

Surface Coatings for SUPERIOR gears

By Jerry van der Kolk, Christian Strondl, Roel Tietema, Darrell Lewis, Ton Hurkmans, and André Hieke

Surface-hardened materials are widely used in manufacturing gears, and carburizing, and sometimes nitriding, is normally used as a hardening treatment, which results in the reduction of macro-pitting—the main failure mechanism of hardened materials. This has to do with the extremely high local stresses due to the roughness of the tooth flanks. For special applications, PVD coatings are now applied on a small scale. The coatings that are mainly applied so far are: B4C, WC-C:H (or W-DLC), and CrN. Bodycote's U.S. operations, formerly known as Diamond Black Technologies, has played a pioneering role in demonstrating the capabilities of PVD coatings, especially B4C.

In collaboration with Hauzer, Bodycote's European operations has broad industrial experience with WC-C:H coatings and CrN coatings. The effects of PVD coatings on gears will be discussed in this article, as well as some examples of PVD coatings.

Failure Mechanisms

Pitting, or rolling contact fatigue is one of the primary failure modes. Fatigue cracks form in the contact surface and are then filled with small-particle debris. This failure mode is linked with contact pressure: If the contact pressure is kept below a threshold value, this type of failure can be avoided. This can be achieved by proper dimensioning of the gears; the contact pressure should be kept relatively low by using wider gears, for example.

Root bending failure, resulting in complete removal of the tooth, is another failure mode, which is mainly caused by fatigue cracking of the tooth-root. It is also linked mainly to gear design, including the base material.

Micro-pitting and scuffing can lead to another failure mechanism. Scuffing leads to adhesive wear, resulting in tooth deformation and eventually large chipping. Micro-pitting results in the formation of fatigue cracks, giving rise to macro-pitting. Both micro-pitting and scuffing have mainly to do with the surface structure. Parameters like surface roughness, hardness of the surface and sub-surface of the two counter materials, friction coefficient, and hence lubrication film thickness all play a role. The local stresses, initiated by the surface roughness, quite often are considerably larger than the Hertzian stresses, even when the gears are grounded (figure one).

Especially with the carburized gears that are currently in use, the surface effects play a dominant role.

Effects of PVD Coatings

Physical Vapor Deposited (PVD) coatings can be used mainly to influence the near-surface properties, such as:

- surface hardness
- surface roughness
- friction coefficient
- oil wettability

Surface hardness: The hardness of PVD coatings can be matched, for example, from 1,100 Vickers to 4,000 Vickers. A high hardness reduces the abrasive wear of the coated surface. Typically the abrasive wear scales inversely with surface hardness, so a wear reduction of the coated part is expected when they are PVD coated.

Surface roughness: PVD coatings do not have a levelling or smoothing effect, as do galvanic coatings. Generally PVD magnetron coatings increase the "peak to peak toughness" Rz with 0.1- 0.3 µm per µm film thickness. It's even worse for PVD-ARC coatings when pure metal droplets are introduced into

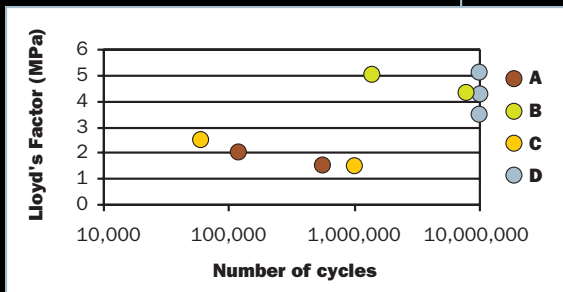


Figure 1 — Number of cycles under various loads for:

- A) ground gears
- B) ground gears with WC-C:H coating
- C) micro shot-peened gears
- D) micro shot-peened and WC-C:H coated gears

(taken from Murakawa et al., 2)

the coating, resulting in a peak to peak roughness Rz increase of typically 1 µm per µm film thickness. Still, coatings can be used to reduce the effects of surface roughness. A surface with a high hardness will influence the wear behavior of the uncoated counterpart. Normally one

would expect an increased wear of the uncoated counterpart. When properly done, however, the coating can have a polishing effect, initially resulting in a high wear of the counterpart, followed by low wear due to the well-polished surface.

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Friction coefficient: The friction coefficient of PVD coatings can range from 0.1 to 0.8. Typical values for W-DLC (W containing diamond-like carbon, or WC-C:H) are between 0.1 and 0.2 .

A reduced friction coefficient will also result in lower micro-pitting. This is especially important when there is a compromise of lubrication conditions. It has been demonstrated by Murakawa et al. (2) that when a loss-of-lubrication situation occurs after a period of normal lubrication, surface improvements may extend the time period for running before catastrophic failure occurs. The two surface improvement methods they have investigated are:

Micro Shot-Peening (MSP), which involves a mixture of metallic and ceramic powder with particle size 40-100 µm being shot-peened onto a grounded gear surface, resulting in a gear surface without grinding traces. The MSP treatment alone hardly increased the lifetime under dry conditions, and;

PVD Coating: WC-C:H coatings were used to coat both untreated gears and MSP treated gears. The PVD coating prolonged the running time under loss-of-lubricant conditions by a factor of two to three, relative to the uncoated gear. Combination of an MSP and PVD coating prolonged the running time considerably.

Figure one shows the results obtained by Murakawa et al. The Lloyds factor K (in MPa) is a measure of the contact pressure on the gear surface.

$$K = 10T/2R^2 b(i+1)/i, \text{ with}$$

T = transferred torque (N.m)

R = radius of reference circle for the drive side of the gear (mm)

b = gear face width

i = gear ratio

Oil wettability: While additives are normally mixed with

the gear lubricant, there is an environmentally driven tendency to reduce these additives. It has been demonstrated by Weck et al. (3-5) that the role of additives can partly be replaced by WC-C:H coatings, or W-DLC. Biodegradable synthetic ester oils, in combination with WC-C:H PVD coated gears, have a similar or improved performance as compared to regular oil with additives and uncoated gears.

Examples of PVD coatings

PVD coatings that are currently applied in the industry for gear coating and relevant properties are presented in the following table:

Table 1 — Number of cycles under various loads for:

	B4C	WC-C:H	CrN
Hardness (GPa)	30	10-15	20-24
Dry friction coefficient	0.2-0.3	0.1-0.2	0.4-0.6
E-modulus (GPa)	250	150	200
Internal stress (GPa/µm)	1-2	1	0-1
Main effects	Polishing of counterpart Friction reduction	Polishing, Material transfer Friction reduction Wettability	Polishing of counterpart
Practical thickness	2 µm	2-4 µm	1-2 µm
Deposition method	Magnetron sputtering	Magnetron sputtering with high plasma density	Cathodic ARC evaporation
Remarks			Post polishing needed

Typical production units are shown in the figure 2 on the next page.

A cross-section of the unit is given in figure three. The step to deposit hydrogenated DLC is important, for during this step carbon is coming mainly from a carbon-containing gas like acetylene.

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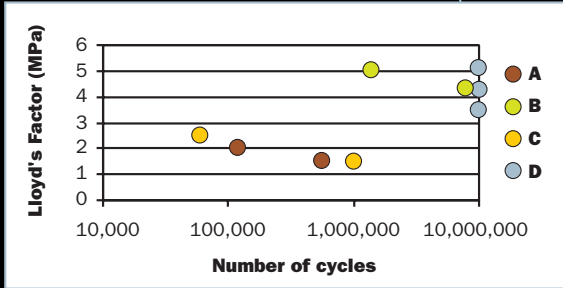
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To create the right coating properties, it is important to have a proper plasma density. In the Hauzer units, this is generally achieved by having closed magnetic field lines from one cathode to the next. Along these field lines electrons spiralize and reflect close to the cathodes. Consequently, the plasma density is increased. High plasma densities are necessary for the formation of sufficient carbon atoms and radicals.

The coating can be optimized for different applications. Typically, a W-DLC coating can be optimized for fatigue properties or for abrasive wear properties. Strondl et al. (6) have described that a standard W-DLC process can be modified by simply changing the multilayer structure. At low rotation speeds, a pronounced multi-layer structure is formed, enhancing the fatigue properties. At high rotation speed, a uniform structure is formed, with nano-sized WC crystallites in an amorphous DLC matrix that is superior in abrasive wear resistance.

This is illustrated in the following figures, where properties such as hardness are shown for three rotation speeds.

Figure 2 — HTC-1500 and HTC-1200 units for production of W-DLC or CrN



Future Outlook for Coating of Gears

So far, the coating of gears has only been applied in cases where the additional cost of PVD coating was less than having to redesign the gear box, or where the extra performance with PVD coatings under loss-of-lubrication conditions is valuable. The application so far has been limited to a small percentage of gear boxes. Cost effectiveness is critical for a wider application of this solution. Here, PVD as a

developing technology is still improving. There are a number of reasons why the use of PVD coatings may become more widespread in the gear industry:

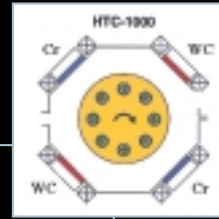
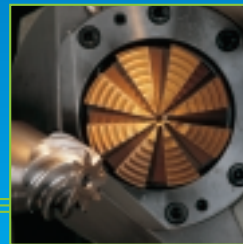


Figure 3 — Cross-section of HTC-1200 unit with coupled unbalanced magnetrons

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Figure 4 — Hardness and E-modulus of hydrogenated W-DLC for three rotation speeds

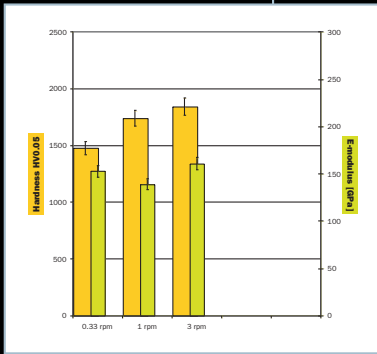


Figure 5 — Abrasive wear of hydrogenated W-DLC for three rotation speeds

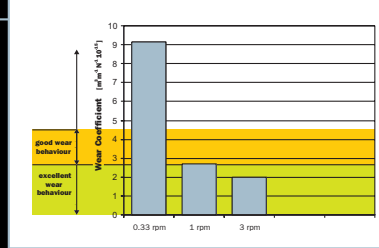
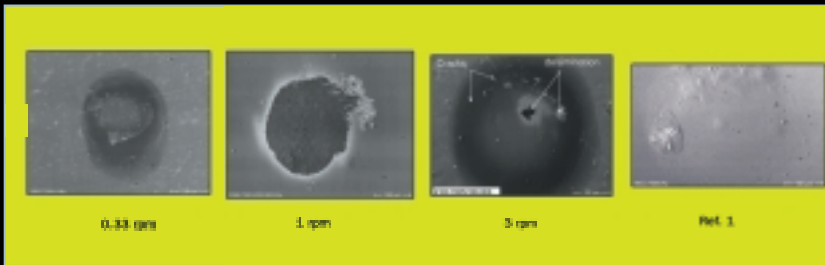
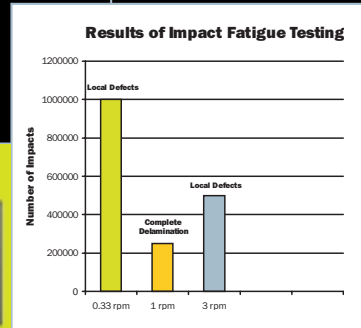


Figure 6 — Fatigue resistance of hydrogenated W-DLC for three rotation speeds



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The average cost of PVD in modern large-scale production units is considerably less now than in recent years. Historically, PVD prices have been reduced by a factor of two every five years.

The industry is focusing on reducing the number of different designs for all major components. Major industries are working on a limited number of platforms, as well as a limited number of gear boxes. This means that the torque in a given size of gear box may reach the limits for uncoated gears.

Longterm, environmental regulations will force the industry to use less-harmfull products, which would force manufacturers to address wetting behavior not through additives, but through the surface structure for the heaviest-loaded gears.

For more information on Hauzer equipment, visit their Web site at [www.hauzertechnocoating.com]. To learn more about job-coating by Bodycote, access their Web site at [www.bodycote.com].

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Jerry van der Kolk, who has a Ph.D. in physics from Delft University, the Netherlands, is managing director of Hauzer and has more than 20 years of experience in thin films.

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Ton Hurkmans has a Ph.D. in materials science from Sheffield Hallam University, in England, and **André Hieke**, who has a master of science degree from Braunschweig University, in Germany, are responsible for the market and coating development of low-friction coatings for Bodycote Europe.

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