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Improving Cutting Tool Life a Review

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Abstract:- The cutting tool is an important basic tool required in the machining process of a part in production. It not only performs the cutting action but helps in getting required surface finish and accuracy of the part. In order to perform these tasks the tool has to be strong enough to withstand wear resistance and serve for long period of time to produce more number of components with the same accuracy. Machining is important in metal manufacturing process to achieve near-net shape, good dimensional accuracy and for aesthetic requirements. In modern machining process and using the CNC machine tools the cutting tool will play a vital role in machining process and in improving the surface finish. Many reputed cutting tool manufacturing organizations globally with their rich experience of research and development, invented different ways of enhancing the life of cutting tool in order to optimise the rate of the production and to reduce the cost of production, which is highly acceptable to the manufacturing Industry. This paper deals with the ways of improving the tool life by various coatings on tungsten based cemented carbide cutting tool. The coatings like TiN, $Al_2o_{3,}$ TiN/Al_2 $O_{3,}$ and TiC/ Al_2 O_3/ TiN respectively are extensively in use. In this review, the machining performance of coated tungsten based cemented carbides, with 55^0 diamond shape, were investigated during finish turning of AISI 1018 steel under dry conditions. The coatings are of TiN, Al_2 O_3, TiN/ Al_2 O_3 and TiC/ Al_2 O_3/TiN respectively. For comparison, uncoated cemented tungsten carbides are also tested under the same cutting conditions. The coated tools exhibited superior wear resistance over the uncoated tool. The TiC/ Al_2 O_3/TiN coated tool had the lowest flank wear .The Al_2 $O_{3,}$ coated tool showed superior wear-resistance over the TiN/ Al_2 O_3 coated tool. The TiN coated tool showed the least wear resistance with respect to the other coated tools. Surface roughness appeared to increase with flank wear while oscillating for all the tested tools except for TiN coated tool. The coated tools produced lower surface roughness compared to the uncoated tool. The TiC/ Al_2 O_3/ TiN coated tool produced the lowest surface roughness of all the tools tested.

Keywords:- Coated carbide insert, coating Materials, Alumina, Titanium Nitride and Steel AISI 1018.

1. INTRODUCTION

The manufacturing industry is constantly striving to decrease its cutting costs and increase the quality of the machined parts as the demand for high tolerance manufactured goods is rapidly increasing. The increasing need to boost productivity, to machine more difficult materials and to improve quality in high volume by the manufacturing industry has been the driving force behind the development of cutting tool materials [1]. Numerous cutting tools have been developed continuously since the first cutting tool material suitable for use in metal cutting, carbon steel, was developed a century ago [2].

Cemented carbides are the most popular and most common high production tool materials available today [3]. The productivity enhancement of manufacturing processes is the acceleration of improved cutting tools with respect to the achievement of a superior tribological attainment and wear-resistance [4]. This resulted in developing hard coating for cutting tools; these hard coatings are thin films of one layer to hundreds of layers. These hard coatings have been proven to increase the tool life by as much as 10 folds through slowing down the wear phenomenon of the cutting tools. This increase in tool life allows for less frequent tool changes, therefore increasing the batch sizes that could be manufactured and in turn, not only reducing manufacturing cost, but also reducing the setup time as well as the setup cost.

In addition to increasing the tool life, hard coating deposited on cutting tools allows for improved and more consistent surface roughness of the machined work piece. The surface roughness of the machined work piece changes as the geometry of the cutting tool changes due to wear, and slowing down the wear process means more consistency and better surface finish.

The majority of carbide cutting tools in use today employ chemical vapour deposition (CVD) or physical vapour deposition (PVD) hard coatings. The high hardness, wear resistance and chemical stability of these coatings offer proven benefits in terms of tool life and machining performance [5-6]. The first technique of CVD deposits thin films on the cutting tools through various chemical reactions and coatings were traditionally deposited using the CVD technique. Another technique is PVD. This method deposits thin films on the cutting tools through physical techniques, mainly sputtering and evaporation.

The reason PVD is becoming increasingly favourable over CVD is the fact that the coating process occurs under much lower temperature. The high temperature during the CVD process causes deformation and softening of many cutting tool substrates and especially hard steel speed (HSS).

The use of coolant to increase tool life has been an issue with different views [7]. The inherent brittleness of carbides makes them susceptible to severe damage by cracking if sudden loads of thermal gradients are applied to their edge [8]. Conventional machining uses 300-4000 l/h of coolants during machining. Environmental considerations mandate use of minimal coolant in the range of 6-70 ml/h. This is termed dry machining [9].

Dry machining is desirable to avoid the extra costs and environmental problems associated to cutting fluids. High speed machining of hardened steel has the potential of giving sufficiently high quality of the machined surface to make finishing operations such as grinding and polishing unnecessary [10].

1.1. Goal

It is to improve the effect of different types of coating materials on the performance of carbide cutting tools. To achieve this goal, turning tests were conducted with a CNC lathe using commercially available carbide cutting inserts with different coating materials. The performance of the cutting tools is evaluated by considering the progression of tool wear and the surface finish of the work piece.

The specific objectives of this research study included:

1. Study the flank wear progression on each of the cutting tools used.
2. Study the change of surface finish throughout the tool life of each cutting tool.
3. Assess and analyze the results obtained for each tool, and evaluate their performance based on the effects of the coating materials used.

LITERATURE REVIEW

In order to achieve the objectives of this research a literature review was conducted. The literature included information on carbide cutting tools used in turning, coating materials for cutting tools, wear observed during turning operations and surface finish of the machined work piece. This information served as a guideline in the course of this study.

The boost in wear resistance gave room for a significant increase in cutting speed and thereby improved productivity at the machine shop floor. And today, 70% of the cemented carbide tools used in the industry is coated [11].

Coating composites are designed to specifically improve tribological and chemical functions. It is thus natural to select the bulk of a component to meet the demands for stiffness, strength, toughness, formability, cost, etc. and then modify or add another material as a thin surface layer. Application of coatings on tools and machine elements is, therefore, a very efficient way of improving their friction and wear resistance properties [12].

The combined substrate-coating properties ultimately determine the important properties such as wear, abrasion resistance and adhesion strength of a coating. A hard wear resistant coating cannot perform well unless complimented by a hard and tough substrate. Thus, a hard coating deposited on a soft substrate leads to poor properties [9].

2.1. Wear

The prediction and control of wear is one of the most essential problems emerging in the design of cutting operations [13]. A useful definition for a worn out tool is: “A tool is considered to be worn out when the replacement cost is less than the cost for not replacing the tool” [14]. Tool failure is said to occur when the tool no longer performs the desired function whereas total failure (ultimate failure) is defined as the complete removal of the cutting edge, a condition obtaining when catastrophic failure occurs [15]. Therefore, in machining operations, tools are considered to be worn out and are changed long before total failures to avoid incurring high costs associated with such catastrophic failures.

Some of the tool life rejection criteria presented in ISO 3685 is listed below [16]:

1. Average flank wear = 0.4 mm
2. Maximum flank wear = 0.6 mm
3. Notching = 1.0 mm
4. Nose wear = 0.5 mm
5. Surface roughness (Ra) = 6.0 µm.

Machining of metals is a complex process. The cutting tool environment features high-localized temperatures (~1000 ºC) and high stress (~700 MPa). The tool may experience repeated impact loads during interrupted cuts, and the work piece chips may chemically interact with the tool materials. The useful life of a cutting tool may be limited by a variety of wear processes such as crater wear, flank wear or abrasive wear, built up edge, depth of cut notching and nose wear [9]. The main types of wear on a carbide-cutting tool are shown in Figure 2-1 below.

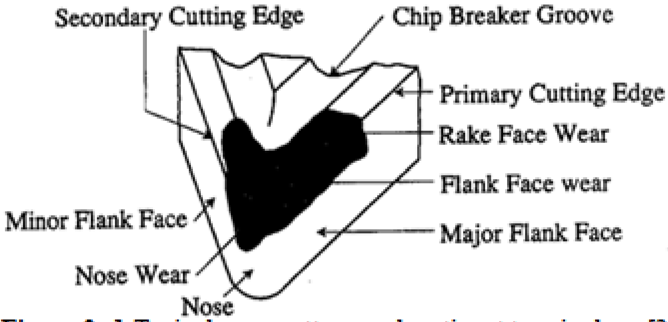


Figure 2- 1 Typical wear pattern and pertinent terminology [21].

Flank wear is observed on the flank or clearance face of a metal cutting insert and is caused mainly by abrasion of the flank face by the hard constituents of the work piece [17]. This failure mechanism is commonly observed during machining of cast irons and steels where the abrasive particles are mainly Fe3C and non-metallic inclusions [9].

Crater wear is observed on the rake face of cutting tools and is caused by chemical interactions between the rake face of a metal cutting insert and the hot metal chip flowing over the tool. Depth of cut notching is attributed to the oxidation of the tool material. Nose wear or tool tip blunting results from insufficient deformation resistance of the tool material [9].

Fracture is the least desirable mode of tool failure because it is unpredictable and catastrophic. When machining using carbides under typical cutting conditions, the gradual wear of the flank and rake faces is the main process by which a cutting tool fails [7]. However, flank wear is the preferred mode because it progresses gradually and can easily be monitored [9]. Most tool material development work is focused on minimizing flank wear and preventing unwanted tool failure modes such as catastrophic fracture, gross plastic deformation, built up edge and crater wear.

Severe abrasion occurs at the flank face because of the lower temperature, the more rigid work piece relatively to the chip, and the constraint in the movement of the work piece and tool [21]. The intimate contact between the flank of the tool and work piece, high compressive and shear contact stresses acting on the flank of the tool and cutting temperature of around 850^{o}C can encourage atomic dissolution-diffusion wear [22].

Cemented carbide tools worn off by dissolution/diffusion exhibit smoothly worn through carbide grains [18, 19, 23]. In many previous studies, a very smooth surface at the worn flank face possessing voids between carbide grain boundaries was observed on a carbide insert. This smoothly worn surface topography is a characteristic of dissolution/diffusion wear. Inter-diffusion between cobalt in the tool and iron in the steel and decarburization of the tool has been reported as the major diffusion reactions that occur [24, 25].

According to Jiang and Xu [26], the tool wear process can be divided into five stages: initial stage of wear, regular stage of wear, micro breakage stage, and fast wear stage and tool breakage. Other studies have divided the tool wear process into three stages in which rapid flank wear occurred at the beginning of machining at cutting speeds of 200250 m/min, followed by a gradual and steady wear growth, and finally by an accelerated wear towards the point of tool rejection [27].

2.2. **Coating**

Machining efficiency is improved by reducing the machining time with high speed machining. When cutting ferrous and hard to machine materials such as steels, cast iron and super alloys, softening temperature and the chemical stability of the tool material limits the cutting speed. Therefore, it is necessary for tool materials to possess good high-temperature mechanical properties and sufficient inertness.

The machining of hard and chemically reactive materials at higher speeds is improved by depositing single and multi-layer coatings on conventional tool materials to combine the beneficial properties of ceramics and traditional tool materials [21].

Schintlmeister et al. [28] had summarized the effect of coatings in the following statements:

1. Reduction in friction, in generation heat, and in cutting forces
2. Reduction in the diffusion between the chip and the surface of the tool, especially at higher speeds (the

coating acts as a diffusion barrier)
3. Prevention of galling, especially at lower cutting speeds.

2.3. **Coating Materials**

The majority of inserts presently used in various metal cutting operations are cemented carbide tools coated with a material consisting of nitrides (TiN, CrN, etc.), carbides (TiC, CrC, W2C, WC/C, etc.), oxides (e.g. alumina) or combinations of these [10,21]. Coating cemented carbide with TiC, TiN and Al2O3 dramatically reduces the rate of flank wear [19]. A primary contributor to the wear resistance of the coating materials is that they are all much less soluble in steel than WC at metal cutting temperatures.

High hardness is beneficial in resisting the abrasive wear. Retention of hardness even at higher temperatures is very important since the tool bit experiences a temperature in the range of 300-1000°C depending on the machining parameters and the materials to be machined [9]. Micro hardness values of different coatings measured at different temperatures are shown in Figure 2-2. They all exhibit a decrease with an increase of temperature, and the decrease of hardness was much more pronounced in the case of TiC. Interestingly, the micro hardness of Al2O3 was significantly lower than TiC at room temperature but retained almost 40 % of its room temperature hardness at 1000 °C

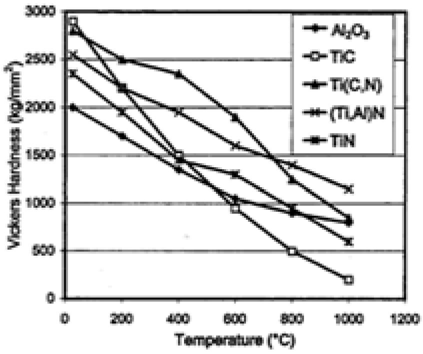


Figure 2- 2 Temperature dependence of micro hardness [17, 29]

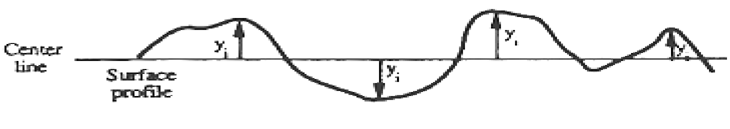
Coating with three layers of TiC-Al2O3-TiN as seen from the substrate are widely used for machining of many types of steels [10]. This type of coating improves the wear resistance of the tool by combining the properties of the three materials. The ranking of the solubility products and limits of TiC, TiN and Al2O3 in iron, compared to the carbide substrate, is in the order TiC > TiN > Al2O3 [19]. Therefore there is less driving force for significant dissolution-diffusion wear of Al2O3 to take place.

Thus, having a coating layer of Al2O3 over an under layer of TiC help decrease the dissolution/diffusion wear at the TiC coating layer. This enhances the performance of the cutting tool, by including the TiC layer with a low wear rate and protecting it with a layer of Al2O3 to decrease the effect of diffusion/dissolution wear. The softer TiN outer layer helps in reducing the propagation of cracks into the inner coating layers, in addition to decreasing the welding of the chips to the cutting tool. Another reason for having the TiN as an outer layer, as opposed to inner layer, is that at higher temperatures of oxidation, the growth of TiO2 (rutile) under layer may affect the performance of the protective alumina over layer of the oxide [9].

2.4. **Surface Finish**

Surface roughness and tolerance are among the most critical quality measures in many mechanical products. As competition grows closer, customers now have increasingly high demands on quality, making surface roughness become one of the most competitive dimensions in today's manufacturing industry [29]. .

There are several measurements that describe the roughness of a machined surface. One of the most common is the arithmetic average (AA) value usually known as Ra. [32]. The AA value is obtained by measuring the height and depth of the valleys on a surface with respect to an average centreline. The higher the AA value is, the rougher the machined surface. Figure 2-3 shows a magnified cross section of a typical machined surface.



$$\text{Arithmetic Average (AA) Value} = \frac{\sum_{i=1}^{n} y_i}{n}$$

Figure 2- 3 Illustration of surface roughness [30]

Many factors influence the formation of surface roughness in the turning process. These factors include chip deformation and side flow, vibration of the machine-tool fixture work piece system, geometrical contribution of the feed and tool nose radius. Classical surface roughness related equations calculate geometrical contribution:

$$h \approx f^2/ 8R, \quad , h_{CLA} \approx f^2/ 18\sqrt{3}R$$

Where h is the peak to valley height, h_{CLA} the centre line average roughness, f the feed and R the nose radius. This show that surface roughness is primarily dependent on feed rate and tool nose radius. However, the above equations give ideal surface finish values under satisfactory cutting conditions [32].

The tool wear influences the surface roughness of the work piece and the value of surface roughness is one of the main parameters used to establish the moment to change the tool in finish turning [20]. Carbide tool wear may occur by the mechanical detachment of relatively large fragments of tool material (attrition wear). This causes the surface roughness to increase significantly and promote the formation of ridges [19, 23].

The geometry of tool wear also causes a change in surface roughness as machining time elapses. Flank wear is along with groove wear are the types of wear that most influence this change in surface roughness [33]. Some studies have claimed that the change in surface roughness is primarily caused by cutting-tool flank wear [31].

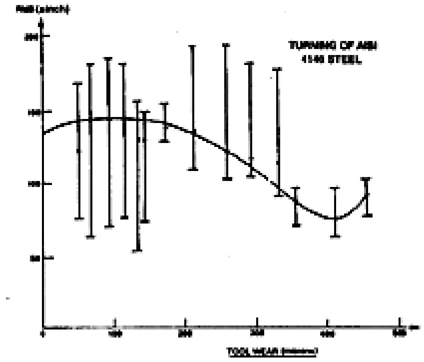


Figure 2- 4 Surface roughness's vs. tool wear [34]

The relationships between Rmax, Ra and Vb with cutting length, lc, was studied by Petropoulos [35] and the results for machining steel are shown in Figure 2-7, where Rmax

2.5. **Work-piece Material**

The cutting performance tests were performed on AISI 1018 cold rolled steel. Based on the AISI-SAE standard carbon steel table, it is a non-resulphurized grade steel and its composition is 0.15-0.2% C, 0.6-0.9% Mn, maximum of 0.04% P and maximum of 0.05% S. The work piece material used was 1.5 inch in diameter and 20 feet long. However, in order to meet the requirement of the ISO 3685 [17] that the length/diameter ratio of the work piece material to be used should be less than 10 during testing, the bar was cut into 20 pieces (12 inch length) using the metal cutter shown in Figure 2-5 which is located in the machine shop of the Industrial Engineering department.

Figure 2- 5 Metal-cutter for cutting the work piece material.

RESULTS AND ANALYSIS

The results for the machining performance of the four different coated cutting tools and the uncoated cutting tool in turning AISI 1018 steel. The results for the flank wear of the uncoated tool and the surface roughness of the machined

AISI 1018 work-piece are first presented. The results of the other coated tools are then shown and are compared to those obtained using the uncoated tool in order to obtain the effectiveness of the different coatings on the flank wear and the surface roughness.

The flank-wear and the obtained surface roughness results for each of the coated tools are then compared in order to confirm the machining performance rankings of the different coatings considered.

3.1. Wear of TiN Coated vs. Uncoated Tool

To compare the performance of the TiN coating, the flank wear of the TiN coated tool was compared with the flank wear of the uncoated tool. Table 3-1 shows the SAS output for the regression of flank-wear on the number of cuts for both TiN coated and the uncoated tools. A null hypothesis (Ho) that the TiN coating has no effect on the flank wear and an alternative hypothesis (Ha) that the TiN coating has an effect on flank-wear were used. Again using a a-value of 0.05, the null hypothesis is rejected in favor of the alternative hypothesis since the P value for this regression is <0.0001. And so it can be concluded that the TiN coating has a significant effect on tool flank wear for the TiN coated tool.

Table 3- 1 Regression of flank wear on the type of coating for TiN and uncoated.

The SAS System

The REG Procedure
Model: MODEL1
Dependent Variable: wear

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.21497	0.10749	128.58	<.0001
Error	37	0.03093	0.00083597		
Corrected Total	39	0.24591			

Root MSE	0.02891	R-Square	0.8742
Dependent Mean	0.33069	Adj R-Sq	0.8674
Coeff Var	8.74340		

The flank wear for the five different types of cutting tools tested are shown in Figure 2-4. The uncoated tool exhibited the largest wear within the 60 cuts machined in the test. All the coated tools were observed to have better wear resistance than the uncoated tool as expected.

The TiN coated tool showed a slight improvement compared to the uncoated tool. The TiN/Al2O3 had the third highest flank wear. The improvement of the wear resistance compared to the TiN coating was due to the addition of the Al2O3 layer. This layer protected the TiN coating.

However, the Al2O3 coating had the second highest flank wear resistance and showed an improvement in wear resistance as compared to TiN/Al2O3. Hence, using one layer of Al2O3 appears to have better wear resistance to flank wear as compared to using 2 layers of coating with TiN interlayer and Al2O3 outer layer.
The TiC/Al2O3/TiN coated tool appeared to have the best wear resistance under the testing conditions used. This was as expected since the combination of TiC with high abrasive resistance, chemically stable Al2O3 with low thermal conductivity and the added wear resistance of the TiN coating improved the overall wear resistance of the cutting tool.

The photographs of the flank face for each of the machined tools are shown in Figure3-1. The flank-wear on the uncoated and TiN coated tool can be easily seen. The lower flank-wear on the TiN/Al2O3, Al2O3 and TiC/Al2O3/TiN coated tools displays their higher wear resistance performance.

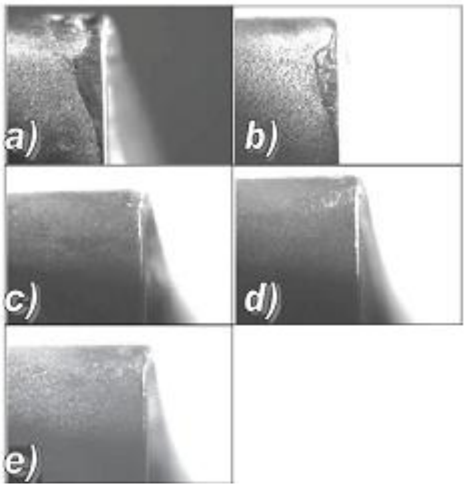


Figure 3-1 Photographs of the final flank wear for a) uncoated tool, b) TiN coated tool, c) iN/Al2O3 coated tool, d) Al2O3 coated tool and e) TiC/Al2O3/TiN coated tool.

The machined part surface roughness appeared to decrease with the addition of a coating layer for all cases except the TiN/Al2O3, in which the addition of this coating tended to increase the value of the surface roughness compared to that obtained using the uncoated tool.

The TiC/Al2O3/TiN coated tool exhibited the lowest surface finish followed by Al2O3 coated tool, TiN coated tool, uncoated tool and the TiN/Al2O3 coated tool respectively. The statistical tests conducted in the previous sections confirm these results.

CONCLUSIONS

This study evaluates the machining performance of five commercially available cutting tool inserts in turning AISI 1018 steel. Uncoated, TiN coated, TiN/Al2O3 coated, Al2O3 coated and TiC/Al2O3/TiN coated tools were examined and their flank wear and the resultant machined work piece surface finish were analysed.

The tool coatings were found to improve upon the wear resistance of the cutting tool. This was shown by the decrease in wear on the flank face of the coated tools compared to that of the uncoated tool. The wear of the TiN coated tool was around 12% lower than the wear observed on the uncoated tool. TiN/Al2O3 coated tool showed a decrease of around 65% compared to the uncoated tool. The decrease in wear was due to the wear resistance properties of the TiN and Al2O3 materials and the high chemical stability of the Al2O3 layer.

The Al2O3 coated tool showed a decrease of around 92% compared to the uncoated tool. The increased wear resistance of the Al2O3 coated tool compared to the TiN/Al2O3 coated tool was believed to be due to the oxidation of the TiN material and the appearance of TiO2 under the Al2O3 layer which deteriorated the performance of theAl2O3 layer. The TiC/Al2O3/TiN coated tool appeared to have the lowest wear of all the tools tested, and showed a decrease of around 96% in wear compared to the uncoated tool.

In the case of the machined surface roughness, all the coated tools produced lower surface roughness than that produced by the uncoated tool except for the TiN/Al2O3 coated tool. This was believed to be due to factors other than the coating material and mainly the different chip breaker geometry on the tool which produced longer chips that got in contact with the work piece material and increased its surface roughness.

The TiC/Al2O3/TiN coated tool produced the lowest average surface roughness during the 60 cuts with a decrease of around 38% compared to the uncoated tool. The Al2O3 coated tool produced the second lowest average surface roughness with a decrease of around 23% compared to the uncoated tool. The TiN coated tool produced the third lowest average surface roughness with a decrease of around 7%. While on the other hand, the TiN/Al2O3 coated tool produced the highest average surface roughness with an increase of around 21%.

The surface roughness increased while oscillating for all the cutting tools used except for the TiN coated tool in which surface roughness oscillated around a constant value and produced more consistent surface roughness that was not affected by the flank wear of the tool.

This research may be extended to study the effects of multi-layer coatings on cutting tool performance. Multi layers are composed of alternating layers of two different materials that can vary in number from few up to tens of thousands. Multi layers are believed to offer very high strength, hardness, heat resistance, and many new properties that could greatly enhance the performance of the cutting tools..

Also this coating technique can be further extended by application of Nano technology. Nanocomposite coating offer enormous potential for new applications in industrial areas.. The insert with a coating of Zerconia Toughened Alumina (ZTA). is done by RF (Radio Frequency)-sputtering process and the productivity and surface roughness of ZTA coated is being tested and compared with uncoated tungsten carbide insert under the same cutting conditions. ZTA coated turning tool insert exhibits higher hardness, superior wear resistance and higher fracture toughness when compared with the uncoated and TiN coated insert. (36).

The nano crystalline coating it created has a needle-like surface structure. This surface allows the TiCN coating, which the company calls Nanolock, to “interlock” with a succeeding layer of an aluminum oxide coating. This very strong adhesion between the two coatings makes the aluminum oxide, which offers protection against excessive heat during machining, less likely to delaminate during a cut.

The Nanolock technology is currently available for Boehlerit’s LC 228E universal bar-peeling inserts, LC 239Q crankshaft-machining inserts and Steeltec rotary inserts. Cutting tests comparing the Steeltec grade LC 215K Nanolock inserts with conventional inserts resulted in Steeltec achieving cutting speeds higher than 300 m/min during a continuous cut in 4140 steel while providing 50 percent longer life.

Most benefits of nanotechnology depend on the fact that it is possible to tailor the essential structures of materials at the nanoscale to achieve specific properties, thus greatly extending the well-used toolkits of materials science. Using nanotechnology, materials can effectively be made to be stronger, lighter, more durable, more reactive, more sieve-like, or better electrical conductors, among many other traits.

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