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An Insight into TiN, TiAlN and AlTiN Hard Coatings for Cutting Tools

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The evolution of the metalworking industry over the centuries was greatly influenced by the development of a large range of cutting tools. Tool surface quality improvement with hard coatings generated considerable progress in the metal cutting industry. Hard coatings were composed mainly of nitrides, carbides, borides, and oxides of transition metals (typically Ti, Cr, Zr).[1-5]

Tool surface hardening includes chemical vapor deposition (CVD, e,g. plasma activated CVD), physical vapor deposition (PVD, e.g. cathodic arc, sputtering, evaporation), combined PVD (e.g. sputtering and arc evaporation) or combined PVD and CVD processes.[1-5]

Hard coatings can be grown on the tool surface at a maximum deposition temperature of 1000°C for CVD and 500°C for PVD. The thickness of CVD and PVD coatings can be over 20 µm, and up to 10-15 µm, respectively. In industrial production, 0.5-4 µm thick PVD coatings are usually selected for specific applications. Coating architecture can be designed as a single layer, multilayer, graded, nanostructured or nanocomposite layer.

The performance, durability and service life of tools and coatings used in metalworking processes are determined mainly by friction and wear phenomena. The interfacial wear of the sliding surfaces appears due to the interactions among the interfaces between the cutting tool and the workpiece or among the cutting tool and the environment.

Solutions for wear control of tools exposed to severe thermal and tribological conditions consider the tool geometry, properties of the tool materials, heat and mechanical pre- and post-treatments, the surface state of tool and workpiece, the optimum deposition process, and the selection of right coatings. The choice of cutting fluid is very important in wet machining.

Hard coatings provide a long service life of the cutting tools and reduce the tool damage. Comparatively to uncoated tools, coated tools ensure better performance and protection against high mechanical and thermal

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loads generated by excessive heat during the cutting process, decrease tool-chip friction and interactions, increase cost efficiency and machining productivity.

Since their introduction around forty years ago, hard PVD coatings based on transition metal nitrides expanded. Titanium nitride (TiN) was the first commercial PVD industrial coating that is still in use for certain applications. TiN crystallizes in the cubic B1 NaCl structure and is a solid solution containing 37.5-50 at.% nitrogen.[1] TiN coatings exhibit high hardness, low friction coefficient, high chemical inertness, good adhesion strength, high wear and corrosion resistance, and good oxidation resistance.[1-3]

The second generation was based on titanium aluminium nitride (TiAlN) hard coatings. TiAlN and AlTiN (Al content > 50 %) coatings were intensively studied and widely applied in the cutting industry since in severe conditions they offer higher temperature resistance and hot hardness than TiN coatings.[1-5] $Ti_{1-x}Al_xN$ (x is defined as the Al/ (Al+Ti) molar ratio) are nowadays among the most versatile PVD coatings due to high resistance to abrasive wear, excellent thermal stability, oxidation resistance, and age hardenability.[4] However, the crystal structure and mechanical and thermal properties of $Ti_{1-x}Al_xN$ strongly depend on the coating chemistry that in turn depends on the deposition process.[1-5]

Properties and typical applications of hard PVD coatings (Table 1) are disclosed by industrial companies as approximative values that depend on application, environment and test conditions. Moreover, no uniform specification exists for hard coatings.

Table 1: Properties and typical applications of TiN, TiAlN and AlTiN hard PVD coatings

Coating material	Thickness (μm)	Indentation hardness, H_{IT} (GPa)	Vickers hardness $HV_{0.05}$	Service temperature (°C)	Friction coefficient vs. steel (dry)	Typical applications
TiN	1 - 7	22 - 33	2200 - 2800	500 - 600	0.40 - 0.55	General, wet machining of less hard materials
TiAlN	1 - 4	29 - 36	2800 - 3300	700 - 900	0.35 - 0.60	General dry machining of hard materials
AlTiN	1 - 4	32 - 39	3000 - 3500	850 - 1000	0.50 - 0.70	High speed dry machining of hard materials

TiAlN and AlTiN coatings are typically obtained in multilayered or graded architecture. The as-deposited $Ti_{1-x}Al_xN$ coatings can exhibit at low Al contents (x < 0.55) a single-phase cubic NaCl structure (c-$Ti_{1-x}Al_xN$), at high Al contents (x > 0.69) a single-phase wurtzite ZnS structure (w-$Ti_{1-x}Al_xN$) or at intermediary Al contents ($0.55 \leq x \leq 0.69$) a mixed cubic-wurtzite phase.[4]

$Ti_{1-x}Al_xN$ structure depends on the Al contents and the annealing temperature. Thermal annealing of c- or w-$Ti_{1-x}Al_xN$ solid solution at 700-900°C causes the decomposition into their stable c- or w-TiN and AlN inducing self-hardening effects.

The change in crystal structure affects the coating microstructure but can improve the hardness, oxidation resistance and wear behavior.[1-5] A fine columnar morphology was found for c-$Ti_{1-x}Al_xN$, and glassy morphology or coarse agglomerate-like structure for biphase c-TiN/w-AlN structure.[3] The mechanical strength and oxidation resistance of as-deposited c- or w-$Ti_{1-x}Al_xN$ increase with Al content increase but decrease for mixed cubic-wurtzite structure.[2]

Another trend to improve the machinability and tool performance was the coating deposition on cutting tools manufactured with micro- or nano-textures on the rake or flank surface, as TiAlN coated tools with grooves in the perpendicular direction of the chip flow confirmed.[5]

The main feature of $Ti_{1-x}Al_xN$ is excellent thermal stability at high heat (> 800°C) dry machining due to the formation of a hard and oxidation resistant thin layer of Al_2O_3 and TiO_2 mixed oxides.[2] The passive layer dissipates the heat via chip removal allowing production increase at higher cutting speed. When compared to uncoated tools, depending on the application, the service life of TiN, TiAlN, and AlTiN coated tools can increase up to 3, 10 and 14 times, respectively.

The expanding demands in the metalworking industry required multicomponent coatings by alloying TiAlN with one or more elements (Ta, Si, Hf, Cr, Y, Zr, Nb, Mo, W, B, V, C or O) to enhance coating properties. For instance, the alloying elements like Ta, Si and Hf enhance the thermal stability, Cr and Y increase the oxidation resistance, Zr, B, V and Mo enhance the wear resistance, while Si improves the hardness and chemical inertness.[1-3]

Great progress was reported by obtaining nanostructured, multilayered and graded coating architecture (e.g. TiN/TiAlN, TiN/TiAlSiN, TiN/TiAlVN, TiAlN/TiAlCN, TiAlN/TiAlCrN, TiAlN/TiN) with superior properties when compared to single layer coatings.[1-3]

Promising research directions involve further studies on thermodynamics and kinetics of the nucleation and growth of crystal size to develop tailor-made coatings. Innovative coating processes need to be also addressed.

Concluding Remarks

TiN, TiAlN and AlTiN hard coatings for cutting tools are remarkable for both academic and industrial communities. Different coating materials and deposition processes were researched and implemented into production over the last four decades. Tailor-made coatings with specific architecture pave the way to obtain high performance coatings by combining modeling studies with key enabling technologies. Special demands on tool materials and hard coatings for modern machining technologies require further works.

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Conflict of Interest

No potential conflict of interest related to this article was reported by the author.

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