

# PVD

PHYSICAL VAPOR DEPOSITION

# COATINGS

for IMPROVED  
GEAR PRODUCTION

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**L**ow-temperature Physical Vapor Deposition (PVD) coatings show proven functionality, both in increasing the performance of cutting tools used to machine gears as well as in imparting beneficial layers on the gear itself. In both applications, the coatings improve tribological response of the cutting tool or gear, although the wear environments are quite different. The continuing evolution of PVD coating technologies has led to tailored properties to fit specific material applications.

## Why Coat Gear-Cutting Tools?

Hobs and shaper cutters are tools used in gear cutting that have benefited from parallel developments in tool materials, coating, and gear manufacturing equipment. Advancements in each area have converged to enable higher productivity with metal-cutting parameters at elevated speeds, and even in dry conditions. Higher cutting speeds and greater machine tool rigidity obtained in modern gear manufacturing equipment also necessitate tool materials that should have higher wear resistance and high temperature stability at the cutting edge. An estimated 90 percent of all hobs today are coated.

**Not only do PVD coatings extend the life of your gear-cutting tools, they can also impart beneficial properties to the actual gears being produced.**

Tool substrate materials include conventional cast high speed steel (HSS) alloys which have been upgraded to powder metallurgy versions. At the upper end of high performance tool materials, carbide hobs with increased wear resistance have been introduced later. The most recent material development is the so-called "bridge material," designed as an HSS alternative to carbide, with properties approaching carbide wear resistance while sacrificing HSS toughness. All these hob materials are now coated with several types of PVD coatings to match the particular metal cutting conditions.

To obtain the highest productivity, with the expensive hob having complex tool geometry, it must be reconditioned and reused. The original coated hob, after a certain amount of wear on the hob teeth, can be de-coated, reground, recoated, and returned to service. Thus, the total useful tool life of the hob is extended over, say, 10 cycles of grinding and recoating. To realize the level of performance of the original coated hob, certain technical issues in regrinding and stripping of the coating must be taken into account.

## Why Coat the Gear?

There is an ever-increasing demand for improved performance of automotive transmissions and gears for other applications. Typical requirements are higher power output, reduced friction losses, reduced need for lubrication, increased lifetime, improved reliability, and reduced heat development. Most, or all, of these requirements can be satisfied by applying a thin, wear-resistant, low-friction coating to the gear surface.

The most common hard and lubricant PVD coatings in use today, and the relevant properties for these two types of applications—to be discussed below—are shown in Table 1. Note the coating microhardness values, which can be compared to those of gears being machined prior to hardening, typically at equivalent Vickers hardness of ~ 400; and after hardening treatments, the finished gear at ~ 650 Vickers hardness.

## Role of Coatings in Hobbing

The following discussion focuses on hobs, although similar considerations apply for other gear shaper cutters. The impact of TiN coating on gear cutting tools was significant from the earliest days of PVD coating commercialization in the early 1980s. The improved performance derives from the following factors.

PVD allows for a lower temperature deposition of a hard coating (typically <500° C/930° F, unlike chemical vapor deposition (CVD) technology applied to carbide materials at ~1000 C/1830° F) which does not degrade the strength of high speed steel hob substrates. The coating increases wear resistance of the cutting edges and lengthens effective tool life.

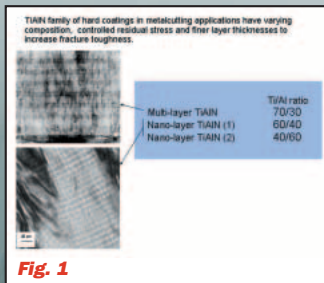
From known metal cutting theory, two sources of heat combine to potentially damage the tool cutting edge: the plastic deformation energy at the primary shear zone during chip formation, and frictional heat generated at contacting surfaces between the tool and workpiece surfaces. The tribological function of the coating is to reduce friction and the associated frictional heat component. A second coating functionality derives from its low thermal conductivity. Transmission of the total generated heat to the tool is theoretically reduced via this coating thermal barrier effect (the relative significance of the latter is still in question, however).

Metal removal by hobbing is accomplished through interrupted cutting of the workpiece, where the main mode of failure is edge wear and chipping of the hob teeth due to fatigue mechanisms against which PVD hard coatings are particularly effective. In addition to increased wear resistance, edge chipping and microfracture are thus delayed, prolonging useful tool life

## Hob Tool Material and Coating Developments

There has been a tandem evolution of hob materials and hard coatings. The first generation coatings, TiN, improved tool life two to 10 times over uncoated HSS hobs and had an immediate impact on the gear cutting industry. The application of powder metallurgy (PM) to process HSS and recent development of so-called "bridge materials"—with higher alloying content to increase the carbide content in the microstructure—brought more wear resistance and incremental speed capability. Dry hobbing became possible, and this capability is now further enhanced by newer TiAlN coatings having higher temperature capability. Cemented carbide hobs are more wear-resistant than HSS, but are also more brittle. The interrupted cut nature of hobbing leads to thermal cracks due to fluctuations of load and temperature as the cutting edge goes in and out of the cut. The ability to suppress the initiation and propagation of such cracks is more critical in brittle materials. It is known to cutting tool specialists that dry interrupted cutting prolongs tool life in carbide tools because the thermal shock component is less, compared to wet cutting. Higher speeds are actually attained at dry cutting conditions with carbide hobs. It is also clear that particular high-temperature coatings will further improve the wear resistance of carbide hobs.

A less-known, more-subtle, performance-enhancing mechanism is the presence of compressive residual stress within PVD hard coatings. This effect can be likened to shot peening in metals to increase fatigue life by improving resistance against surface crack initiation and propagation. Ion



bombardment during the PVD coating process induces compressive stress and increases the resistance against surface cracking at the (coated) cutting edge where stresses are highest during operation. The downside of too high compressive stress, however, is a tendency for coating delamination at sharp cutting edges, which gets worse with coating thickness. On hob teeth that are properly sharpened and honed, an optimal coating thickness range is four to six microns.

## Reconditioning Issues

High performance tools entail more quality requirements in their manufacture (and are therefore more expensive). The liability of harder, wear-resistant tool materials arises from inherently lower toughness, and their consequent sensitivity to brittle fracture must be properly addressed during reconditioning processes. This involves regrinding to remove worn cutting edge material and generate a new cutting edge profile, removal of prior coating layers, and recoating of the reground cutting edge.

Consider the bend rupture strengths of three classes of HSS materials and common K or P carbide grades in Table 2. With lower fracture toughness there is a higher propensity to grinding cracks so that care must be taken to use prescribed grinding wheels and parameters to minimize burning and/or thermal cracking. The bridge material is particularly susceptible to grinding-induced fine cracks at the base of hob teeth. Any pre-existing crack will contribute to early failure in the hobbing operation.

Along with resharping of a used hob, reconditioning requires removal of the coating, usually with chemical stripping solutions. These preferentially attack and remove the nitride-based hard coating, but will also react to a certain extent with the carbide constituents in the substrate microstructure. Bridge material hobs are more susceptible to such an attack compared to regular HSS compositions, as are the P grades compared to K grades of cemented carbide. Proprietary stripping solutions must therefore be implemented with good controls to inhibit unwanted reactions with the tool material substrate. Instances of lowered hob performance due to poor stripping practice have been observed, particularly with bridge material HSS. P carbide grades are generally avoided in favor of K grades due to this factor.

Nevertheless, reconditioning of HSS and carbide hobs is an accepted practice today, proving that satisfactory controls both in regrinding and stripping can be maintained.

## Modern PVD Coated Hobs, Application Examples

Two decades after the first-generation PVD TiN coating appeared in the market, a few other coating types have been introduced, as seen in Figure 1. Besides composition, the variable

coating properties are microhardness, high-temperature stability, and compressive residual stress, which dictate the effectiveness of the coating under given cutting conditions. Among the newer coatings, the most commonly applied coating for hobs is the nano-layered TiAlN coating. This coating allows for higher cutting speeds due to its better high-temperature wear resistance relative to TiN. It is also excellent for dry hobbing operations. It has moderate compressive stress, which makes it suitable for interrupted cuts, while not being overly sensitive to spalling at a very sharp cutting edge. These coatings can be stripped with the right chemical treatments to allow for regrind/recoat cycles of the hob.

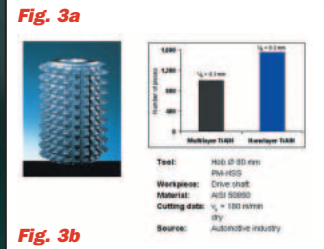
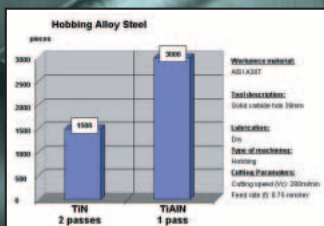
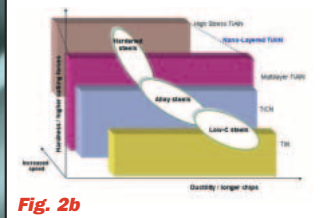
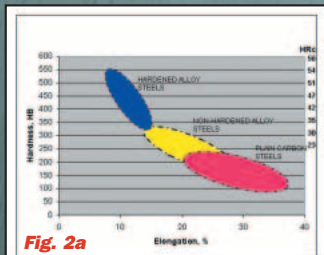
The common workpieces in hobbing are alloy steels machined prior to hardening, which are below 35 HRC in hardness, as seen in Figure 2a. During machining, these steels have chip formation characteristics for which TiN, TiCN, and TiAlN coatings are applicable, as shown in figure 2b. This application diagram is supported by a large body of empirical data, which show that TiAlN coatings are preferred at increased speeds and dry cutting conditions. Some typical comparisons of hobbing performance with different coatings are given in Figures 3a and 3b.

## Low-Friction Coatings for Gears Carbon Based PVD Coating

Gears and other precision machine and engine components subjected to high loads can also benefit greatly from being coated. Typically, a carbon-based, tungsten-carbide doped coating (WC/C) is used for such applications. This coating provides an excellent and unique combination of high wear resistance and low friction coefficient. The PVD coating is deposited at ~200° C/400° F, and coating thickness is usually in the two micron range. Different carbon-based coatings available today display a wide range of hardness values (700-4000 HV). Since a gear coating is subjected to repeated high loads, it must have very good fatigue properties. Therefore a slightly softer (1000 HV) and more compliant coating is usually the best choice for gear applications. It is important that the gear base material can withstand the coating temperature without losing hardness. If the gears are made from a heat sensitive steel, a low temperature deposition process of ~150° C/300° F can be applied.

## Low Friction Properties

The main feature of carbon-based PVD coatings is their ability to resist cold welding, material transfer, and galling when sliding against steel and other metals under dry conditions. This results in very low friction coefficient and very good wear resistance. The low friction behavior of the carbon-based coating is illustrated in Figure 4, which shows a typical friction graph from the ball-on-disk test.



In Figure 4, the friction behavior of a WC/C and a titanium nitride (TiN) coating is compared. As seen the two coating materials display completely different friction properties. For TiN the initial friction coefficient is approximately 0.25 but increases up to a steady-state value of 0.6 whereas the initial friction coefficient for WC/C is approximately 0.45, but rapidly decreases to 0.15 at steady-state. The explanation is that material from the steel ball is worn off and sticks to the TiN coating surface. For every passage of the ball in the wear track, more steel is sticking to the coating and, eventually, when steady-state is reached, it is basically a steel to steel contact rather than a TiN to steel contact. For WC/C the situation is the opposite: material is transferred from the coating to the steel ball, and at the same time the coating is polished, resulting in a very smooth and easily sheared contact which translates to very low friction coefficient.

Evidence of the material transfer is shown in Figure 5, where a black transfer layer of carbon from the WC/C is visible in the wear scar on the steel ball. Another very important conclusion from Figure 5 is that the ball wear rate is significantly lower when the steel ball is sliding against WC/C as compared to TiN, in this particular experiment approximately 10 times lower. This indicates that not only the coated, but also the uncoated, surface is protected from wear by the WC/C coating.

The time period from the start of the pin-disk experiment until the steady-state friction has been reached is normally referred to as the break-in period: a very important process that can be greatly improved by the WC/C coating. Figure 6 shows two high magnification cross-sections of a coated gear tooth. Figure 6a shows the as-deposited coating where it has not been in contact with the mating gear. Note the relatively rough gear surface, and that the coating is more or less copying the surface profile of the base material. Figure 6b shows the same gear in an area where it has been in contact with the mating gear. As seen, the gear surface is still rough, but the coating surface has been polished by the other gear, which indicates a very beneficial break-in situation.

## Gear Tribology Considerations

It is important to keep in mind that the coating is a part of a complex tribological system. To reach its full potential, several system parameters should be considered and optimized: e.g. surface roughness of the coated as well as the uncoated gear, base material hardness, and hardness of the mating gear. Recent

research suggests that a less-formulated transmission oil could be used in a gear-box with coated gears.

Although the coating is hard, it is a misconception that a gear made of hardened steel can be replaced by a coated gear made of soft steel and still loaded to the same level. Due to the very thin nature of the coating, it can not protect the component from plastic flow if the component is overloaded. The maximum hertzian shear stresses are located not at the surface, but rather at a depth that is typically much higher than the coating thickness. When the shear stress reaches the yield strength of the base material, plastic flow will start no matter how hard the thin coating is. So it's a good idea to use nitrided or case-carburized or otherwise hardened steel as base material for the gear and subsequently apply the WC/C coating.

## Application Examples

Figure 7 shows a slow moving and poorly lubricated concrete mixer planetary gear. As seen, the initial wear rate is almost the same with coated or uncoated gears. However, after the break-in, the wear rate goes down dramatically for the coated gears, whereas the wear rate stays the same without coating.

In Figure 8, the wear rate of a worm gear is shown. Again, the dramatic effect the WC/C coating has on the break-in behavior is clear. Although lower than the uncoated gear, the initial wear rate for the coated gear is relatively high. Once the break-in is completed (after about 50 hours in this test) the wear rate for the coated gear is approximately 10 times lower as compared to the uncoated gear.

## Conclusion

The use of PVD coating technology in gear production is in different phases of market maturity, with respect to applications. It has been well established in cutting tools for gears such as hobs and shaper cutters after almost two decades of development, continually raising standards of performance in gear cutting. In comparison, the use of PVD coatings on gears is in its relative infancy. The current state has already demonstrated quite successful improvements in performance and the trend might follow a parallel history with coated hobs. The most promising application areas are highly loaded transmission gears now in common use in sports cars and motorcycles, as well as in various industrial gears whose performance can be improved with better lubrication.

For more information, visit the Balzers Web site at [www.bus.balzers.com](http://www.bus.balzers.com).

## About the authors:

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Coating/Matrix	100	100%	PVD
Hardness (HV0.05)	2000	2000	1000
Coef. Friction (against steel)	0.4-0.6	0.4-0.6	0.1-0.2
Coating Thickness (microns)	4.5	4.5	1.5
Residual Stress (MPa)	-1.0	-1.5	-1.0
Operation Case Temperature (°F)	500°C	500°C	500°C
Process Application	Coating, Lining	Coating, Lining	Coating, Lining

Table 1

Hard Material	Composition, wt %	Hardness (Strength) (ksi)
SS304	Fe-18%Cr, 8%Ni, 0.025%N	700
SS304	Fe-18%Cr, 8%Ni, 0.025%N	650
SS304	Fe-18%Cr, 8%Ni, 0.025%N	420
Carbon 100-H grade	WC-10%Co	360
Carbon 100-P grade	WC-20%TiC-10%Co	270

Table 2

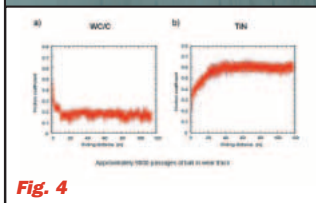


Fig. 4

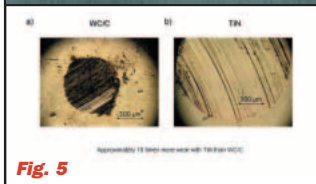


Fig. 5



Fig. 6

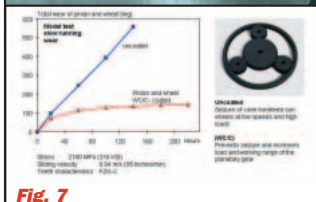


Fig. 7



Fig. 8