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Review Article

Performance of Multilayered Nanocoated Cutting Tools in High-Speed Machining: A Review

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In machining processes, cutting tools play a dominant role in producing quality products. The quality of finished goods is directly related to the cutting tool condition. Several types of research have been carried out in cutting tool condition monitoring. On the other hand, the manufacturing industries should be aware of the cutting tool selection, operating conditions, and performance of cutting tools. This article emphasizes the performance of coated cutting tools and tool materials for various machining operations. Nowadays, the nanocoating of CNC tool inserts increases the wear resistance, vibration emissions, metal removal rate, etc. These coating techniques influence the manufacturing industry to increase the productivity and quality of the finished goods and reduce the machining cost. The performance of thin film multilayered coatings such as TiN, TiAlN, AlTiN, Ti, and TiCN on plain silicon carbide tool inserts is revealed by the researchers to guide the manufacturing industry for proper tool selection and standard machining inputs for metal removal operation. The influence of coating material such as TiBN, TiN, TiAlN, and CrAlSiN in cutting tools leads to increase the life time of the cutting tools, which decreases the material sticking and cutting forces. Titanium carbo nitride is wear-resistant and corrosion-resistant. Compared to TiCN, TiAlN is harder due to the higher hardness of 32 GPa. This article concludes the material selection based on the work piece material which yields good metal removal with less cutting forces. The article concludes the cutting material selection based on the work piece for machining operations.

1. Introduction

In the manufacturing industry, the quality of components plays an essential role in satisfying the engineering needs. Precision and accuracy of components can be attained only by machining with appropriate machine tools and machining conditions. In engineering, steel is majorly used in automotive, aerospace, and other industrial applications. In general, machining processes such as drilling, turning, tapping, reaming, and hobbing are being used in manufacturing processes. Turning is the predominant operation among all the machining operations [1] after the machining process. In conventional lathe machines, instead of replacing the whole tool setup, to reduce the replacement cost, inserts are being used for replacement, in which tool inserts are being used in machine and worn out tool inserts are replaced by another insert. In the manufacturing of components, tool wear monitoring is essential, and it is the most challenging one for the manufacturing industry to meet precision and accuracy. The precision and accuracy of the computer numerical control (CNC) lathe are more compared to the conventional lathe. In practice, after a prescribed period, the performance of machines was reduced due to the depreciation of tools and machine parts [2].

The reduction of machinability is due to the wear of cutting tools. The wear is classified as crater wear, flank wear, adhesive wear, polishing wear, corrosion wear, wear due to temperature, fretting wear, and cavitation damage. In several researches, crater wear and flank wear are taken into account due to the key role in material deterioration.

Several types of research are being carried out to increase machine life and tool life prediction using mathematics. Another predominant way of increasing the tool life is tool coating. In general, for machining of steels and ferrous alloys, silicon carbide materials have been widely used as coating materials. Tool inserts are coated with harder materials to increase the tool life [3]. Accordingly, materials are selected which are harder than base materials. Generally, tungsten, diamond, and carborundum materials are used as coating materials. These harder materials are coated with two different processes, i.e., physical vapor deposition and chemical vapor deposition methods. In most practical applications, the coating thickness is in the range of 0.0025 to 0.0005 μm [4].

Coating of inserts results in resisting the diffusion and shocks while machining, due to the higher hardness of coated inserts which has high wear resistance. Tool wear occurs in inserts due to the diffusion of atoms between the tool and chip material. If diffusion is arrested, then the crater wear rate can be reduced [5]. The present work reveals the technique of reducing tool wear by coating harder materials to control the crater wear and flank wear for ductile materials like steel. In general, predictors of wear are feed rate, depth of cut, and spindle speed. Based on the applications, machining processes for product demands were very high accuracy, surface finish, and precision. Predictors of tool wear are correlated, and the relation between the surface finish, accuracy, feed rate, depth of cut, and speed has been exhibited in the present work. Traditionally, Taylor's tool life equation $VT^n = C$, where V is the cutting speed, T is the tool life, C is the constant, and n is the material constant, is used to predict the tool life. The constant "C" for machining of high speed steel is 0.125, cemented carbide is 0.25, cast alloys is 0.50, and for ceramics is 0.6. In the conventional process, silicon carbide tool inserts are coated with more rigid ceramic materials, to obtain better machining characteristics and increased tool life for various machining operations. Carbide-based inserts play better performance for ferrous materials like steel, cast iron, iron, and stainless steel. Further, the reduction of tool wear rate will yield better accuracy and precision of components. Majorly, tool inserts are being manufactured with silicon carbide as the base material. [6, 7]. The coating thickness of 1-4 micrometers is achieved by magnetosputtering physical vapor deposition process for TiAlN and TiCN cutting tool inserts. The wear of TiN-coated tool inserts is 12% less than the uncoated silicon carbide tool inserts. TiN/Al_2O_3 showed the wear resistance which is 65% less than the uncoated tool inserts in machining of steels.

2. Cutting Tool Manufacturing Processes

The tool inserts are selected such that to withstand high temperature and heavy cutting forces at high cutting speeds, hence that the hardest materials make it in the world. A typical insert is made of 80% tungsten carbide, and 20% of the metal matrix binds the hard carbide together. Cobalt, titanium, and other ingredients are mixed in the milling room to reduce the particle size. The ingredient's particle sizes are reduced by mixing ethanol, water, and other organic binders [8]. The milling process is continued from 8 to 55 hours, depending upon the recipe. The slurry obtained in the milling process is pumped into a spray dryer, and hot nitrogen gas is sprayed to remove the moisture of ethanol and water content. After the drying process, spherical granules of identical sizes of ingredients are obtained. The mixed metal powders are pressed with 12 tons of pressure to manufacture the tool inserts. The binder added in the ball milling operation holds the powder together after pressing. The pressed inserts are very fragile and need to be hardened using a heated oven by sintering processes. The processes take place for 13 hours at approximately 1500°C. The inserts are sintered to make an extremely hardened product, almost the hardness of a diamond. After sintering processes, organic binders are incinerated, which leads to a shrink of approximately 50% of their original size. The cutting tool inserts are ground using grinding machines to make the insert with exact dimensions and tolerances. The excess carbide materials in the cutting fluids are recycled for the manufacturing of new inserts [9].

The majority of the tool inserts are coated either through chemical vapor deposition or physical vapor deposition techniques. The tool inserts are fixed in the fixture of the physical coating deposition machine, and a thin layer of coating material makes the tool insert harder. This coating technique also paves the way to get the specific color of the tool insert. The machining performance is influenced by the coating thickness, coating material, and nanostructure of the coating materials. CNC cemented carbide inserts are used for metal removal operations of steels, high-temperature alloys, and other nonferrous materials. In general, the cutting tips are attached to the tool holders [10]. A typical tool holder and tool insert is shown in Figure 1. The selection of inserts is based on the profile of machining and the materials to be machined. Tool inserts for internal and external turning involve high precision and accuracy of finished components. Sandvik Coromant cutting inserts, Kennametal, Mitsubishi, Hitachi, and Panasonic are the commercial machine tool insert manufacturers. These carbide tool inserts are capable of indexing while machining process to change the cutting edges. These tool inserts can be removed easily from the tool holder, which results in a good surface finish and more metal removal rate at higher cutting speeds [11].

3. Deposition Methods

There are two types of deposition methods used for different coating materials on the base material, i.e., physical vapor

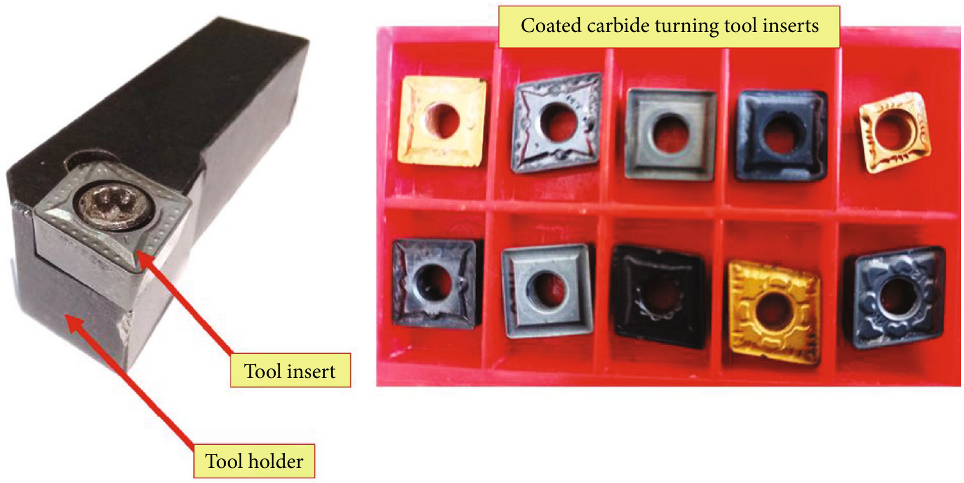

FIGURE 1: Tool insert, tool holder, and types of coated carbide tool inserts.

deposition methods and chemical vapor deposition methods. The physical vapor deposition method involves physical processes like heating and sputtering. The coating material vapor is evaporated from the chamber and forms a coating on the surfaces of the base material. Similar technologies are being used in the manufacturing of solar panels, semiconductor devices, electronic components, integrated circuits, etc. Commonly industries are using coating materials like titanium nitride, zirconium nitride, chromium nitride, and titanium aluminum nitride, while comparing the physical vapor deposition method and chemical vapor deposition method. PVD coatings are harder and possess good corrosion resistance, and it yields better results than electroplating. These coatings have very high thermal resistance and good impact strength [12]. While doing physical vapor deposition, the system requires a cooling water system. The cooling water system operates at a very high temperature, and it needs highly qualified personnel for operation. However, physical vapor deposition can fulfill the needs of complex geometries. In general, coating materials like TINALOX SN2, Hyperlox, ALOX SN2, HSN2, CC AluSpeed, SUPERSPEED, CCplus C, and CCplus D were widely used in research to improve the quality of machining. These materials are used in the machining of materials like steel, stainless steel, cast iron, nonferrous metals, graphite green compact materials, and Ti-Al alloys. Coated tool inserts increase tool life by increasing toughness, resistance to abrasion, resistance to thermal deformations, modulus of elasticity, and wear resistance, which results in achieving precision and accuracy in machining components [13]. Also, these coated tool inserts broaden the range of depth of cut, cutting speed, and other machining parameters and reduce the time of machining. Coating of tool inserts gives longer tool life and higher cutting parameters leading to reliable performance while machining. The coating process applies to turning, milling, drilling, tapping, and dry cutting operations with or without lubrication [14]. The PVD coated indexable Ti-coated tool inserts are often called as AloXSN^2. The coated machine tools of HSN2, CC AluSpeed, and SUPERSPEED are suitable for rough machining which increases 65% of life time compared to the uncoated tool inserts. The Sandvik Coromant, Mitsubishi, and Panasonic multilayer-coated tool inserts are used to machine the steels, alloys steels, brass, and aluminum alloys.

4. Performance of Coated Tool Inserts in Wear Resistance

The effect of grain size and hardness of wrought alloy 718 with cemented carbide tools is revealed in the turning operation. It is stated in the work that four different conditions of the same materials were studied. A large amount of grain size resulted in a deformed layer of the workpiece was clearly shown in this work. It was reported that transverse turning of discs was done with EMCO 635 CNC lathe with cutting fluids used [15]. It was stated that chip breakers were not used to investigate the morphology of chips and the hardness of the specimen. Uncoated standard cormorant tool inserts were used for experimentation purposes. It was inferred from the relationship between the hardness of the material and flank wear, i.e., flank wears strongly correlated with the hardness of the specimen. Grain size did not influence flank wear, and also, notch wear is associated with the formation of burr [16].

Antiwear resistance analysis in coating materials like chromium nitride and chromium carbonitride was carried out with multilayers. It was reported that chromium and chromium carbonitride coatings improved the quality of machining. TINA 900 M system cathodic evaporation techniques were employed in the research work [17]. The physical vapor deposition method was utilized in this work. Young's modulus, Poisson ratio, and stress were measured, and it was reported that antiwear multilayer coatings improved the quality of machining. Precipitation hardened stainless steels in dry turning using carbide tool inserts results in adhesion wear [18]. It was reported that, due to the adhesion process, diffusion of tool particles results in crater wear and abrasive wear. Tensile strength, yield strength, and hardness parameters were measured in the investigation. The microscopic structure was studied by a digital microscopic system attached with a readout connected with processors and display units. Flank wear and cutting temperature were analyzed. Tool wear and quality of workpiece in a milling operation are investigated with chilled air flow [19]. It was shown that chilled airflow reduced the working temperature drastically and increased the lifetime of the milling tool. It was reported that chilled airflow increases the quality and surface finish. CFRP (carbon reinforced fiber plastic) material was used for the investigation, and it was shown that chilled air flow increased the quality even at high cutting speeds. Adhesive wear by the physical vapor deposition method was investigated in hot stamping production tools. It was stated that CrN-coated hot stamping or press hardening and stamping tools investigated through the physical vapor deposition method [20]. It was reported that AlcrN-coated tools adopted the same experimental procedure. Imaging confocal microscopic technology was used to view the microscopic pattern change of tool insert before coating and after coating. Topography and material thickness were analyzed by OLYMPUS stereoscopic lens. In drilling die-cast magnesium alloys with high-speed steel uncoated tool inserts, microanalysis of the tool was done to study the grain structure, and orientation of abrasive wear and adhesive wear was taken into account. It was concluded that a change in the trend of the flank face of the drill bit occurred after the drilling operation [21]. Flank wear dominated in drilling operation of die-cast magnesium alloys. Based on the scanning electron microscopic analysis, there were three types of wear reported, i.e., abrasive wear, adhesive wear, and diffusion wear. It was reported in the work that the diffusion process takes place from drilling tool to specimen, tool grains were diffused into the specimen, and the same was observed by microscopic analysis of chips [22]. As reported in work, adhesive wear occurs due to the adhesion force between the drilling tool and specimen, and it was reported that abrasive wear occurred due to the erosion of tool particles due to the cutting force given by the drilling tools [23].

The properties of the single crystal diamond (SCD) tool and polycrystalline diamond (PCD) tools during the machining of silicon and aluminum matrix composite materials are investigated. It was reported that there are many investigations were done on composite materials, ferrous alloys, and other alloys. It was reported that ultraprecision turning technique was introduced in this research. Chipping, peeling, and abrasive wear of SCD and PCD tool materials were observed by SEM analysis [24]. From the reported work, it was inferred that transferring silica particles into aluminum matrix composites results in wear behavior. It was reported that due to the high stiffness of the cutting system, stress relaxation in the cutting tool was observed. The graphitization of SCD tools was observed while machining copper and copper alloys [25]. The properties of coated carbide tools for milling operation are investigated with tool inserts coated with the chemical vapor deposition method. Ti and Cr were used for coating, and the adhesion of the material was tested by indentation adhesion test (Rockwell hardness "*C*" indentation test was carried out). The investigation was carried out with two different categories of coating materials, i.e., coating materials with pretreatment and without pretreatment). It was concluded that pretreated coating materials achieve high abrasion resistance, and tool life was increased. The quality of milling was improved by increasing high accuracy and precision. The surface coating of the cutting tools is achieved by the physical vapor deposition method by electrosputtering technique, chemical vapor deposition method, and LASER texturing techniques [26].

5. Wear Pattern with Diamond Tools

The wear pattern of the diamond tool while machining Al6061 and 1215 steel is revealed. The cutting force was measured in turning operation by a dynamometer, and three-axis transducers were used to measure cutting forces. In tool wear analysis, wear of edge radius, flank wear, and crater wear was taken into account, including the worn volume of inserts. It was reported that there are two categories of materials were used for machining in the investigation, namely, steel and aluminum alloy [27]. It was observed that cutting forces were lower for aluminum alloys than stainless steel. In the machining of AISI 1045 steel, the finite element modeling technique was used to apply the boundary conditions, governing equations were solved by software, and wear behavior was studied in AISI 1045 steel [28]. Cutting velocity, feed rate, and depth of cut were the parameters taken into account, and diffusive wear was observed predominantly at 700°C. Simulations were carried out by deform 3D simulation software. It was reported that 110,000 tetrahedral elements were used in the finite element model [29]. This method involves cost-effective and time-saving simulation processes. In all machining conditions, temperature places a predominant role [30]. In this investigation, temperature, pressure, and stress-induced in tool inserts were included. The study and improving the tool wear resistance property in stamping operations were carried out. Instead of the coating machine tools, die and punch tools were heat treated, and experiments were carried out for boundary lubrication conditions. To improve the wear property further, ceramic thin film AlCrN was coated on tool materials, and wear progressions were monitored [31].

6. Tool Wear Analysis in Turning Operation

The properties of Hastelloy C22HS evaluate tool life and study tool failure in the turning process. TiN, TiCN, and Al_2O_3 were coated on the tool by both chemical vapor deposition and physical vapor deposition coating techniques. Results showed that the physical vapor deposition method performance was better than the chemical vapor deposition method. The relationship between the cutting force and process parameters was plotted. Flank wear, crater wear, adhesion wear, and abrasion wear were studied. A vertical machine center OKUMAMX45-VA was used for machining processes [32]. It was concluded that tool life decreases with increasing the depth of cut and feed rate. It was reported that axial depth and feed rate play a predominant role in tool life. It was observed that flank wear, cracking, chipping, adhesion, and abrasion were the failure modes of tool inserts [33]. Tool life equations were developed from the turning test data and the machining properties of TiAlN coatings in the turning of a nickel-based specimen. Energy dispersive X-ray spectroscopy and SEM analysis have shown that, in nickel-based alloys, workpiece material adhered to tool insert rake face, flank wear, a crater on rake face, and notch in the depth of line were observed. The adhesion process was continuously monitored and observed that adhesion was in periodic formation by stacking and plucking [34]. It was reported that sticking of workpiece material in tool inserts affected the machinability of tool inserts and reduced the cutting forces and decreased accuracy and precision [35]. This investigation was carried out with predominant process parameters such as feed rate, depth of cut, and spindle speed. It was observed that plucking workpiece material adhered from the tool insert led to crater wear, and it was observed that transfer of grains of tool insert grains was into the workpiece. Experiments were carried out in wet conditions, and it was concluded that flank wear, crater wear, and adhesive wear were predominant parameters affecting the tool life in the machining of nickel-based alloys, and coated tool inserts increased the tool life, accuracy, and precision of machining components. CGI (compacted graphite iron) in the machining of cemented carbide milling tools coated with Al2O3 medium temperature chemical vapor deposition technique was utilized for coating. It was concluded that of workpiece material influenced tool life. Three types of materials were used for research and compared with each other [36]. It was shown that it proves cemented carbide cutting tools and Al2O3 coated milling tools performed in varied dimensions while machining with grey iron and compacted graphite iron (CGI). The microstructure of the milling tools (similar to our previous references) was as follows. Kristel dynamometer was used to measure the cutting force while machining. The white light interferometer was used to measure the surface roughness of the specimen. Scanning electron microscopy results showed that, if the microstructure is perpendicular to the cutting edge, it was reported. If that microstructure is perpendicular, it will give a better surface finish, accuracy, and precision in the workpiece [37]. A focused ion beam system observed microstructures with liquid gallium ion sources. FEI Quanta 3D FEG technique was used to fabricate the tool materials [38].

Hence, the microstructures were perpendicular, i.e., 90° to the rake face, and it was shown that it increases the lifetime of tool materials. The tool wear patterns in the machining of carbon steel were coated with cemented carbide inserts. This research involves the usage of lubricants in different conditions. AISI steel with 25 HRC was in milling operations with three types of lubrication: MQL, flooded, and minimum requirement of lubrications. It was concluded that the reduced flow rate of lubricants increased the quality of the workpiece compared to a flooded type of lubrication, and it was observed that adhesion and abrasive wear occurred in machine tools. The experimentation in tool failure and failure modes in forming of stainless steel were carried out. It was reported that the wear of forming tools leads to failure and inaccuracy of forming components. It was concluded that the increase of hardness of the forming tools led to an increase in galling resistance and increased the tool life [39–44].

The development of a new wear index by analyzing the mechanical properties of diamond tool inserts was also done through the petrographic study of diamond and calcium alkali-type rocks, i.e., ceramics. It was observed that the mechanical property table diamond plays an essential role in hardness [45]. Hence, it is used predominantly used in all cutting tools as coating materials. Silicon carbide tool inserts were more economical than diamond tools. Biotite, feldspar, quartz, plagioclase, and hornblende type ceramics were used as coatings. A conceptual design of new materials for coating turning tools was reported in this investigation by reference to the machining of granites and other ceramic specimens [46–49]. It was concluded that quartz and feldspar performed better, and it was widely used in the stone processing industry. The investigation has shown that ceramics like quartz and feldspar were used widely in the stone processing industry, and it was rarely used in turning and other machining purposes or not used commercially since hardness property cannot satisfy the machining of steel or other engineering components [50–54]. The work in TiAlN coatings for drilling operation was carried out. Effect of tool geometry on the wear of cemented carbide coated with TiAlN in the drilling of compact graphite iron was reported. It was concluded that adhesion mechanism was observed in TiAlN coated drill bits, and surface finish and accuracy were better while using drill bits coated with TiAlN in the machining of compact graphite iron (CGI) [54–59].

7. Conclusions

The recent advances in multilayered coating material for cutting tool inserts are reviewed in this article. The manufacturing techniques of cutting tool inserts from the slurry are discussed. The performance of coated tool inserts over uncoated silicon carbide inserts was discussed. The coating techniques, such as the physical vapor deposition method and chemical vapor deposition method, are revealed in this article. From the various researches, the coating material and thickness play the predominant role in wear pattern and tool life. The coating material is selected to withstand high cutting forces and temperature while machining. The wear resistance of the coating material depends on the pressure and temperature applied while manufacturing the tool inserts [60]. The single, bilayer, and multilayer coating of tool inserts leads to increasing wear resistance properties and metal removal ability. The recent advancements of nanolayered coatings lead to a reduction of ball sizes which increases the adhesive property [61, 62]. The increasing adhesive property reduces the adhesive wear of tool inserts. The performance level of multilayered coatings increases the performance level over conventional coating methods. The radial, feed force, and cutting force for the coated tool inserts are increased after the coating. The cutting force of TiN-coated high speed steels is 25% greater than uncoated silicon carbide tool inserts.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interests.

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