LATEST DEVELOPMENTS IN PVD COATINGS FOR TOOLING

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ABSTRACT

The paper presents the recent developments in the field of PVD coating for manufacturing tools. A review of monoblock, multilayer, nanocomposite, DLC and oxinitride coatings is discussed, with the emphasis on coatings which enables the manufacturers to implement high productivity processes such as high speed cutting and dry speed machining.

Keywords: PVD, coatings, multilayers, nanocomposites, high speed cutting

1. Introduction

The studies have shown that in the manufacturing industry a 30% reduction of tool costs, or a 50% increase in tool lifetime results only in a 1 % reduction of manufacturing costs. But an increase in cutting data by 20% reduces manufacturing costs by 15% [1]. In order to achieve higher productivity different approaches such as high performance cutting (HPC) and high speed cutting (HSC) can be chosen.

The introduction of PVD coatings for cutting tools in the metal cutting industry is one of the main success stories in the industrial application of modern coating technology over the last 40 years. The first PVD coating material that have a commercial application on cutting tools was TiN in the early 1980s and since the 1990s most cutting tools are PVD coated, particularly in applications where sharp edges are required (threading, grooving, end-milling) and in cutting applications that have a high demand for a tough cutting edge (drilling). In solid carbide cutting tools (end-mills and drills) PVD is the standard coating technology. The TiAlN PVD coating is currently the most widely deposited PVD coating for cutting tools, but other coatings such as TiCN and CrN offer better solutions in certain applications.

The development of PVD coatings followed the steps:

- first generation (1970): pseudo ceramic materials based on binary compounds (TiN, TiC, TiB_2, etc.);
- second generation (1985): ternary and quaternary interstitial solid solutions (Ti-Al-N, Ti-Al-N-C, etc.);
- third generation (1990): multilayer structures, superlattices (M/MN/M and MN/MC/MN, etc., where M – metallic component);
- fourth generation (2002): nanolaminated structures and nanocomposite structures, nanostructures doped with solid components as dry lubrifiant;
- present generation (2008-2010): DLC and OXI coatings

Advances in manufacturing technologies (increased cutting speeds, dry machining, etc.) triggered the fast commercial growth of PVD coatings for cutting tools. On the other hand technological improvements in coating types (TiAlN, AlTiN, AlCrN, multilayer coatings, nanocomposite coatings, DLC and OXI coatings) enabled these advances in manufacturing technologies.

The use of new materials (high temperature aerospace alloy, higher strength ductile iron used in automotive, silicon aluminum and magnesium alloys, composite materials) will increase over time and the development of new cutting tools, machine tools, and metal cutting processes, under dry machining conditions will offer many opportunities to tooling and machine tool manufacturers in the years to come.

For tooling suppliers and machine tool builders the reliance on cutting fluids to remove heat, provide lubricity, reduce wear, provide chip evacuation, act as a rust preventative, and keep dust to a minimum, must be replaced by some other cost effective technology or process to keep the metal cutting application personally and environmentally safe and productive. It is expected that there will come a time when the costs associated with the purchase, maintenance, and disposal of cutting fluids will exceed that of the metal cutting benefits gained by their use.

In the areas of machining and tooling PVD coatings are widely used to increase the life and productivity of production cutting tools saving companies milliards of euro worldwide. The use of

PVD coatings on cutting tools saves money in three ways:

- PVD coated cutting tools can be run faster reducing cycle times and enabling the production of more components in less time;
- PVD coatings on cutting tools reduce wear; in metal cutting different wear processes exist depending on the cutting tool, crater wear on the rake face, caused by chemical interaction between the cut chip and the tool surface, built-up edge on the cutting edge and depth-of-cut notching caused by abrasion by the outer edge of the chip; none of these wear mechanisms exists in isolation however one usually predominates; PVD coatings are resistant to all forms of wear increasing the life of cutting tools reducing tool-changing costs.
- PVD coatings on cutting tools reduce the need for cutting fluid; cutting fluids cost companies today up to 15% of their total production costs. High speed cutting and dry machining involve extremely high temperatures at the cutting edge; some PVD coatings have incredible thermal stability, hot hardness and oxidation resistance; PVD coatings can therefore be run dry or with very limited amount of cutting fluid.

PVD processes have the fastest market growth in the latest years, replacing the CVD technologies. This is due to their certain advantages upon other surface engineering technologies:

- the high vacuum employed makes it possible to achieve coating properties that are not available with gases and baths at atmospheric pressure (thermal spraying, nitriding, electro or chemical deposition); the resulting coatings offer high hardness, good adhesion and wear resistance, and these properties can tailored for every specific application;
- PVD processes are used for component coating operate at relatively low coating temperatures of 250...500°C; these temperature are chosen to lie at or below the tempering temperature of steels in order to avoid the altering the fundamental material properties;
- PVD coatings are thin, typically 0,5...4 µm; this feature, in conjunction with close tolerances, means that the component retain its form, fit and dimensions after coating, without the need of costly refinishing;
- PVD processes are environmentally benign and do not entail the use of emulsions or pollutants; the gases used are noble ones, as argon together with working gases such are hydrogen or acetylene; no toxic reactions occurs.

2. Types of coatings

2.1. Monoblock coatings

The first generation of hard PVD coatings was single metal nitrides such as TiN, CrN and ZrN. They have been commercially exploited since the middle of the 1980s in cutting applications (because of their higher hardness compared to high speed steel and cemented carbide) and for decorative purposes because of their attractive appearance: TiN has a distinctive yellow gold color, CrN looks like silver, ZrN has a white gold color.

Alloyed coatings improve hardness, wear resistance, toughness and oxidation resistance by introducing other elements such as C, Al and Cr into the TiN lattice.

In Table 1. there are shown the most used monoblock coatings and their properties and applications [3, 4]. The three basic coatings - TiN, TiCN and TiAlN - currently make up more than 70% of the world's coating market.

Table 1. Monoblock coatings

Coating	Color	Hardness H [GPa]	Friction coefficient µ	Maximum usage temperature T [°C]	Application
TiN	gold	24…28	0,4…0,5	500	General purpose coating for cutting, forming, injection, moulding, tribological applications;
CrN	metal-silver	18	0,3…0,4	700	Standard coating for non-cutting applications: deep drawing, extrusion; machining of copper; semicold forming of brass; metal die casting;
ZrN	white-gold	20	0,4	550	Machining of aluminum and titanium alloys;
TiCN	blue-grey	37	0,2…0,4	400	For interrupted cutting, milling, tapping; stamping, punching, forming

					of ferritic and austenitic steels; plastic injection moulding;
TiAlCN	burgundy-violet	33	0,3	500	Universal coating (milling, hobbing, tapping, stamping, punching);
TiAlN	violet-black	28…35	0,3…0,6	700…900	High performance coating for cutting (drilling, milling, reaming, turning); suitable for dry machining; also for moulds and dies;
AlTiN	black	38	0,7	900	For dry high speed machining; machining of hard materials >52HRC (titanium alloys, inconel);
AlCrN	blue-grey	30…32	0,3…0,6	1100	For coating on carbide and HSS end mills; gear cutting tools; CBN indexable inserts for turning; Al die casting; punching, hot forging;
TiCrN	dark-grey	21	0,5	700	Tools for demanding sheet forming;
AlTiCrN	blue-grey	34	0,55	900	Coating for universal use.

2.2. Multilayer coatings

Further improvements of the properties of hard PVD coatings were achieved by the deposition of multilayer structures. By selecting a suitable combination of materials for the multilayer structure it is possible to improve the resistance against wear, corrosion, oxidation.

Multilayer structure has higher toughness and lower hardness comparable with monoblock coatings. The "sandwich" structure absorbs the crack by sublayers, therefore a multilayer coating is usually preferred for high dynamical load, e.g. for roughing.

Table 2. presents a synthesis of most used multilayer coatings and their properties and applications [3,4].

Table 2. Multilayer coatings

Coating	**Color**	**Hardness H [GPa]**	**Friction coefficient μ**	**Maximum usage temperature T [°C]**	**Application**
TiN/Ti	gold	28	0,4	500	Sawing, tapping, hobbing, injection moulding;
TiN/TiAlN	violet-black	28...35	0,5...0,6	700...800	For interrupted cutting;
TiN/CrN	metal-silver	30	0,4	600	For molds, dies; HSS cutting tools in high alloyed materials;
TiAlN/AlCrN	blue-grey	33	0,35...0,4	>1100	For solide carbide tools used in roughing and finishing of hardened steels and difficult to machine materials (>60HRC).

2.3. Nanocomposite coatings

Nanocomposite structures represent a new class of materials, consisting in two or more phases coexisting in a very low volume, crystals having dimensions of 3...10 nm. In the case of nanocristallyne materials the number of atoms in a crystal grain is comparable, or even less, than the number of atoms that are in the grain limits. In such conditions the formation of dislocations is inhibited by the grain limits, and mechanical deformation takes place by the mechanism of slipping at the grain limits, not by dislocation movement, which is the mechanism of deformation in conventional materials. This leads to a significant increasing of hardness of nanocristallyne materials and to the development of superhard materials [2].

By depositing different kinds of materials, the components (like Ti, Cr, Al, and Si) are not mixed, and two phases are created. The nanocrystalline TiAlN or AlCrN grains become embedded in an amorphous Si_3N_4 matrix. Nanocomposite coatings are commercially available since 2003 and they have outstanding properties and applications (Table 3) [3, 4].

Table 3. Nanocomposite coatings

Coating	Color	Hardness H [GPa]	Friction coefficient µ	Maximum usage temperature T [°C]	Application
nc-AlTiN/ a-Si_3N_4	violet-blue	40…45	0,45	1100…1200	For high performance machining; decorative blue top layer;
nc-AlCrN/ a-Si_3N_4	blue-grey	40	0,35	1100	For hobs, cutting inserts, molds and dies;
nc-AlTiCrN/ a-Si_3N_4	blue-grey	42	0,4	1150	All-in-one coating for universal use;

2.4. DLC and OXI coatings

Diamond Like Coating (DLC) is a metastable form of amorphous carbon with a high percentage of cubic sp3 elements. DLC coatings improve the running-in characteristics of chip removal and forming tools and play an important role in the treatment of soft and adhesive materials which cause built-up edges. Today, DLC coatings are mainly used in component mass production to protect against wear and tear through less friction.

Oxide and oxinitride coatings serve to separate tool/component and workpiece and to achieve a low affinity between the two, especially in dry cutting processes where high temperatures are reached. They offer the following advantages:

- high resistance against adhesive wear, abrasive wear, oxidation, oxygen diffusion (the layer already is as an oxide);
- chemical and thermal isolation and chemical indifference;
- reduced friction even at temperatures of more than 1000 °C;
- fewer built-up edges and less material interdiffusion in the tribo contact zone.

3. Discussion and conclusions

The properties of PVD coatings for tooling are constantly improved in order to meet the requirements of new materials and applications. All tool manufacturers can handle cutting materials and tool geometries, but the competitiveness will be decided by the used coatings. Even if TiN and TiAlN are the most used coatings in tooling, there are now commercially available more than 80 different types of coatings with all kind of chemical composition. There are even more than 250 considering all the different stoichiometries.

Monoblock coatings are improved by adding new elements in standard TiN coating. As Figure 1 and Table 1 shows, the addition of C leads to a higher hardness and a reduced coefficient of friction in TiCN. The addition of Al is followed by a reduction of grain dimensions, internal stress and friction coefficient and an increasing in hardness, hot hardness, wear resistance and oxidation resistance in TiAlN and AlTiN coatings.

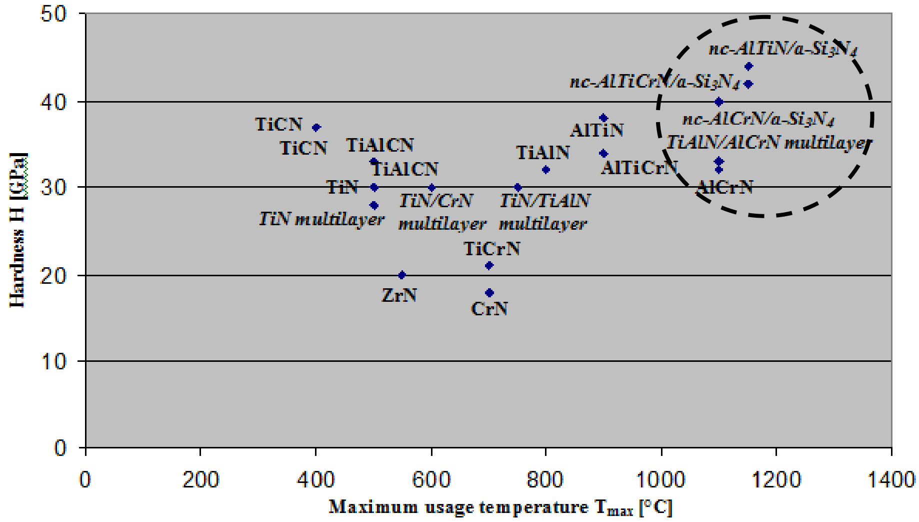

Fig. 1. Hardness and maximum temperature usage in the case of most used monoblock, multilayer and nanocomposite coatings

introduced, based on the Al-Cr-N system. For AlCrN coatings recommended applications are:

for roughing and finishing, HSS end mills for roughing and finishing, carbide and HSS hobs, forming and punching tools, aluminium pressure die-casting moulds (figure 2). Besides superior resistance against abrasive wear also hot hardness and resistance against oxidation is improved (figure 3). It was shown by a wide range of cutting tests, that the Al-Cr-N coating system has a big potential at conventional cutting parameters, but also at high performance and high speed cutting conditions.

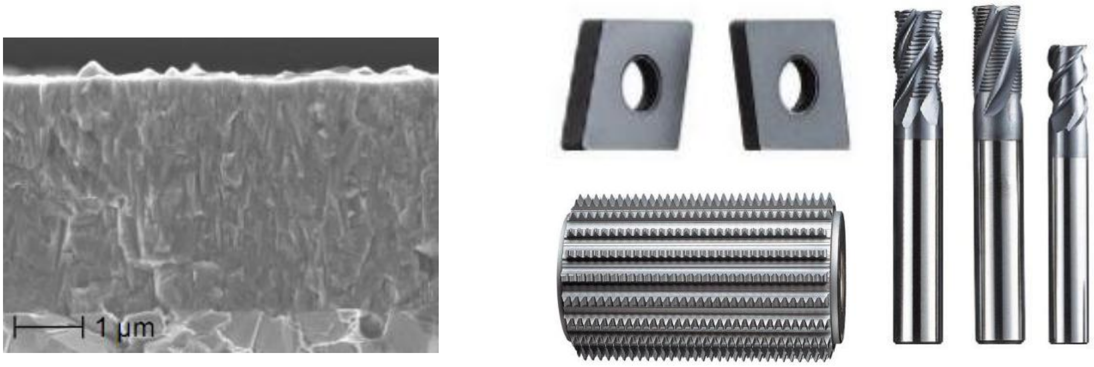

Fig. 2. Cross sectional micrography of an AlCrN coating and application of this type of advanced monoblock coating in tooling [3]

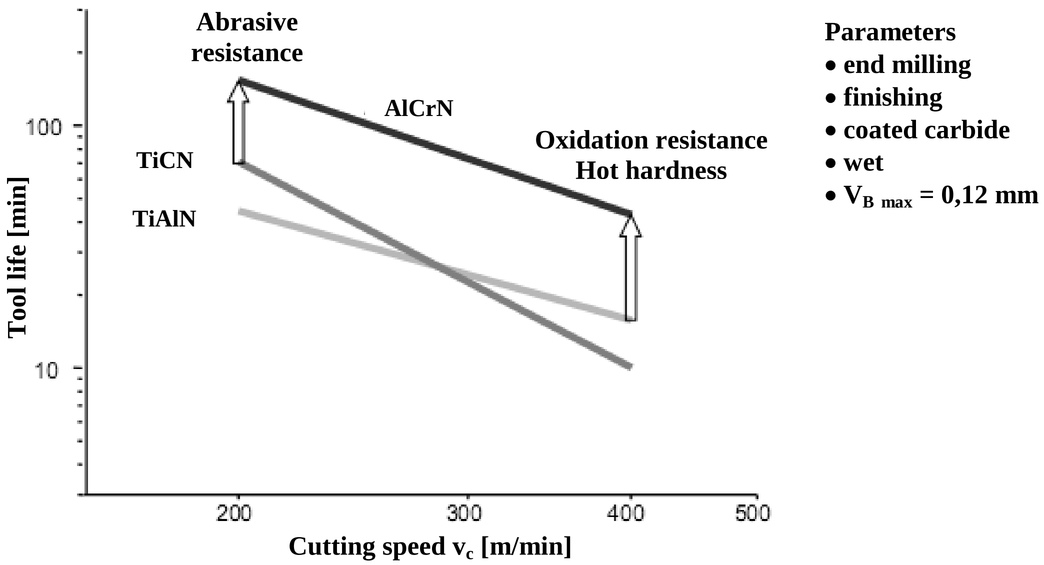

Fig. 3. The improvement of cutting performances in the case of milling carbon steel with tools with advanced AlCrN coatings [3]

Nanocomposites show an extremely high hardness and excellent thermal shock stability as well as a high resistance against abrasive wear. Due to their different structures the nanocomposites lend themselves for all kinds of applications. Figure 4 shows the improvement in tool life, measured by corner wear, in the case of drilling in heat treated steel by using nanocomposite coating on drills in comparison with monoblock TiAlN coating and multilayer TiAlN and AlTiN coatings, in the same cutting conditions (cutting speed 120 m/min, feed 0,35 mm/rot).

Regarding the technology that is used to develop above mentioned coatings it is to say that it have to offer an increased nucleation rate of crystalline grains and a decreased growing rate of crystals in order to controll the nanostructured coating. The main technologies that are involved in PVD coating for tooling are cathodic arc evaporation, ion platting and sputtering. PVD processing is carried out in high vacuum at temperatures between 150 and 500°C. The high-purity, solid coating material (metals such as titanium, chromium and aluminium) is either evaporated by heat or by bombardment with ions (sputtering). At the same time, a reactive gas (e.g. nitrogen or a gas containing carbon) is introduced; it forms a compound with the metal vapour and is deposited on the tools or components as a thin, highly adherent coating. In order to obtain a uniform coating thickness, the parts are rotated at uniform speed about several axes. The properties of the coating (such as hardness, structure, chemical and temperature resistance, adhesion) can be accurately

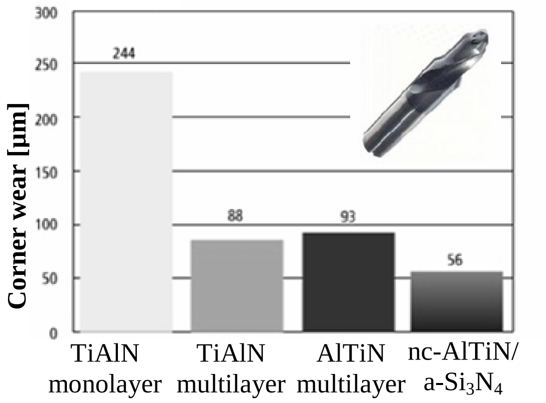

Fig. 4. Performance comparison in the case of drilling in heat treated steel with different types of coatings deposited on tool [4]

It is to conclude that, in comparison with standard coatings (TiN, TiAlN) where the hardness decreases upon annealing to 500…700°C, advanced monoblock AlCrN coatings, multilayer TiAlN/AlCrN and nc-(Al,Ti,Cr)N/a-Si_3N_4 nanocomposite coatings remain stable up to high temperatures of 1100°C (see Figure 1). This is a significant advantage of these coatings in industrial applications, such as high speed cutting and dry machining, where high temperatures are reached at the cutting edge of the tool.

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