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Wear Resistance Enhancement of Cutting Tools in CNC Machine

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Abstract: ***Cutting Tools form the basis of the machining industry. The Machining industry relies on various processes such as cutting, welding, bending, rolling, turning, profiling, drilling, milling, finishing, which require an effective set of cutting tools. These machining activities need the right cutting tools so that the day to day operations can be performed in an extremely efficient manner while increasing the productivity of the industry. The basic function of a metal cutting tool is to get rid of the extra material from the workpiece and help in producing products with a better surface finish. The material used for the manufacturing of the cutting tools has a significant role to play in deciding the effectiveness and the longevity of the tool. Coated cutting tools were used in the industry for a long time. In recent times more than three fourth of all tools are coated with TiALN and TiN. The mechanical properties of these tools tend to change drastically under elevated temperatures and thus cause the failure of such tools. In this paper, our objective is to use Carbon Nano Tube nanoparticles as coatings for cutting tools. We aim to compare the mechanical properties of these coated tools and do a comparative analysis of tools coated with CNT nanoparticles versus the conventional multi-layered tool coatings.***

Keywords: cutting tools, coatings, CNT, mechanical properties, tool failure

I. INTRODUCTION

Tool coatings play a tremendous role in enhancing the performance characteristics of the tool during machining. Over the years, the types of coatings and their coatings have advanced significantly and have lead to tremendous advancements in tool life. The year 1969 saw the introduction of the first cemented carbide inserts, which were used for turning operations, which had a tremendous impact on the metal cutting industry.

The first material that was used for coating was Titanium Carbide (TiC), which was deposited by CVD and was only a few microns thick. The coating was found to significantly improve the abrasive and chemical resistance of the inserts. These results paved the way for significant research on tool coatings, and results have shown that such tool coatings can also allow for an increase in the cutting speeds, thus bringing about improved efficiency on the shop floor.

However, certain limitations came to the fore during the early experimentation with these tool coatings.

The high-temperature requirements of CVD lead to the diffusion of chemical elements of the carbide substrate with the coating. This phenomenon leads to the embrittlement of the coating edge. Substrates that were less sensitive to such diffusion losses were selected to overcome this hurdle.

In recent times coatings of TiAlN/ TiCN/ ceramics, diamonds, etc. have been evaluated. Studies have shown that the strength of the coating depends on the material used, but a layered coating of an adhesive layer, intermediate layer, and wear-resistant outer layer will lead to further improvement of the coating hardness and increase resistance to wear. The used abbreviation in this paper is shown in Table 1.

Table 1. Nomenclature

FNG	Functionalized-Nano-Graphite
NBA	Nano-Boric-Acid
$nMoS_2$	Nano-Molybdenum-Disulphide

II. ADVANCEMENTS IN THE AREA OF HARD COATINGS WITH THEIR ADVANTAGES

Generally, to achieve a higher productivity rate, it is expected that the cutting tool should work for a long time with a high material removal rate under extreme temperature conditions. Besides, this expectation cannot be met by traditional hard metal tools in the current scenario. That's why a growing market of coated cutting tools has come to reality.

The investigation of depositing TiC on the cutting tool has already started in the 1930s, and it took further 20 years more to investigate the coating on steel substrate**[1]**. There was a rise in the development of using CVD and PVD coating techniques. With the increase in time, various researches have been done to optimize the deposition process, to coat different materials on a substrate with different compositions, for example, deposition of Al_2O_3 on various substrates and much more. With the rise of nanotechnology, nano-coated tools showed their performance. Multilayer coatings are increasing degradation resistance and life tools due to some reasons. Reasons are: -

1. This type of coating enhances the adhesion with the substrate.
2. This type of coating reduces the size of the crystal within it.
3. This type of coating stabilizes the stress between coating and substrate generated internally due to different thermal expansion coefficients.

2.1 Advantages of Nanocoating on cutting tools are: -

1. It enhances the tool life so that we can utilize the same tool for a long time.

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2. Machining performance can be improved.
3. Coolant requirements can be cut. (i.e., the possibility of dry machining).
4. Oxidation, as well as wear resistance, can be increased.
5. Thermal Shock and metal fatigue resistance can be enhanced.

F. M. Kustasz **[2],** with his other authors in the article, suggested the importance of dry machining and told that it could be achieved by using multilayer nano coated cutting tools. Authors also classified multilayer nanocoatings on cemented carbide tools in four categories from lubrication, wear, and friction point of view.

Before the advent of coating in the cutting tools, cutting fluids were always used during machining. Cutting fluids was considered as a problem solver for many issues like cutting tool cooling at higher speeds, enhancing the life of the tool, and many more. There are many harmful and uneconomical effects of its use, and its use also breaks the environmental regulations. So, there was a need to find an alternative way by which tools can remove material at a higher rate with a high cutting speed that can lead to environmentally friendly manufacturing.

Nano coated tools are of great use rather than tools having a layer of thickness in micrometer range because of enhancement in each mechanical property required for machining operation in comparison with the latter.

H.Holleck and V. Schier discussed in their research article about the advantages of the concept of multilayer coatings over new and advanced coating concepts in almost all fields of application **[3]**. Multilayer coatings from the CVD technique are usually an arrangement of 3 to 13 single layers. The benefits of this coating can be seen in the laboratory as well as in the industry. Multilayer coatings are classified concerning the number of layers and layer properties. The chemical bonding character of hard materials is a basis of classification for selecting the material for the coating process.

Various Specialists believed that nanotechnology might soon contribute significantly to the GDP. Experts in material science are trying to develop different nanomaterials with a unique composition to get the desired properties in nanocoatings and also the development of high-strength nanostructured hard alloys and nanostructured wear-resistant coatings for cutting tools**[4]**.

III. DRAWBACKS OF PREVIOUSLY USED MATERIALS IN NANOCOATING

In micro and nanocrystalline diamond coating with 1%,3%, and 5% concentration of CH_4, Lusheng Liu **[5]** observed that the resistance to crack propagation is poor in the case of 1% CH_4 sample as compared to other two samples. As the CH_4 concentration is increased in the diamond coating to 3% and 5%, the adhesion strength decreases, which leads to the delamination of coating from the large region when kept under cycling stress during machining. The diffusion of internal cracks in micro-diamond coated tools leads to coating failure.

Weiwei wu **[6],** in his research paper, finds out that the AlCrN coated tool shows a serious plowed groove scratches in the chip removing direction because of abrasion wear in the early stage of the wear mechanism. Marco Sortinoa **[7]** also find out that the AlCrN coated tool has significantly shorter tool life as compared to AlCrSiN. Marco Sortinoa **[7]** reported that the nickel coating on cutting tools during machining of different to cut materials, improves the degradation, but it slightly diminishes the tool life.

S.C. Deevi **[8]** gives the data about the start of oxidation of the TiN coated tool, which starts oxidation at 550^o c, which is very less as compared to TiAlN which starts oxidation at 700^oC. this is mainly because of the addition in the Al content in the coating which helps in increasing the oxidation resistance of the material.

IV. LAYER THICKNESS OPTIMIZATION

A.A. Vereshchaka **[36]**, worked on the nanoscale layered coatings for improving the properties of tools under heavy cutting conditions. The process used for depositing the coating of the tool is Filtered Cathodic Vacuum Arc Deposition. One of the major parameters to determine the characteristics and features of a cutting tool is thickness. Since this is a multilayered coating, there were 3 respective layers. Adhesion underlayer Ti had a thickness of about 0.2-0.3 μ m, followed by the intermediate layer TiN, and thickness of the intermediate layer is 15 nm, followed by a wear-resistant layer (Composition- TiCrAlN- multilayered), its thickness being 2.0 μ m, and subsequent thicknesses of wear-resistant and intermediate layers being 25 nm. A comparison was made with different compositions and layer thickness, coating with composition TiC-TiCN-TiN and 10 μ m thickness, turned out to be having least wear resistance coefficient and the composition with Ti-TiN-TiCrAlN and 4.0 μ m thickness turned out to be having highest wear resistance coefficient. **[36]**

Alexey Vereschaka **[37]**, worked on another aspect of coating, which focused on multilayered composite coatings for turning austenitic steels. Many material compositions were used for coating. Few of them are- TiN, the thickness being 4 micrometers, TiTiN(Ti, Al)N, the depth being 5 μ m. The addition of Aluminium results in improved hardness and degradation resistance of the workpiece. Various microstructures of the coatings containing different compositions were studied and found that the mean depth of nanolayers was 65-98 nanometre. Using such coating materials resulted in great improvement in the tool life by 2.5 times. And among the coating compositions used, (Zr, Nb) N (Cr, Zr, Nb, Al) N had the best results in terms of wear resistance, nature of hardness.**[37]**

The importance of coatings can be felt when cutting tool performance improvement can be seen by performing various tests. Tool life, cutting speeds, and cutting modes, all these are certain properties that are immensely improved just by the usage of certain coatings. To make the above-mentioned characteristics better, the thickness of those coatings determines the quantity of improvement of those properties for their machining processes. Alexey Vereschaka **[38]** worked on yet another journal that involves discussions on the effect of thickness of multilayered nanostructured coatings on cutting tools. With varying cutting speeds, the tool life changed accordingly. The compositions used have coating thickness varying from 4±0.8 μm to 7±0.5 μm. It was found that at cutting speed of about 400m/min, insert without coating showed excess wear just one minute into the cutting implied the necessity of nanocoatings. At cutting speed of about 250m/min, thicker coatings resulted in the longest tool life, but as cutting speed increases after this, thinner coatings showed better results. This occurs due to the propagation of interior stresses developed in dense coatings. Composition- TiTiN(TiCrAl) N and Zr-ZrN-(ZrCrNbAl)N,

these were found to have an insignificant reduction lifespan of the tool, while the cutting speed was increased simultaneously. **[38]**

Sergey Grigorieva **[39]** studied the importance of thickness of nanolayers and the effects it had on the lifespan of the tool and degradation resistance due to the coatings. In this study, all the coatings have identical composition and thickness of about 4 micrometers but vary in the depth of the nanolayers of about 40nm - 80nm. Microstructure and nanostructure of the coatings were studied with different cutting speeds. At cutting speed 200m/min, an uncoated tool cannot be used as its wear limit is reached after one minute of cutting. At the same cutting speed coatings with thinner nanolayer- 40nm showed longer tool life than coatings with nanolayer thickness >40nm. **[39]**

Gurjeet Singh **[40]** has studied the influence of coating depth during the process of turning cold work steel. During his study, he experimentally determined the performance of these multilayered coatings while varying the thickness. The multilayer-coated inserts used in this study are - TiN/TiCN/Al2O3/TiN with different thicknesses. During the lathe operations, cutting speed, rate of feed, as well as the thickness of the coatings, were varied and the respective surface roughness was noted down. The optimized parameter values for least Ra value are feed- 0.1 mm/rev, speed- 120 rpm and coating thickness 8 µm. **[40]**

V.METHODS OF COATING OF TOOLS

5.1 Physical Vapour Deposition

William D. Sproul **[13]** provided a detailed explanation of the two different types of PVD methods, namely, LVEBE (low voltage electron beam evaporation) and cathodic arc deposition method **[13]**. These two methods are the most widely used PVD methods. The techniques mentioned above were said to be reactive processes, which means that the coating metal is vaporized, while gas is fed into a coating chamber. The gas then reacts with the coating metal type to form the required coating characteristics. In the LVEBE process, reactive gas atoms are evaporated very effectively with an estimated amount of ionization of about 50%. This process is extremely consistent for producing a smooth and hard TiN coating. In the cathodic arc process, the amount of ionization is found to be about 90% of the vaporized material, which in turn leads to the formation of an extremely dense coating that is well adhered to the base metal.

5.2 *Plasma Enhanced Magnetron sputtered deposition*

Ronghua Wei et al. **[12]** briefly discussed the PMD to achieve coatings of high adhesion and excellent wear properties. PMD is different from PVD because it mixes magnetron sputtering with a plasma that is independently generated and hence allows for independent control of the plasma ion bombardment as well as the sputter deposition processes. The PMD set up for TiN coating deposition consisted of 2 vacuum chambers, one big and one small. A direct current power supply is used along with a hot filament to produce the plasma, which does not depend on the plasma made by the magnetrons. The workpiece (negatively biased) was then enveloped with the independently produced plasma from either of the chambers to carry out the cleaning of the sputter before the deposition process began and ion bombardment while the process was taking place.

5.3 Chemical Vapour Deposition

W. Schintlmeister **[10]** and X. X. Pan **[11]** elaborated about the use of CVD coatings using cemented carbides as the base metal. According to them, the temperature needed does not have any effect on the properties of the base metal. In CVD, a reaction of a gas mixture on the base metal is responsible for the coating. The temperature of the gas, the rate at which the gas flows in the coating chamber, the composition of the gas, and the coating time were found to be the most influential parameters that affect the deposition rate of the coating. It was observed that CVD offers better adhesion of the coating to the base metal than CVD. However, when performing a CVD of diamond coating, the presence of cobalt on the base metal was found to hinder diamond nucleation and thus lead to improper adhesion of the coating to the tool surface. To counter this phenomenon, etching with HNO3 and H2O in the ratio 1:1 was done at low temperatures.

The CVD equipment consists of 4 coating chambers with a usual diameter of about 360 millimeters and a height of about 900 millimeters as well as 2 heaters. The chambers are normally automated and allow for a fully automated operation of the coating cycle.

VI. CHARACTERISTICS OF THE CNT COATED TOOLS

The strength of coated specimens was estimated using the Hounsfield tensometer **[41]**. Electrochemical properties are enhanced. The ultimate intensity of the coated tools is heightened when they are annealed at 890 and 950 degrees with an increase in holding time. The ductility of steel drastically reduces with the rise in carbon content **[42]**.

The stress required to deform the tools is reduced because the carbon atom occupies the interstitial spaces on the surface of the tool, which hinders the movement of the dislocation **[41]**.

Diffusion of carbon increases with the rise in temperature. The maximum yield strength of the tool can be increased by intentionally prolonging the holding time irrespective of heat treatment temperature. The tool surface hardness rises with the rise in treatment temperatures. This is because of the interaction between disconnected carbon from the carbon-nano-tubes and the surface of the tools forming carbides near the boundary between the coating and tool surface. The toughness of the tools was found to decrease slightly during heat treatment. The corrosion rate on the tool surface is reduced. Due to the increase in holding time, coating efficiency is increased, which ultimately reduced the corrosion rate **[41]** 0.0016828 to 0.001145 699 (A cm−2) and 19.51438 to 13.28595 (mm yr−1).

VII. ADVANTAGES OF NANO CUTTING FLUIDS IN MACHINING

As said by Khandekar S, Ravi Sankar M, Agnihotri V, and Ramkumar J due to the evolution of the technology and its development, it is increasing the thermal loads that need quick cooling The old and conventional processes of increasing cooling rates are already increased to their limits.

As said, recent studies noted that the suspension of Nanoparticles could change the features of the presently used cutting fluid.

The tiny quantity of Cu nanoparticles (not more than one percent volume by ratio) or CNTs diluted in (CH2OH)2 can boost 40 ethylene glycol's poor heat conductivity by 40% to 150%. Nanoparticles close to the liquid-solid surface can improve the base fluid's wettability features. Wettability is evaluated using the macroscopic contact angle technique of water, standard cutting fluid, and Nanocutting fluids.

7.1 Wettability

The wettability of Nano cutting fluids and two other fluids is examined to prove that Nano cutting fluids ' wettability characteristics are better. After doing so, it reveals the better cutting performance among dry machining, cutting force, and chip thickness, machining with these fluids in terms of tool degradation **[21]**. They have proven that Nano reducing fluid's wettability is better than conventional fluid and water**.** Fig.1 shows the images of the droplets on the tool **[21].**

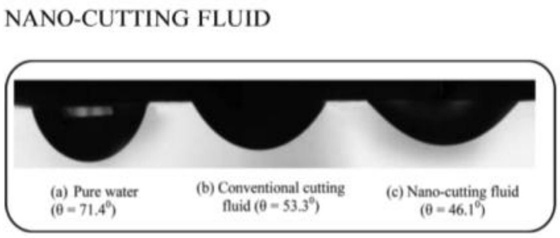

Figure 1: Images of the (a) Pure water (b) Conventional cutting

(c)Nano-cutting fluid droplets on the tool. **[21]**

7.2 Tool wear

As per the latest research, tool wear is nothing but the morphology of crater and flank wear. It is triggered primarily by the temperature in the primary and secondary share zones. It improves chipping, cracking and the tool inserts fracture because of the existence of cutting edge stress and tool material brittleness. In the absence of the cutting liquid, severe flank wear is caused by the constant rubbing of the tool on the flank face **[21]**. Compared to dry situations, adequate quantities of cutting fluids help to decrease the heat produced in the machining area. Vigorous rubbing of the work with the flank causes the removal of layers of the surface of the tool flank. The device maintains its hardness due to the suitable cutting ability of fluid lubrication and thus wear on the flank is partly lowered compared to the dry technique. In the case of Nano cutting fluid, both generate and flank wear dramatically decreases and the reasons for this are its convection, conductivity, and wettability **[21]**. Fig.2 shows the crater and flank wear under different conditions.

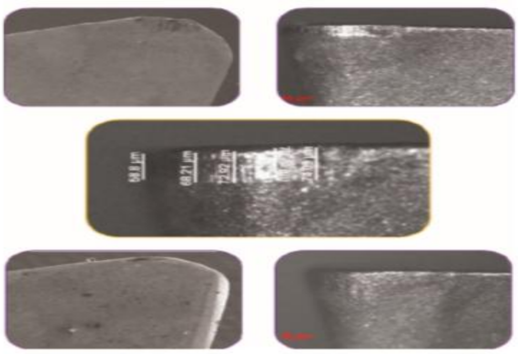

Figure 2: Crater and flank wear in dry turning, turning with conventional cutting fluid, and turning with Al2O3 based nano-cutting fluid. **[21]**

7.3 Cutting Force

Sleman Rasul, Nihat Tosun, Sarkawt Rosta said that the cutting edge gradually degrades irrespective of the existence of the fluid **[22]**. In the case of the Nano cutting fluid, however, there is no fast rise in cutting force due to the enhanced cooling and lubrication.

7.4 Chip Morphology and Chip Thickness

A cutting fluid layer that is hydrodynamic is formed between the rake face and the chip during cutting with conventional fluids **[22]**. Due to the presence of the Aluminium Oxide in the Nano cutting fluid the longer chips which are formed during the machining process are forced to break, resulting in small segmented chips.

7.5 Surface Roughness

As the cutting fluid is not present, the wear of the cutting edge happens quickly in the dry machining method. Hence the process of dry machining does not produce a smooth surface value of Ra on the surface of the workpiece. Because of the presence of fluid, it protects the edge of the tool because of its lubrication and cooling characteristics when machining with conventional cutting fluid. This method of machining is therefore partly smooth and hence the value of Ra produced is comparatively good than dry machining (i.e. partly decreases surface roughness) **[22]**. When it comes to Nano Cutting Fluid it significantly increases the wetting characteristics of the region. The net impact results in comparatively better heat dissipation and hence the method of machining is smooth and helps the cutting edge hardness to be retained. Thus, the roughness of the surface or the Ra value is comparatively better compared to the other two machining conditions.

Emulsifier oil-based nano cutting fluids

7.6 Temperature

As shown by M. Amrita, S.A. Shariqa, Manoja, Charan Gopala, the red and violet colored lines represent that the temperature is very large in dry machining and also up to some degree in wet cutting. Minimum quantity lubrication with Nanoparticle incorporation has been discovered to be considerably better compared to machining in lowering the cutting temperature. With FNG and nMoS2 **[19]** emulsifier cutting oil, the temperature produced at the interface of the chip tool is discovered to be nearly the same. NBA initially represented the least temperature and subsequent decrease in temperature was found to be the same compared to FNG and nMoS2. Fig.3 shows the temperature in dry machining is comparatively higher compared to other machining processes **[19]**.

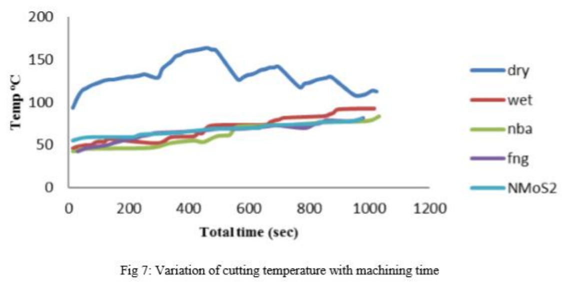

Figure 3: Cutting Temperature versus time. [19]

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VIII. PERFORMANCE OF MULTI-LAYERED CUTTING TOOLS

Alexey A. Vereschaka **[23]** stated that by deposition of multi-layer Nanostructured coatings of (Ti, Zr) N(TiN/ZrN) and TiN(TiAl)N(TiN/(TiAl) on the tool, they were able to improve the machining properties of the tool.

The outer layer (wear) consisted of (TiN and ZrN) or TiN and (TiAl)N, respectively. After conducting the performance tests, an increase in degradation resistance by (20 to 80) % was found. This was found on the tool which is mixed ceramic Al2O3TiC but whereas when it was tested with the tool Al2O3ZrO2Ti (C, N), it showed no increase in wear resistance at all.

In **[26],** to study the machining performance of tools coated with diamond, milling tools were made of the composition of diamond-coated cobalt cemented-tungsten carbide. From various experiments, it showed that the cutting tool coated with ACD had a better service life and cutting quality than single layer coating and tools without coating. The main cause of failure of Nanometric diamond coated tools was by the delamination of film from the stratum. This occurred due to internal stress. For the tools coated with a micrometric diamond, the spreading of internal cracks failed the coating. The Ra of the work and cutting ability of the tool coated with ACD shows the reliability and feasibility of the machining and cutting processes of hard brittle materials.

In **[24]**, by scratch test, the strength of linkage bonds was observed. A sublayer was introduced in addition to the three layers. Three different coatings were studied and from that, it was shown:

In the TiTiN(Ti, Cr, Al, Si) N coated tool, a sublayer with more thickness induced no significant outcome on the failure of the coating in a certain case i.e. when the size of sub-layer was greater than the mean size of the Nano layers by roughly two times.

In (the ZrZrN (Zr, Al, Si) N coated) tool, during machining, a local separation occurred on the edges of the sublayer in another condition i.e. when its thickness is greater than the average thickness of the Nano layers by roughly four times.

In ZrZrN (Nb, Zr, Cr, Al) N coated tool, the sublayer which is in observation has a size of roughly nine times greater than the mean size of the Nano layers, there is notable delamination across the external boundary of the above-mentioned sublayer. From this, we could generalize that when the thickness of the sublayer is greater than two times the average Nano layer thickness, wear resistance of the coating increased.

The machining tests were carried out by Alexey Vereschakaa **[24]** for three different types of coating. The tool coated with TiTiN(Ti, Cr, Al, Si)N shows a better life. The next observation was that the tool coated with ZrZrN(Zr, Al, Si) N exhibits a greater uniform degradation trend and lower concentrated degradation once the machining is completed. It was also found that with rising temperature the temperature in the machining area also rises. Along with that, the degradation concentration along with the Coefficient of friction values differ. At high temperatures, a workpiece coated with ZrZrN(Nb, Zr, Cr, Al)N coating exhibited the least COF and showed the lowest strength of linkage bond to the stratum. Under this study, a tool with this coating revealed the lowest life among the other coatings on the tool.

IX. MATERIALS CURRENTLY USED IN COATINGS

Cutting is one of the most fundamental machining processes. It is required in the production of a large variety of products. This makes these tools very vital, and hence improving on their properties for cost-cutting is necessary. The required characteristics of these tools are decided based on the process as well as the material of the tool. The changes in the requirement of the industry are the driving force of advancement in cutting tool technology.

The requirement of the cheap, long-lasting cutting tool leads to the development of the coated tool. The coating is done in two ways

a) Single-layer coating
b) Multi-layer coating

The material used to coat the tool is selected based on the desired properties for the cutting process. The single-layer coating is generally used on obtaining a single required property. On the other hand, the multi-layer coating is done to obtain a combination of required properties. The multi-layer coating is done in a combination of three. The first layer is a binder that improves upon the tool’s ability to resist fracture and to provide a strong bonding between the coating and the base metal. The second layer is generally Al_2O_3 that improves upon the tool’s ability to resist corrosion and chemical decay. The third layer is the one that remains in contact with the workpiece. The material is selected based on the required hardness, surface finish, production rates, cutting speed and cutting temperature.

Some of the most common materials used for coating are

a) Titanium Nitride

Titanium Nitride increases a tool's hardness and since it has a very high oxidation temperature, it improves the tools corrosion resistance. This coating is best used with HSS tools or inserts.

b) Titanium Carbo-Nitride

Titanium Carbo-Nitride also increases a tool's hardness, but most importantly, it also increases the surface lubricity of the work material. This drastically brings down the surface friction and increases the tool life significantly.

c) Titanium Aluminium Nitride

Titanium Aluminium Nitride gives the tool a better life in high heat operations, owing to the development of an Al2O3 layer. This coating is generally used on carbide tools and inserts in operations where little cooling is available.

d) Titanium Carbide

Titanium carbide is one of the most common coating materials. It improves the tool’s hardness but it is also not very ductile, therefore not suitable for interrupted cuts.

e) Diamond

The diamond coating increases hardness, hot hardness the tool ability to withstand compression and hence interrupted cuts. It also increases wear resistance and decreases work-tool friction.

X. CONCLUSION

This review paper gives us a comprehensive overview of the need for tool coatings and how they have helped to improve the efficiency of cutting operations and how they massively impact tool life. In the machining industry, characteristics of cutting tools play an important role in the quality and surface finish of the workpiece. Tools are mostly manufactured using cemented tungsten carbide, which is often not up to the mark when it comes to the issue of tool life. Hence, tool coatings of different materials have been made use of to improve the mechanical properties of these tools. Nano Coatings are also employed when machining is done for parts that require immaculate surface finish. PVD and CVD processes are the most commonly used for applying the coatings onto the tools. However, in some cases, when excellent adhesion is required, Plasma Enhanced Sputtered Deposition is also used to coat the tool. The materials used for the coatings also provide the tools with specific characteristics and can be used strategically to obtain the most desired output. Our studies indicated that coating thickness is the most significant parameter to achieve optimized machining. Different materials, as well as the thickness of the coating, can be iterated to find out the most optimum material – thickness relationship for machining. More in-depth studies can be carried out in the field of multi-layer coating thickness optimization to come out with more accurate results which could then be implemented to maximize the efficiency and production rate of the machining industry.

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