

## Cutting with coated tools: Coating technologies, characterization methods and performance optimization

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### ABSTRACT

Coated tools constitute the majority of the tools applied in material removal processes, rendering the employment of uncoated ones as an exception. A broad growing market of coated cutting tools has been developed. Moreover, numerous material- and manufacturing-engineers have joint their expertise, aiming at developing coatings meeting the needs for processing the most difficult-to-cut materials at the most extreme cutting conditions. The emerging of new workpiece, tool and film materials, the evolution of sophisticated coatings' characterization methods and the continuous need for higher productivity rates, maintain vivid the industrial and scientific interest for further advancing this field.

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### 1. Introduction

Coated tools have compound material structure, consisting of the substrate covered with a hard, anti-friction, chemically inert and thermal isolating layer, approximately one to few micrometers thick. As such, coated tools compared to uncoated ones, offer better protection against mechanical and thermal loads, diminish friction and interactions between tool and chip and improve wear resistance in a wide cutting temperature range [82].

The elevated cutting performance of coated tools can also be explained by the mechanical and thermal loads acting on the cutting wedge during the material removal. In an example of milling hardened steel, the maximum equivalent stress in the coating determined by finite elements method (FEM) calculations reaches 5.6 GPa on the cutting edge roundness close to the flank, remaining below the film yield stress of 5.9 GPa (see Fig. 1). Additionally, the substrate is less stressed (max. equivalent stress  $\approx 3$  GPa) compared to the uncoated tool (4.9 GPa). In the uncoated tool, the stress of 4.9 GPa exceeds its yield strength of ca. 3.2 GPa, thus leading to cutting edge micro-breakages and accelerating the wear growth. The maximum temperature in the coated insert amounts to ca. 266 °C, at a tool-chip contact time of 4.8 ms (see Fig. 1). In the case of an

uncoated tool, a comparatively higher amount of the total cutting thermal energy is transferred during the same chip contact time into the tool, leading to a significant increase of the maximum temperature up to 652 °C. In interrupted cutting, depending on the tool-workpiece contact time, the maximum tool temperature is commonly lower than the corresponding steady-state temperature of continuous material removal processes [4,54,85,104].

In the latter procedures as well as at higher cutting speeds and feed rates increased heat is generated. As a result, tool suppliers placed emphasis on developing heat-resistant cutter materials and inert coatings also at elevated temperatures, especially for cutting processes with continuous material removal. Herewith, the coating and the less inert substrate are effectively protected against interactions with the chip material.

The present paper is organized as follows. In the next section, insights in the coating deposition techniques and in current evolution trends of cutting tool coating materials and related manufacturing methods are provided. Moreover, innovative characterization methods are introduced for determining pivotal material, functional and film dimensional data, which allow the prediction of the coated tool performance and the adaption of the cutting conditions to the film properties. In a further section, appropriate substrate and coating thermal as well as mechanical treatments, which contribute to cutting performance improvement, are presented. Finally, applications of coated cutting tools in difficult-to-cut materials and appropriate coated tools reconditioning procedures are highlighted. In its last section, the paper wraps-up with conclusions.

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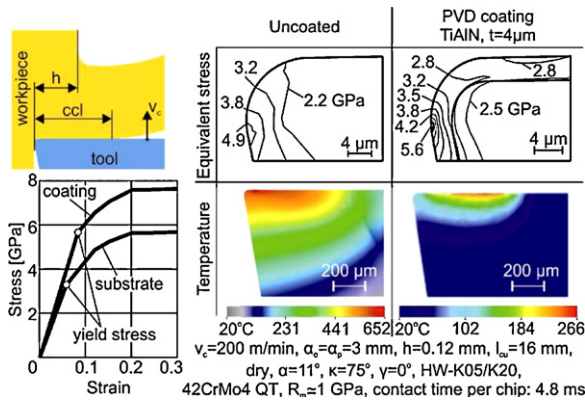


Fig. 1. Decrease of mechanical and thermal loads of cemented carbide tools in milling by the application of PVD-coatings.

## 2. Trends in manufacturing cutting tool coatings

### 2.1. Coating deposition techniques for cutting tools

Fig. 2 presents the coating deposition technologies for cutting tools, classified according to pressure and temperature required for the process.

Physical vapor deposition (PVD) covers a broad family of vacuum coating processes in which the employed material is physically removed from a source by evaporation or sputtering. Then, it is transported by the energy of the vapor particles, and condensed as a film on the surfaces of appropriately placed parts under vacuum. Chemical compounds are deposited by either using a similar source material, or by introducing reactive gases (nitrogen, oxygen, or simple hydrocarbons) containing the desired reactants, thus reacting with metal(s) from the PVD source. Most of the PVD processes are known by various phrases or acronyms and they are typically named for the physical vapor source; for example, diode or triode sputtering, planar or cylindrical magnetron sputtering, direct current (DC) or radio frequency (RF) sputtering, electron beam evaporation, activated reactive evaporation, and ARC evaporation (DC or alternate current (AC)).

Chemical vapor deposition (CVD), unlike to PVD vacuum processes, is a heat-activated process based on the reaction of gaseous chemical compounds with suitably heated and prepared substrates. Primary reactive vapors can be either metal halides (chloride, bromide, iodide, or fluoride) or metal carbonyls,  $M(CO)_n$ , as well as hydrides and organometallic compounds. To decompose or reduce the metal compound, a transfer of heat energy is involved, and the substrate is usually held at a substantially higher temperature than any other part of the system. For this reason, the reaction chamber may present more of a high-temperature problem than any other part of the system. Most reactions are also conducted in an anhydrous and anaerobic environment, and frequently at sub-atmospheric pressures. Typical deposition temperatures range from 800 to 1200 °C. The ability to provide

uniformly thick coatings with refined grain is also influenced by the deposition temperature. In both cases, low-temperature processing is frequently desirable, although a compromise in the rate of deposition must often be made. Fewer CVD reactions are available for use at temperatures below 800 °C than above (moderate temperatures, MT-CVD). However, the temperature required for a given reaction can be lowered by exposing the substrate to an electrical plasma in the gas phase during deposition, referred to as plasma-assisted (PA-CVD). Metalorganic CVD (MO-CVD) has been reported for strengthening  $Al_2O_3$ -based ceramic tools [89].

CVD coatings were already commercialized for carbide inserts in the 1960s. PVD was developed almost 20 years later and today both CVD and PVD are sharing the coating market of cutting tools. PVD coatings for cutting tools can be deposited at temperatures lying in the range of 450–550 °C, which allows the film deposition on high speed steel (HSS) tools. Moreover, the ability to control thicknesses on the edges, when PVD is employed, guarantees a sharp coated edge. High intrinsic hardness and compressive stresses inhibiting the crack growth in tool material are among the beneficial properties of PVD. The possibility to produce thick layers by CVD at increased deposition rates renders the CVD coated tools suitable for high material removal operations, whereas PVD ones are selected in medium finish and finish operations. PVD films can be produced without any chemical interaction with the substrate. CVD coatings easily interact with the substrates, occasionally producing brittle carbides at the interfaces. The ease of decoating and resharpenering of PVD coated tools opened a large industrial market highly sensitive to cost reducing opportunities.

### 2.2. Evolution of coating deposition processes and characteristic film systems

The most extensively investigated coating system is the (Ti,Al)N, due to the ease of deposition parameters and material's contents manipulation, as well as its potential to increase the cutting performance of tools. With an augmentation of aluminum content the oxidation resistance of coatings increases, however, a barrier is set to PVD process technology by the deposition of insulating films at a film composition of approximately 65–67 mol.% AlN. The high ionization sputtering (HIS) process technology leads to an asymptotic convergence toward this limit. The films become insulating whereas the sputter sources remain conductive [66,67].

Although TiN and AlN show no solubility under equilibrium conditions, a wide solubility of these two phases can be achieved under the condition of non-equilibrium in PVD. This target is fulfilled through the process control far away from equilibrium, so that a metastable phase, in a local, kinetically determined energy minimum is formed. To overcome the situation just to converge toward the conductivity limit of approximately 65–67 mol.% AlN in the case of one variant of (Ti,Al)N based nitrides, a plasma enhance sputtering process has been developed, which is capable of depositing conductive and insulating coatings in virtually any stoichiometry. The high ionization pulsing (HIP) process technology maintains the glow discharge in front of the sputter sources and makes it possible to deposit films with an Al/Ti ratio up to 5.

The realization of extremely dense plasmas becomes possible through the application of pulsed plasmas and an increase of the potential difference between the pulse electrodes. Thus, the ion energy contributes to the guidance of dense plasmas specifically to the substrate. This plasma enhancement is necessary to shift the transition from the cubic B1 structure to the hexagonal Wurtzite one, toward higher AlN content, and thus the high hardness of the well known, commercially available coatings with Al/Ti ratios of approximately 1 can be preserved. Plasma density measurement results in a region very close to the substrate surface, by means of an energy selective mass spectrometer, verify these evidences [15,61]. The  $Ti^{+}$ -ion concentration is registered during the deposition of a (Ti,Al)N coating in both deposition cases by

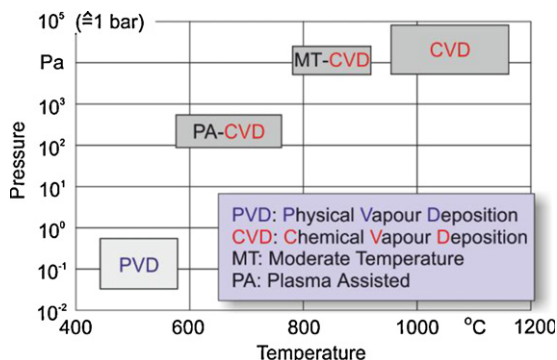


Fig. 2. Coating deposition technologies for cutting tools [122].

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