Myths and Miracles of Gear Coatings

William R. Stott

Three years ago, coated gears seemed to be the perfect solution for the Micro Marine Corporation. The early designs for the gear drive of their MicroCAT human-powered boat used a combination of thin-film dry gear coatings with lubrication and wear-resistance properties. These coatings simplified their design, provided corrosion resistance, made the gear drive environmentally safe and eliminated the need for gear drive lubrication and maintenance. It was a success story in the making.

However, the MicroCAT of today doesn't use coated gears. Instead, the gear drive employs stainless steel gears and a semifluid grease lubricant. "It's not that the coating didn't work," says Micro Marine president Bill Hulbig. The company had found that relatively small amounts of water seeping past the seals of the underwater drive were causing corrosion in the bearings. By using stainless steel gears and filling the gear case with grease, they were able to avoid the problem.

Micro Marine's story isn't exactly one of gear coatings failure, but it isn't exactly one of resounding success either.

An Industry of Contradictions

The preponderance of evidence suggests that gear coatings work. But even when they do work, as in the case of Micro Marine, companies don't always continue to use them. Also, coatings have been used for decades on gears in a wide variety of applications, yet there are no standards or specifications written specifically for gear coatings. Nearly every coatings manufacturer or vendor claims to have gear customers, yet few manufacturers of geared products are willing to talk about their use of coatings. The automotive industry has spent huge amounts of time, money and effort researching and developing coatings for their transmissions, and they seem to work, yet few transmissions have ever used coatings in production. The subject of coatings for gears seems to be filled with contradictions, and the lack of available information complicates the issue for the average gear designer.

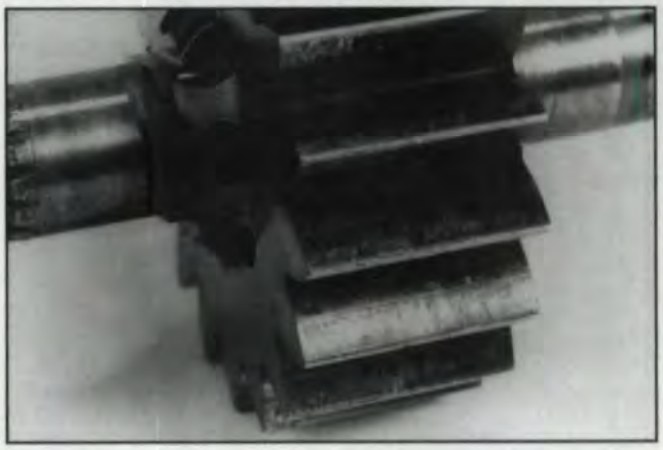
If They Work, Why Not Use Them?

Gear coatings have been available for decades. They offer lubricity, hardness, corrosion protection or some combination of these properties (see the accompanying article, "Types of Coatings for Gears"). Coated gears have been used and proven in a variety of niche and specialty applications, and they have been written into military, federal and contractor standards for many different types of products as well.

However, there seems to be an industry-wide prejudice against the use of coatings. To the average gear designer or manufacturer, most examples of gear coatings are academic. They may be used in aerospace applications, says the voice of conventional wisdom, but not mine.

"Coatings are typically viewed as a failure mode waiting to happen," says Joseph Rogers, product and business development manager for Diamonex Performance Products, a maker of diamond-like carbon coatings. "Few gear manufacturers want this

Gears coated with Hi-T-Lube® by General Magnaplate Corp.



Spur gear treated with Hi-T-Lube® by General Magnaplate Corp.

as their first choice for improving gears."

If coatings are improperly applied, or if the wrong coating is selected for a given application, the gearbox will definitely have problems, says Richard Hickey, president of Microfin, providers of thin-film coatings and platings. "With gears, if the coating starts to flake, pieces will break off, and you'll tear the living bejeezus out of the gears," he says.

In addition to this reluctance among designers to introduce another possible failure mode, there is also a general lack of information available to gear designers about coatings. In fact, in spite of the long history of the use of coatings for gear applications, the American Gear Manufacturers Association has no written standards or publications that address the issue, and no committee is currently considering the topic, according to AGMA technical vice president William A. Bradley III.

This lack of information may be the biggest reason why more gears aren't coated. "If there isn't information available, what do you do?" says Hickey. "There isn't a resource that's readily available for designers regarding gear coatings."

Successful coatings stories are hard to come by. One big reason is that most manufacturers are unwilling to talk about the coatings they use because they don't want their competitors to know how they achieve their performance levels. One good example is Richard Mellentine, the gear transmission manager for a major North Carolina auto racing team, who has been using a Balzers tungsten carbide coating on racing gears. "It's such a hard coating that it extends the life of the gear greatly," Mellentine says. "It keeps polishing the gear, and there's no wear." Mellentine asked that his team name not be mentioned, because he doesn't want other racing teams to know about this advantage.

Other companies are unwilling to let their competitors and customers know that they're using coatings at all, because it might suggest that the product has been having pitting or wear problems, says Balzers marketing director Frederick Teeters.

Another big issue is the cost consideration. Many times, the improvements gained by coatings aren't

The Diamond Black process is able to handle large volumes of automotive gears.

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NOTICE

The article "Specifying Custom Gears" in the May/June 1999 issue of *Gear Technology* contained a number of errors. We apologize to the co-author, Mr. C. Kent Reece, and our readers for the inconvenience.

We recommend that you avoid using the formulas in the article, because of accidental errors including the inadvertent switching of some metric and English symbols. Please consult a qualified gear engineer and/or the appropriate standards for any questions regarding gear design or specification.

Gear Technology is committed to providing you with the best possible technical information on gears, and we're increasing our efforts to have technical material reviewed by qualified personnel. This includes our panel of technical editors, who didn't have the opportunity to review "Specifying Custom Gears" before it was published. You can count on finding in our pages the highest possible quality and credibility in technical articles.

Michael Goldstein, Publisher & Editor-in-Chief
William R. Stott, Managing Editor
Charles M. Cooper, Senior Editor

worth the additional expense to a manufacturer. Sometimes, improvements in a gear can be achieved in other ways, such as by grinding or peening, which may be easier or cheaper to implement.

Why So Much Interest?

Even though it's hard to get solid information about coatings, there remains a tremendous interest among gear manufacturers.

Robert Zajac is supervisor of the development lab at Peerless Winsmith, one of the leading worm gear drive manufacturers. "If somebody came in and presented a coating that looked interesting, we wouldn't hesitate to look at it," Zajac says.

In fact, Peerless Winsmith has experimented with coatings on their steel worms on at least a couple of occasions. They tried a titanium nitride coating but never had any success with it. "For some reason, it turned out to be abrasive," Zajac says. They've also tried a vendor-supplied coating. "It didn't hurt us, but it didn't help us either," Zajac says.

Despite the lack of success so far, Zajac says the company would be interested in trying coatings again. "We'd like to find something that works," he says. "Because worm gears tend to run hot, we're always trying to reduce friction and increase efficiency."

The biggest reason for gear manufacturers' interest may be the ability of coatings to increase the power density of existing gear drives. Some of these coatings are twice as hard as steel, and most offer a lower coefficient of friction. Manufacturers of geared products are always faced with demands for more power in less space. Continually producing new models to meet higher torque demands and longer life requirements can be expensive. For an operation on the scale of a major auto manufacturer, retooling for a completely redesigned transmission might cost hundreds of millions of dollars, according to some estimates.

Gary Doll is a former staff scientist at the physics department of the General Motors Research Center. "The holy grail out there is coming up with some sort of coating, or a systematic design of coating and product, to effectively improve power density," says Doll.

Chasing the Holy Grail

Although Doll is now a senior research specialist with the material science department of Timken Research, and although he now spends most of his time working with the power density of bearings, he may know as much as anyone about the development and use of hard coatings for automotive gear applications.

In 1993, Doll and his associates at GM authored a paper on the use of boron carbide (B_4C) coatings on sun gears and pinions (Ref. 1). In the paper, they stated that the coatings "greatly reduce wear and increase the life of the transmission several times."

Since that initial research, both General Motors and Ford Motor Co. have had production models of transmissions coated with boron carbide by Diamond Black Technologies, Inc. of Conover, NC. According to company president Gene Robinson, Diamond Black has coated more than a million transmission gears for the major auto makers, and

TYPES OF COATINGS FOR GEARS

Coatings for gears can be either very inexpensive or cost-prohibitive. Their uses range from cosmetic to doubling the life of a gear set. They include technologies that are just emerging as well as some that are more than 50 years old. Some are very precise, while others are useful for only the lowest-precision, lightest-load gearing. The following breakdown should help sort out some of the options available for steel gears.

Black Oxide. A conversion coating formed by a chemical reaction with the iron in ferrous alloys to form magnetite (Fe_3O_4). The finish is usually sealed with rust preventatives or oil post-treatment and may require follow-up maintenance to keep the surface oiled. Black oxiding alone does little more than enhance the aesthetic appeal of the part, and often requires combination with other processes or coatings to provide any real corrosion protection, says Richard Hickey, president of Microfin Corporation.

Boron Carbide (B_4C). A very hard, amorphous ceramic material applied using the PVD process of magnetron sputtering. The Diamond Black version has been used in production models of automotive transmissions by Ford and General Motors. It continues to be an area of intense research and development for gears. See main article for more information.

Conversion Coatings. See Black Oxide, Electroless Nickel and Phosphate Coating.

Diamondlike Carbon (DLC). An amorphous form of carbon with diamond-like bonds. This material has much promise as a gear coating and has been the subject of intense research among automotive and other manufacturers. Multi-Arc, Inc. and Diamonex are two suppliers working with gear manufactures. Applied using CVD or PVD processes. See main article for more information.

Electroless Nickel. A chemical process that takes place in an aqueous solution without electric current. Plating rate and thickness are uniform, so application to gear teeth will not change dimensions. Offers corrosion protection, wear resistance, lubricity and appearance benefits. Many formulations exist for different wear or lubricity requirements. Special additives, such as diamond particles, PTFE or light-emitting substances, can provide additional benefits, says Michael Feldstein, president of Surface Technology, Inc. of Trenton, NJ. See the article "Composite Electroless Nickel Coatings for the Gear Industry" in the January/February 1997 issue of *Gear Technology* for more information.

Electroplating. A metallic coating is applied by electrodeposition. Most plating materials and processes are not suitable for most gear teeth, as they generally alter the dimensions of the gears. Because of this, electroplating is typically reserved to coating the gear blank before teeth are cut. Chrome and nickel plating are common for corrosion protection. Some aerospace applications use gold, silver, lead or other heavy metal platings to prevent galling.

Molybdenum Disulfide. This substance has become the workhorse of dry-film lubrication for gears. It combines a low coefficient of friction with high load carrying capacity, and it works well in a vacuum. For lower precision gears, it can be used in powder form or applied using techniques such as spraying or dipping, followed by curing in an oven. It can also be applied by PVD sputtering, which allows much tighter tolerances and thinner films.

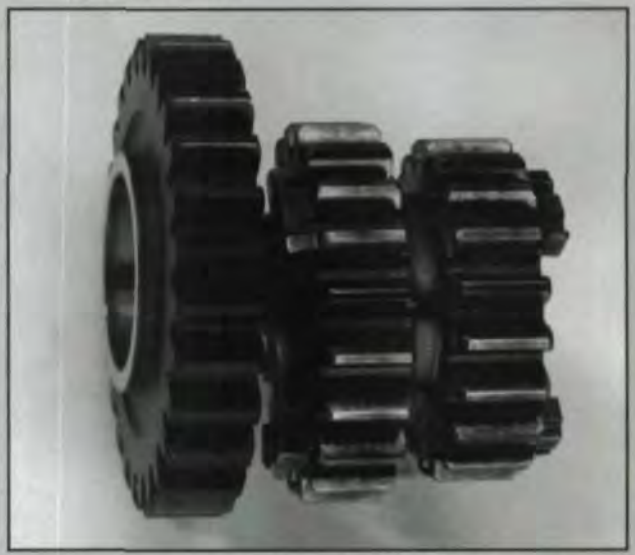
Phosphate Coating. Similar to black oxiding, phosphate coating is essentially the controlled corrosion of a part. A mildly acidic solution removes metal from the part and produces tiny reservoirs that improve the adhesion of dry-film lubricants or oil.

Polymer Coatings. One of the best examples of polymer coatings is polytetrafluoroethylene, or PTFE, which is marketed under a variety of trade names, the most familiar being DuPont's Teflon®. PTFE provides tremendous lubricity and chemical resistance. Although DuPont doesn't recommend Teflon® for use on gears because of its low wear resistance, some manufacturers have experimented with it. PTFE and other polymers are often used as additives in other coatings.

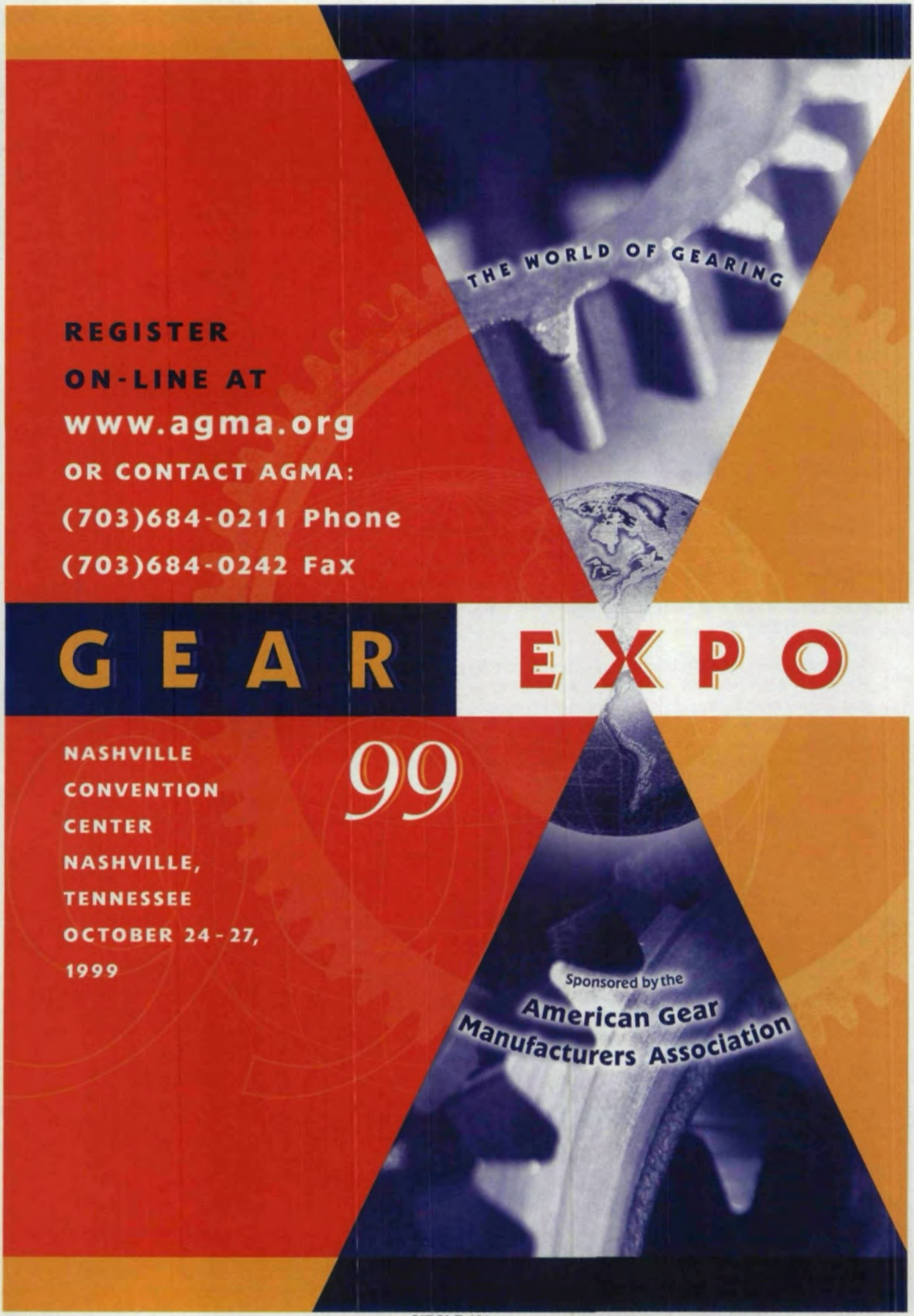
Proprietary Coatings. Many companies specializing in coatings offer special formulations of products to combine lubrication, wear, and other characteristics depending on the application. Microfin's Microlube® and Lubralloy® coatings and General Magnaplate's Hi-T-Lube® are some examples.

Thin-Film Lubricants. Many formulas exist, including a variety of proprietary coatings and application methods. Most are applied by spraying, dipping or painting, followed by curing in an oven. Depending on the material and the process, curing temperatures may not be suitable for all substrates. See also Molybdenum Disulfide.

Tungsten Carbide (WC/C). One of the most promising areas of research for automotive transmission manufacturers. This PVD sputtered coating has been used successfully on a number of production gear applications under the Balzers Balinit® C trade name.



Gears from a racing motorcycle removed after an oil leak occurred during a race. The WC/C coated gear (on the left) shows very little wear, while the uncoated gears show severe adhesive wear. Courtesy of Balzers.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they currently coat gears for the GM-manufactured transmissions of the Volvo S80 Turbo and the BMW Diesel Turbo.

The Diamond Black coating is essentially the same material written about by Doll and associates in 1993. It is boron carbide applied through the physical vapor deposition (PVD) process known as "magnetron sputtering," in which single atoms are liberated from a bulk target of boron carbide and impinged on a substrate to form a coating with a thickness of about 2–3 microns. The coating has a theoretical hardness of 95 Rc with added properties of lubricity and toughness, says Robinson. Perhaps most importantly, the magnetron sputtering process takes place at less than 250° F, which means that the substrate material is not metallurgically altered by the application of the coating.

Even though Diamond Black's boron carbide is the best example of a coating that has been successfully used on an automotive production basis, several other materials have been successfully tested.

One promising area of research looks into the use of diamond-like carbon coatings (DLCs), which are applied using low-temperature chemical vapor or ion beam (PVD) deposition. The coating is a hard (Vickers 1000-3000), low-friction coating of an amorphous form of carbon with diamond bonds. Like Diamond Black's process, DLC deposition temperatures are low enough not to affect most gear steels.

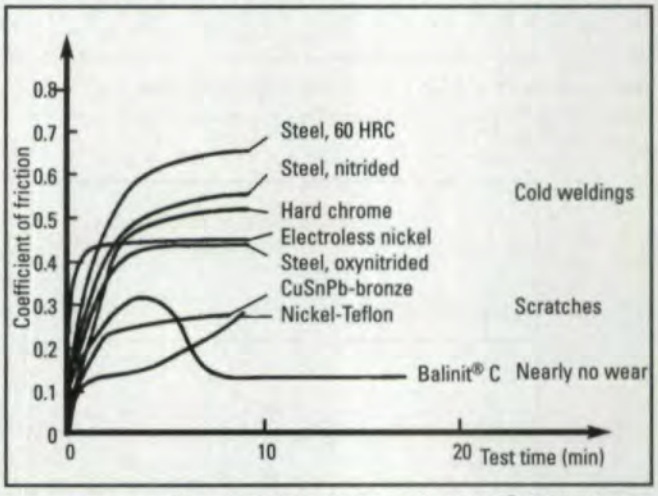
Diamonex Performance Products is one of the companies working in this area, and they are involved in tests with a variety of automotive components, including gears, says DLC product manager Joseph Rogers. Diamonex recently signed an agreement with a major automotive supplier of fuel injection components to supply vacuum DLC coatings on a production basis, Rogers says. Although no one has yet committed to using DLC coatings on transmission gears, proving the technology on other parts may be an important first step, Rogers says.

Multi-Arc, Inc. also has been working with automotive manufacturers to develop amorphous DLC coatings for transmission gears, says marketing director Mark Pellman. The coating definitely works, Pellman says, but that doesn't necessarily make it the right solution. "Even though this technique solves the problem, there are cheaper ways to increase power density, including peening," Pellman says. However, he doesn't rule out future possibilities, as the cost of producing these coatings will drop as the technology improves. In fact, for some applications, the process is already being used by Multi-Arc on a production basis. One example is a chemical pump application, which uses precision gears coated with DLC, Pellman says.

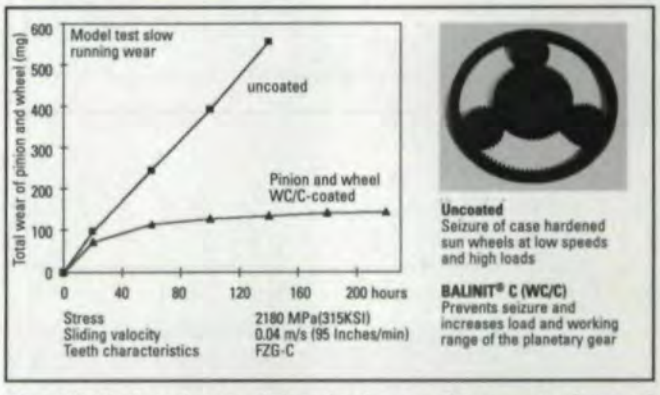
The other big contender for automotive transmission gear coating is an amorphous tungsten carbide (WC/C) such as the Balinit® C coating provided by Balzers. This coating is applied using a PVD ion bombardment technique similar to that used to apply the DLC and Diamond Black coatings.

Balzers has used its Balinit C coating on spur gears for

Examples of gears coated with Hi-T-Lube® by General Magnaplate Corp.



Dry running properties of materials, including the Balinit® C (WC/C) coating from Balzers.



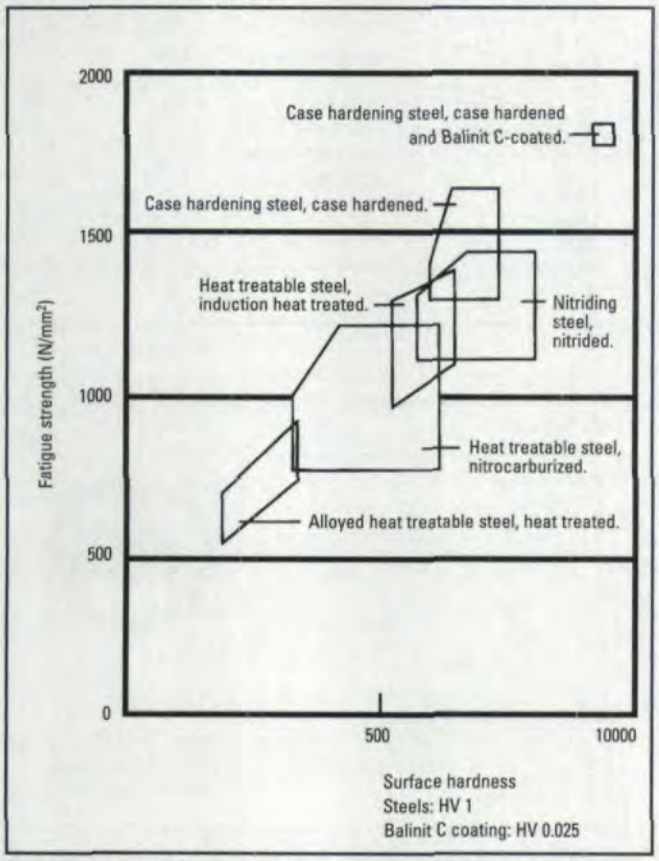
The Balinit® C coating from Balzers has been used to prevent seizure and increase the load and working range of the planetary gear set used in a concrete mixer.

racing motorcycles, highly loaded planetary gears for concrete mixers and precision worm gears, among other applications, and they are aggressively pursuing all gear markets, including the automotive market, says marketing director Frederick Teeters.

The general consensus is that all of these coatings can provide significant benefits for automotive transmission gears. "These coatings work," says Doll. "In some cases, they work rather spectacularly."

But this doesn't mean that we'll see coated gears on every auto transmission any time soon. "It's probably never going to be high volume," Doll says. "I don't think the industry is ready to put a coating on every gear. I don't see it happening."

Gears coated with Hi-T-Lube® by General Magnaplate Corp.



Relative pitting fatigue strength and hardness of steels with different heat treatments. Note the Balinit® C (WC/C) coating in the upper right corner.

Pushing the Envelope

Dr. Dong Zhu, principal engineer and program manager with Eaton Corporation, has been investigating the possibilities of using coatings on medium- and heavy-duty truck transmissions for the past five years. The task is more daunting than that of the consumer automobile manufacturers, because the typical truck transmission faces much higher life and load requirements, Zhu says.

"We've tested virtually every available coating from all manufacturers on both test rigs and actual transmissions," Zhu says. "I have to say that so far our success is quite limited."

According to Zhu, there are still some technical problems to be resolved. "As you know, gears are very similar to hobs in geometry. However, the materials are completely different. When we deposit a PVD coating on the heat treated, very rough and dirty surface of a cheap, carbon steel gear, we have a lot more problems than they have when coating hobs."

Zhu says that Eaton is working in collaboration with the coatings manufacturers and major university research labs on issues such as part cleaning, coating adhesion, coating uniformity and quality consistency. They'll have to overcome these problems before we see any real production examples of coated gears in truck transmissions.

However, Zhu is optimistic that these coatings will be used in the near future. "I think we understand the problems better than most," Zhu says. He estimates that another three years will be necessary before the technology is perfected.

Another possible heavy-duty application for coatings is in off-road equipment. Larry Seitzman is team leader for engineered surfaces at the advanced materials technology division of Caterpillar, Inc., where they are exploring the same kinds of carbon-based PVD coatings technologies being examined at Eaton, Ford, GM and elsewhere.

"The experience of gears, not just at Caterpillar, but in a lot of industries, is that designers are pushing steels right to their limits," says Seitzman. "Coatings are one of the tools that can push you beyond those limits."

Although trade secrecy prevents Seitzman from discussing how gear coatings have been used in production applications, he's extremely postitive about the potential for coated gears, especially considering the rapidly advancing technology.

Seitzman and his colleagues at Caterpillar are working to identify the necessary tools and requirements to make the thin-film process economically viable. "The biggest obstacle is having a manufacturable, reliable process for putting the coatings on the parts," he says.

What About the Rest of Us?

The coatings being examined by the likes of General Motors, Ford, Eaton and Caterpillar might have huge implications for the rest of the gear industry, but for the most part, these technologies are still in the proving stage. They represent the cutting edge of coatings technology, and they may provide the gains in power density everyone is looking for, but only if the cost of the process becomes low enough for mainstream use.

Meanwhile, there are many coatings of a less high-tech nature that are applied to gears in diverse applications every day. Joseph Bregi Jr., president of Doppler Gear Co., Minneapolis, MN, has estimated that somewhere between 5% and 10% of the gears his firm manufactures receive some kind of finish coating or plating. Many of his gears are used in lawn and garden equipment, and the coatings, are often decorative, Bregi says.

"The experience of gears, not just at Caterpillar, but in a lot of industries, is that designers are pushing steels right to their limits. Coatings are one of the tools that can push you beyond those limits."
–Larry Seitzman of Caterpillar, Inc.

Doppler Gear is also the manufacture of splined power take-off shafts that receive a yellow zinc coating for corrosion protection, Bregi says, as well as gears that are coated with a dry-film lubricant.

Despite the fact that gear coatings are common on products manufactured at Doppler Gear, Bregi will be the first to admit that he knows little about the gear coatings themselves. "If a customer specifies it on the blueprint, we just send it out to a local plater," Bregi says.

Coatings and Gear Design

Because the subject of coatings is little understood by most gear designers and manufacturers, and because gears are little understood by most platers and coaters, the use of coatings on gears has often been under less than ideal conditions. All too often, they are brought in after a product has been designed to certain specifications. They're used to fix problems, or they're used to increase life or power density on an existing gearbox. But this is probably not the best approach, say coating and gear industry experts.

The possibility of using a gear coating should be explored in the earliest design phase, says Microfin president Richard Hickey. "It's never too early. Once the designer knows what he wants to accomplish with the gear, that's the time to investigate. Maybe he can use a less expensive material and coat it."

Gary Doll of Timken agrees that designing gears for coatings might be the best approach, but there aren't enough people who understand both gears and coatings

for this to be practical. "Nobody really understands how to effectively design in a coating," Doll says. The standards that exist for coatings are material standards that don't necessarily consider the special requirements of gears. "With gears, you have adhesive wear, fatigue wear, corrosive wear, and a whole gamut of things to deal with," Doll says.

The combination of special knowledge regarding gears and coatings is crucial in the design phase, which means that gear specialists and coating specialists have to work together, says Hickey. Microfin corporation provided coatings for a manufacturer of computer component transfer equipment. "They were trying to use very soft gears, with no heat treating, and they had higher load requirements than we realized. Ultimately, the loads crushed the gears," Hickey says.

Ready or Not, Here they Come

Developing the industry standardization and familiarity with the specifications and capabilities of coatings may be just a matter of time. Although some coatings have been around for a long time, the ones that seem to have the most potential benefit for the most applications are just now being developed.

"The thin-film industry is really in its infancy," says Caterpillar's Seitzman. Both in the U.S. and Europe, there are standardization efforts underway, although none of them are specific to gears, Seitzman says.

However, nearly every coatings material and process supplier sees the gear industry as a ripe fruit ready for plucking. "There's not a major gear manufacturer who hasn't approached us to explore coating their gears," says Frederick Teeters of Balzers. "The gear coating market someday may be bigger than the cutting tool market."

It's obvious from our exploration of various industries that manufacturers share that point of view. "In the next 10 years, almost all new designs that are pushing the limits of gears are going to use coatings," Seitzman says. This optimism extends not just to heavy equipment, but across all disciplines involving gears. "And I strongly suspect it will be sooner."

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