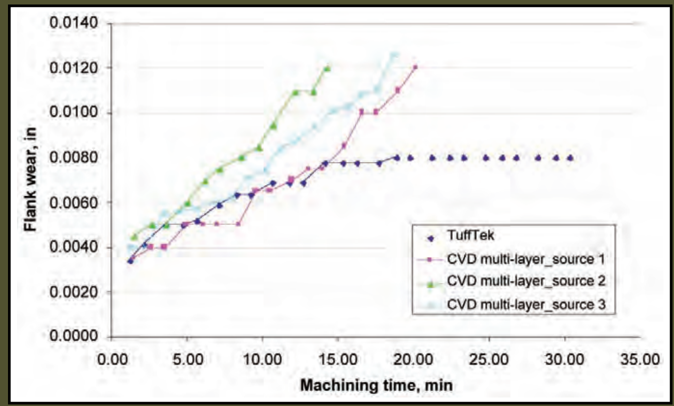
### TURNING NODULAR CAST IRON

The workpiece had a hardness of 150~180 HB. The inserts were cBN coated (TTNC-300) CNGA 433 carbide inserts. Benchmark inserts used for machine performance comparison were CVD A2O3 coated CNGA433 carbide inserts. The machining tests were carried out in turning nodular cast iron (ferritic ductile iron) at the conditions listed in the Table 1. The findings of the testing results are shown in Figures 11 (A), (B), and (C), respectively. The cBN coated outperformed the benchmark inserts by 30~75%, respectively.

## *Coating Analysis and Discussion*

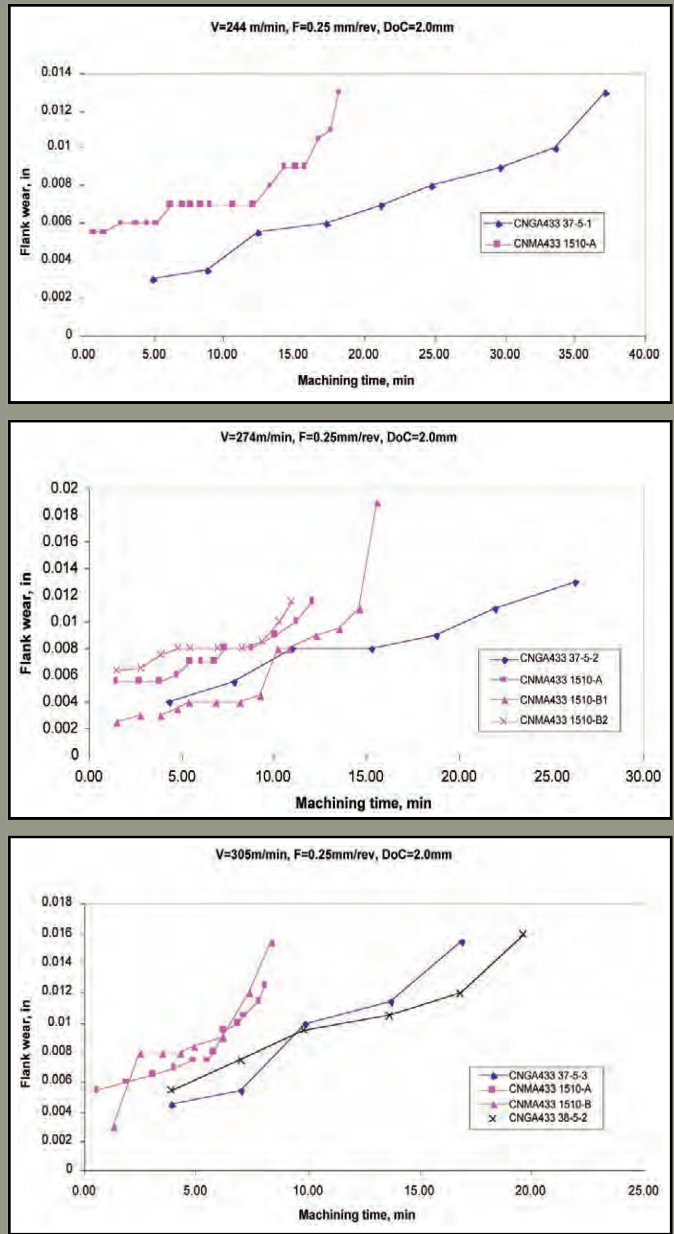
The tested cBN coated inserts, coated with cBN-TiN composite, were with different cBN particulate density over unit volume. The coating design combined the super-hardness of cBN particles along with the lubricity of TiN, making it suitable for machining of the engineering materials. The composite coating adhered well to the substrates of tungsten carbide (WC) with various cobalt (Co) percentages. As well as cBN particles bind very well to the binder phases. More information could be found in the following list of published literature. SEM analysis of the cBN coating cross section showed fairly uniform thickness with cBN particles (black dots) uniformly distributed in the TiN matrix across the coating, as shown in Figure 12. The composite coating is uniquely designed with cBN-TiN composite coating to provide the wear resistance and capped using a layer of TiN that offered the lubricity and superior crater wear resistance. All the machined samples provided on par or better surface finish in comparison to the bench marks. X-ray diffraction (XRD) analysis clearly showed the signature of cBN, without any traces of unwanted

**FIGURE 10: Comparison of tool performance in continuous turning AISI 4140 pre-hardened steel between cBN coated and CVD multi-layer coated inserts.**




***Diamond and boron nitride based tools compliment each other – diamond can cut only non-ferrous materials and boron nitride can cut all ferrous alloys.***

**FIGURE 11: A comparison of tool performance in continuous turning nodular cast iron at (A) V=244 m/min. (B) V=274 m/min, and (C) V=305 m/min, respectively, between cBN coated and CVD $Al_2O_3$ coated inserts.**



| No. | SURFACE SPEED (m / min) | FEED RATE (mm / rev) | DEPTH Of CUT (mm) |
|---|---|---|---|
| 1 | 244 | 0.25 | 2.0 |
| 2 | 274 | 0.25 | 2.0 |
| 3 | 274 | 0.25 | 2.0 |

**TABLE 1: Machining condition for turning nodular cast iron (with water-based cutting fluid)**

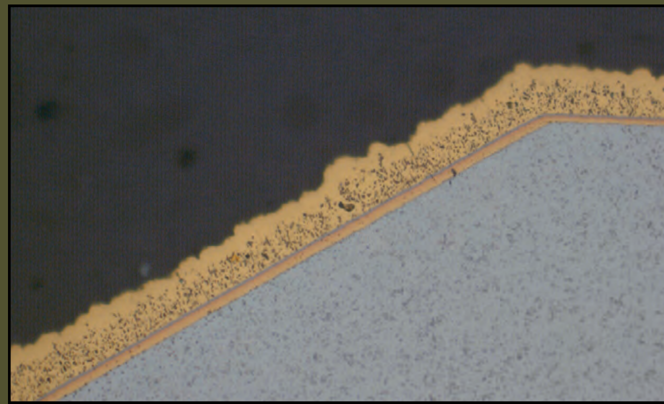


**FIGURE 12: SEM image showing a typical cross-section of cBN coating**

hexagonal and amorphous phases of BN, confirming that the innovative cBN coating manufacturing process does not degrade key cBN phase. Scratch tests run across calo crater provided critical loading as high as 20 kg without local failure. SEM analysis of the tested inserts showed that cBN particles are retained in the TiN matrix on the worn flank surface without any sign of coating delamination (Figure 13) and sub-micron to micron sized crack formation at particle-binder interfaces, confirming that there is good particle-to-binder adhesion in addition to good adhesion between coating and substrate. The unique "3D" coating chemistry design and excellent adhesion provide the strategic properties required for superior tool life in turning the respective highlighted materials in the above discussion.

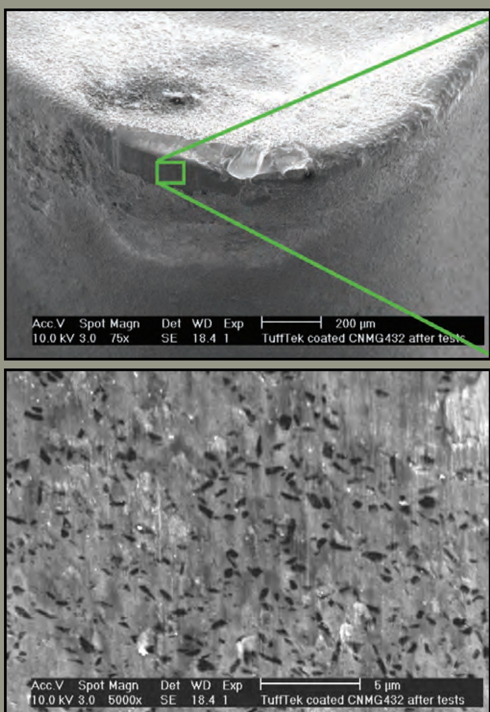



**FIGURE 13: SEM images showing cBN particles well retained in TiN matrix after tool wear.**

## CONCLUSION

Based on all the tests carried out for the application cases, cBN coating of various grades outperformed their respective industrial benchmark inserts in continuous turning of AISI 4340 hardened steels, AISI 4140 pre-hardened steels, and nodular cast irons. During all the tests, the cBN coating adhered well to the substrate, demonstrating superior resistance to abrasive wear. In particular, cBN (TTH-500) coating produced at least the same tool life as PCBN tipped inserts in turning AISI 4340 hardened steel, while its cost is only about 50~70% of that of PCBN inserts, resulting in significantly cost saving. The new cBN coating also produced significantly longer tool life when compared with PVD TiAlN coating, CVD multi-layer coating, and bulk $Al_2O_3$ inserts in continuous turning AISI 4340 hardened steel, indicating the superiority of the coating over the widely used coatings or ceramic inserts. The super performance from the new cBN coated inserts in turning AISI 4140 pre-hardened steel and nodular cast iron demonstrating the wide potential for machining other engineering materials. There is currently a ramping up of the scaled up production as well developing new grades for other significant as well as specialty application markets. ■

*For more information and details contact Dr. Malshe at: ajay.malshe@nanomech.biz or visit: http://www.duralor.com*