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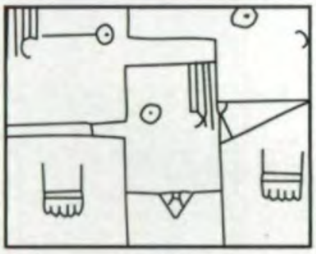

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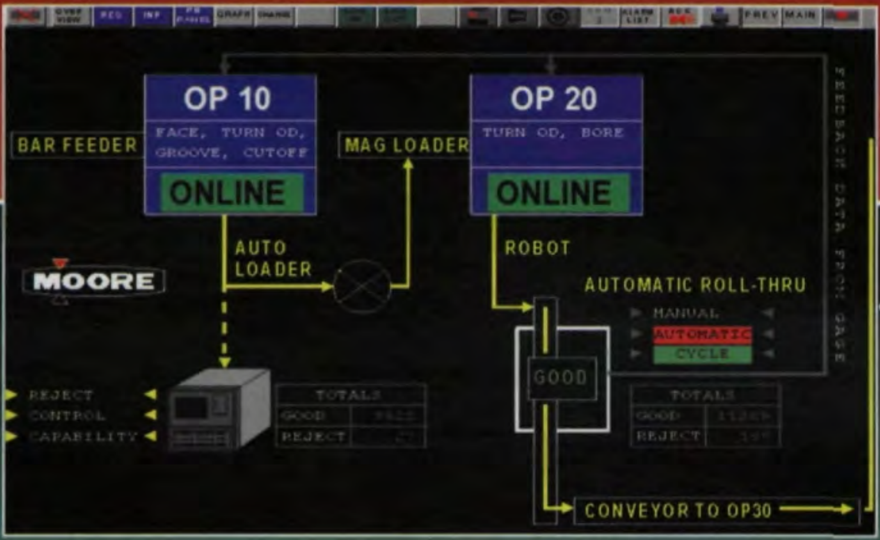

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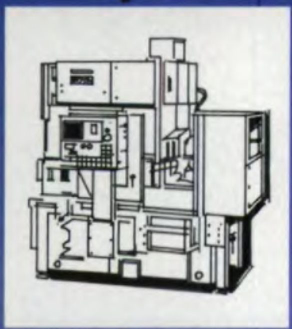

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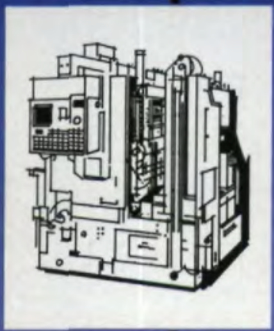

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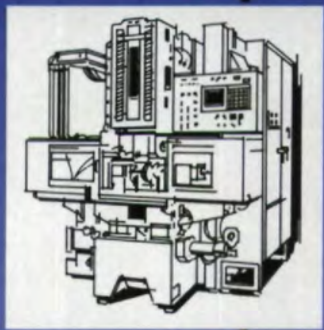

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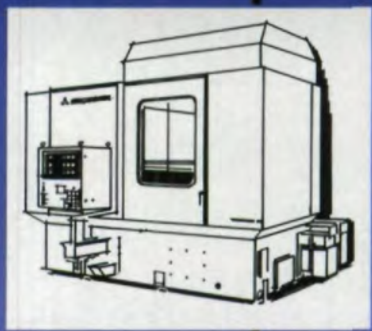

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We've been registered with all the major search engines, and in most cases, the GIHP is one of the first sites that appears in a search list. We're appearing in some more informal listings as well. We've made the "Editors' Choice" page of useful engineering sites at Cahners Publishing's Web site. (See *www.manufacturing.net/resources /websites*.) This is good news for us and even better news for the companies who have put up pages on our site.

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Now a few words for our many readers who don't have—and may never have—an Internet connection. While it may seem like we've been seduced by the electronic revolution, please be reassured that we're not going to neglect you. The print version of *Gear Technology* is still our "core competency," and we have no intention of ignoring it.

One of the things we've learned in our adventures on the Internet is that print and electronic publishing are complementary, not contradictory media. Print can do some things better than the Internet and vice versa. Our goal will be to bring you the best of both worlds.

We are very aware that you, our print readers, have been our most loyal supporters from the very beginning, and we intend to return that loyalty to you. We will continue to work at making the print version of *Gear Technology* better, more useful, more reader friendly and to continue to provide you with the best, most current information on gear design, research and manufacturing available.

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Composite Electroless Nickel Coatings for the Gear Industry

Nathan Feldstein, Ph.D. and Michael Feldstein

Electroless Nickel (EN) plating, a process dating back to the 1940s, is one of the predominant metal finishing methods today. It is especially suitable for the gear industry, whose end uses span innumerable other industries, providing an endless assortment of requirements, environments, materials and specifications. EN plating has a broad array of functional features, which include:

1. Corrosion resistance,
2. Exceptional hardness,
3. Outstanding wear resistance,
4. Perfect uniformity of coating thicknesses on all geometries,
5. Lubricity,
6. Nonmagnetic properties,
7. Solderability,
8. Applicability to nearly all metals and alloys.

Since EN can be produced with a bright and reflective finish similar to chrome, it is also widely used in applications where cosmetics are critical.

Composite Electroless Nickel

The incorporation, or codeposition, of specific finely sized particles within EN coatings can greatly enhance their existing characteristics and, in some cases, add an entirely new feature to the coating.

In typical composite coatings, the fine particulate matter can range in size from 0.1μm to about 10μm and can be loaded up to about 40% by volume within the coating. The ratio of codeposited particles to the metal matrix in composite electroless plating can be adjusted to a fixed and constant ratio. Most commercial practices, however, focus on 18–25% by volume of the particle within the matrix.

Because of the uniform manner in which the particulate matter is codeposited, these coatings are known as regenerative, maintaining their properties even when portions of the coating are removed by prolonged use (See Fig. 1).

Though it is possible to generate thicker coatings, deposits of 0.5–1.0 mil are adequate for most commercial applications. Composite EN coatings on gears are generally 0.8–1.0 mil in thickness.

While a wide variety of particulate matter can be codeposited, commercial composite electroless plating is limited to just a few types of particulate matter for three general purposes. For increased wear resistance and hardness, diamond or other hard particles are commonly codeposited within EN. Enhanced lubricity is achieved with the incorporation of polytetrafluoroethylene (PTFE)

Fig. 1 — Composite EN coating with diamond particles (1000x mag.).

and certain inorganic particles that reduce the coefficient of friction. In addition, a new generation of composite coatings containing light-emitting particles has recently been developed. All three primary categories of composite coatings and their applicability to the gear industry will be discussed in the remainder of this article.

Wear Resistance

Composite EN coatings are most commonly used to improve the wear resistance of machinery parts. Wear to gears and many other machinery parts causes undesirable replacement costs, downtime, mechanical malfunction and inconsistent output or product.

Various test procedures have been employed to evaluate the degree of wear resistance achieved. The Taber wear test is the most common. It evaluates the resistance of surfaces to abrasive rubbing produced by the sliding rotation of two unlubricated, abrading wheels against a rotating sample. This test measures the worn volume.

The merits of composite EN coatings in comparison to conventional EN coatings as shown by Taber wear testing were illustrated by Parker (Refs. 1,2) in Table 1. Parker measured the wear resistance of miscellaneous composites containing diamond, carbides, borides and aluminum oxide. The composites he tested, however, employed particulate matter of

Table 1 — Abrasive Wear Data For Electroless Nickel With Particle Inclusions

Particle	Particle Hardness, Knoop	Taber Wear Index[a] No Heat Treatment	Taber Wear Index[a] Heat Treated[b]
None	—	18	8
Chromium carbide	1735	8	2
Aluminum oxide	2100	10	5
Titanium carbide	2470	3	2
Silicon carbide	2500	3	2
Boron carbide	2800	2	1
Diamond	7000	2	2
Hard chromium, 1000 KHN		3	—
Aluminum hardcoat		2	—

[a]Weight loss in mg/1000 cycles (average of 5000 cycles) with CS 10 wheels and a 1000 g load.
[b]Heated 10 to 16 hr at 290°C.

Table 2 — Taber Wear Test Data		
	Wear Rate	
Wear Resistant Coating or Material	per 1000 cycles (10^4 mils^3)	vs. diamond
Polycrystalline diamond*	1.159	1.00
Cemented tungsten carbide Grace C-9 (88WC, 12 Co)	2.746	2.37
Electroplated hard chromium	4.699	4.05
Tool steel, hardened R_c 62	12.815	13.25

*Composite coating containing 20–30% of a 3μm grade diamond in an electroless nickel matrix.

Coating on Pin	Coating on Ring	Coefficient of Friction	Relative Wear Rate
EN	Cr steel	0.6–0.7	35
EN + PTFE	Cr steel	0.2–0.3	40
EN + PTFE	EN + PTFE	0.1–0.2	1
EN + PTFE[a]	Cr steel	0.2–0.5	20
EN + PTFE[b]	EN + PTFE	0.1–0.7	2

Table 3 — Friction Coefficient and Wear Data for Electroless Nickel-PTFE Composite

a Wear determined in a test machine consisting of a pin and a rotating ring.
b Heated 4 hrs. at 400°C.

Table 4 — Friction Coefficients For Various Composites and Materials

Coating	Load kg/cm²	Friction Coefficient
PTFE	0.1	0.12
EN-BN	0.1	0.13
EN-SiC	0.1	0.15
EN (No particles)	0.1	0.18
Chrome	0.1	0.25
EN-BN	0.3	0.09
PTFE	0.3	0.13
EN-SiC	0.3	0.14
EN (No particles)	0.3	0.16
Chrome	0.3	0.40
EN-BN	0.5	0.08
PTFE	0.5	0.13
EN-SiC	0.5	0.14
EN (No particles)	0.5	0.15
Chrome	0.5	150.00

different sizes, and neither the concentration of particles within the matrix nor the surface roughness for the coating prior to testing was revealed. Accordingly, based on the data published, no definitive conclusion can be drawn about the performance of one particle versus another.

What is clear, however, is that all of the composites, regardless of the particulate matter incorporated, performed substantially better than the EN without any particulate matter.

In Table 2, additional results employing the Taber test (Ref. 3) demonstrate the unsurpassed performance of diamond in a composite EN coating compared with more commonly used materials.

Lubricity

It has been observed (Ref. 4) that electroless composites with certain particles can yield a lower friction coefficient than identical coatings without such particulate matter. In recent years, most commercial interest has focused on the incorporation of PTFE into electroless nickel deposits.

The incorporation of PTFE and other lubricating particles into the EN composite provides several benefits:

- Dry lubrication,
- Improved wear resistance,
- Improved release properties,
- Repellency of contaminants such as water and oil.

Most applications employ composite coating thicknesses ranging from approximately 0.25 to 1.0 mil, sometimes with an un-derlayer of electroless nickel. The presence of the underlying electroless nickel is believed to provide improved corrosion resistance when necessary. Typical electroless nickel-PTFE composite coatings incorporate PTFE in the range of 18–25% by volume. Unlike coatings with wear-resistant particles like diamond, electroless nickel-PTFE composite coatings utilize particles of *1μm or smaller.*

Using a rotating ring apparatus, Tulsi (Ref. 5) investigated the friction coefficients for electroless nickel and for composites with PTFE. Table 3 summarizes these observations, which suggest that the lowest coefficient of friction is attained when both the pin and the ring are coated with an electroless nickel-PTFE composite coating. These results have particular relevance in gear applications where metal gears contact each other. To achieve maximum lubricity and wear resistance, therefore, all mating gears are typically coated.

Table 4 (Ref. 6) documents the friction coefficients for a variety of lubricating composite EN coatings, of which boron nitride yields the lowest coefficient of friction, especially with increased loads employed on the friction machine.

Composite EN coatings with boron nitride and other types of inorganic particles have recently been investigated and commercially developed. These inorganic particles, compared to PTFE, have certain significant advantages that fulfill the demands of the gear industry and other industries, including

1. Temperature resistance to above 600°C.
2. Exceptional hardnesses to about 1,000 Hv.
3. Greater abilities to take direct loads,
4. Lower costs than composite PTFE coatings.

Light Emission

Light-emitting composite EN coatings are a recent and exciting development in the field. These coatings have all the inherent benefits of EN, but, when viewed under UV light, emit a distinct, brightly colored light. This novel property has two main uses. First, the presence of light can be valuable in authenticating OEM machinery parts (for example, in the aircraft industry). Second, the light can serve as an "indicator" layer, warning when the coating has worn off and replacement or recoating is necessary before the part itself is worn and/or produces inconsistent product. This indicator layer can even be applied between the part and another coating to indicate when the first coating has worn through to the light-emitting layer.

Hand-held, battery operated UV lights are readily available and make inspection of the indicator layer fast and convenient at the operating site. In the gear industry, this coating is particularly advantageous for applications employing very expensive gears; it avoids wear into the base metal and provides the opportunity to recoat the gear with a wear resistant coating. It is also beneficial in situations where operating with worn components must be avoided to insure consistent performance or product. ○

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2. Parker, *Plating*, 61, 834 (1974).

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5. Tulsi, *Finishing*, 7(11) (1983); Trans. Inst. Met. Finishing, 61(4), 147 (1983); Proc. AES 71st Annual Technical Conference, Session B-4 (1984).

6. Honnia et al., *Proc. Interfinish* (1980).

About Our Authors:

Nathan Feldstein *was the founder and President of Surface Technology. He earned a doctorate in physical chemistry, held over 85 patents and authored numerous papers on composite coatings. He has passed away since the writing of this article.*

Michael Feldstein *is the President of Surface Technology, Inc., Trenton, New Jersey. He manages the company's operations and develops new applications for the company's advanced coatings.*

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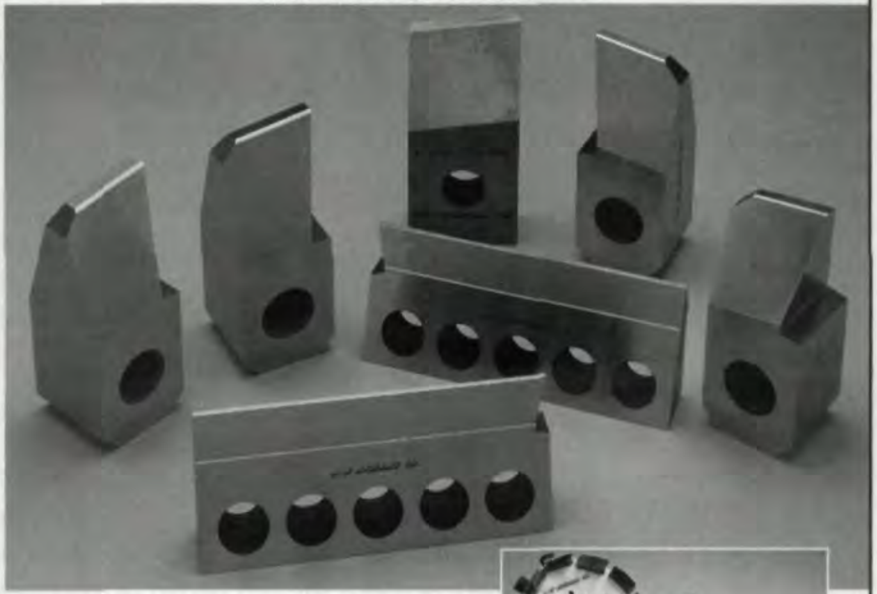

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Coated Gears Provide Slick Solution for Human-Powered Boat

William R. Stott

Design Problem: *Develop a gear drive for a pedal-powered water craft that will be easy to manufacture, use and maintain; that will be lightweight enough for the boat to be portable; and that will eliminate the environmental risk of lubricants leaking into the water.*

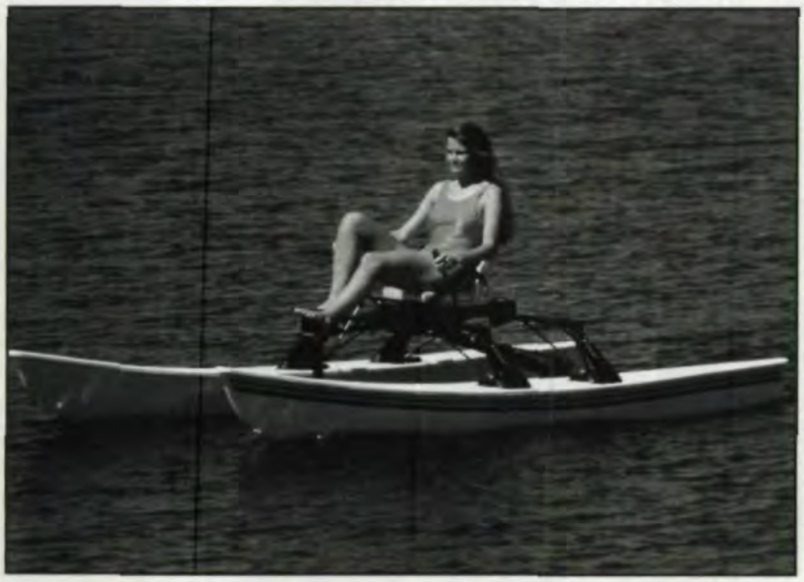
The above describes the situation that faced engineers at Micro Marine, builders of the MicroCAT, a new class of human-powered water craft being produced at the company's Mendon, MA facility.

After careful consideration and testing, Micro Marine decided on a combination of high-tech gear coatings that provided better lubrication than traditional methods and demonstrated resistance to wear, abrasion and corrosion that makes the unit virtually maintenance free.

"We wanted to have an environmentally friendly drive unit on our boat," says Tony Scappaticci, engineering manager for Micro Marine. The boat should be able to go places motors aren't allowed. It should operate quietly and not be a hazard to the environment, he says.

About the Boat

The MicroCAT is available with either an inflatable or a rigid hull. The 64-lb. inflatable version breaks down into 15 pieces that fit in an 18x18x36-inch space—easily portable in a car trunk or even a duffel bag. One hundred MicroCATs have been sold, and they're being used in locations such as Hawaii, Alaska, Puerto Rico and Chile, in fresh water and salt water.



The gear drive, consisting of two sets of bevel gears, gives the boat a much greater performance ratio than a chain drive would have allowed. The 8:1 ratio means that a person pedaling at 60 rpm drives the prop at 480 rpm. This makes the boat much faster—at 5–6 knots—than a typical pedal-powered boat. But having a gear drive means that the entire drive unit has to be enclosed to protect the gears from water.

Why Dry Lube?

With a traditional wet-lubricated gear drive, keeping the lubricants out of the water and the water out of the drive would have required complicated seals, Scappaticci says. With the dry coatings, engineers had only to seal the entire unit to keep water from getting in.

Also, even the best lubricants eventually break down and have to be replaced. Dry lubricant coatings allowed the designers to completely enclose the drive to make it maintenance free.

After testing various products, Micro Marine turned to Microfin Corp., developer of high-tech coatings in Providence, RI. After more testing, the companies discovered that not only would coated gears help them solve the environmental problem, but that incorporating coated gears made the rest of the drive less expensive and the whole product simpler and more lightweight.

About the Coatings

The engineers tested various configurations of coatings for the pinions and bevel gears in the drive unit and chose Lubralloy® for the gears and Microlube® for the pinions.

Lubralloy is a chemically deposited nickel alloy coating with a hardness of Rc 45–49. The hard surface provides increased resistance to wear, abrasion and corrosion. At the same time, it provides exceptional lubrication, with a coefficient of friction of 0.12. Lubralloy was originally developed for use in demanding military and space applications, according to Microfin.

Microlube is an even harder coating (Rc 68–72) with an even lower coefficient of friction (0.05–0.10) as well as resistance to abrasion, wear and corrosion. The higher torque on the pinions of the MicroCAT drive unit required the harder surface and better lubricating ability of the Microlube coating. In tests, Microlube eliminated metal-to-metal pickup, galling, seizing and excessive wear, even under heavy torque loads and aggressive environments such as salt water. According to Microfin, this process produces its most dramatic reduction in coefficient of friction under heavy loads where petroleum-based lubrication and other systems fail most often.

The Results

Because they weren't using a traditional wet lubricant, Micro Marine was able to eliminate the oil seals, drain hole, fill hole and plug. The result was a much simpler product to manufacture and maintain.

Furthermore, because of the hardness of the coatings, the company was able to specify a more machinable, lower grade material (4140 steel) for the gears.

The gear drive itself is resistant to corrosion, abrasion and wear. Exposure to water and salt water won't harm it. The gear drive should never have to be replaced, and because it's enclosed, it never has to be maintained. In addition, the lubricity of the coatings makes the pedals easier to operate.

Finally, the enclosed drive with no wet lubricants created an environmentally friendly product that was appropriate for the areas where it would be used.

Other Applications

The MicroCAT inflatable boat is just one example of the many applications that could benefit from coated gears. Others include food industry products or drives used in environmentally sensitive areas and enclosed mechanisms that cannot be lubricated on a regular basis, according to Microfin.

The coatings used on the gears in the MicroCAT have been used successfully on other types of moving parts, including valves, couplings, bearings, pistons and pumps. ○

HOW COATED GEARS HELPED BUILD A BETTER BOAT.

Made the Rest of the Drive Less Expensive

1. Reduced the number of parts: Fewer seals and no plug, drain or fill hole.

2. Allowed the use of a more machinable (less expensive) gear material.

3. Reduced assembly time.

Improved Performance and Operation of the Gear Drive.

4. Reduced friction, making the boat easier to operate.

5. Made the gear drive corrosion resistant without using stainless steel or other high-tech materials.

6. Made the gear drive environmentally safe.

7. Eliminated the need for gear drive maintenance.

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Hard Coatings on Contaminated Surfaces — A Case Study

Dr. George Fischer

Physical Vapor Deposited (PVD) coatings such as TiN (titanium nitride) have been a boon for cutting tool manufacturers. They reduce wear and, therefore, extend tool life, which in turn reduces production costs. But PVD coatings are expensive, and when they fail, they cost both time and money, and the causes of the failure are not always readily apparent.

Although the present case study deals with taps, its conclusions are equally valid for any ground metallic surface, such as those found in tool and die cutting and forming and medical instrument, firearm, and gear cutting tool manufacturing, or any other process where grinding is one of the manufacturing operations.

Bad Taps

A customer turned to us with the request to analyze a batch of PVD titanium nitride (TiN) coated taps. Although the coating looked perfect, with a shiny, even, deep gold hue, the taps failed prematurely: There was immediate adhesion and edge buildup.

In the beginning, we suspected adhesive failure due to inadequate cleaning prior to TiN deposition. Subsequent analysis of the failed tools showed that the reasons were more subtle.

Taps typically contain three different surfaces: Their shanks are ground on a centerless grinder, often by a third party; their flutes are either milled or ground by a relatively coarse grinding wheel, and the threads are usually ground by a finer wheel which contains the thread profile.

As a rule, the coarsest surface is that of the flute. Therefore, insufficient cleaning would cause coating failure predominantly on the flutes. However, in this case, scratch tests under the microscope revealed stable coating, with good adhesion on both the flutes and shanks, but consistently high failure rate on the flanks.

PVD processes are inherently delocalized: They do not produce large differences in the coating quality of adjacent areas of identically prepared surfaces. The coating differences on flutes and flanks could not be caused by the PVD process, and the good coating quality on shanks and flutes was an indication of correct technology.

Therefore, we concentrated on the flanks. Secondary ion mass spectrometry, auger electron spectroscopy and electron induced X-ray spectroscopy revealed contaminated para-surface regions on the flanks. Moreover, the comparison of surface chemistries of the flanks and the grinding wheel indicated that most of the contamination originated from the grinding wheel.

Grinding Wheel the Culprit

How is material transferred from a grinding wheel to the workpiece? What is the mechanism of impregnation of contaminants into the surface? These questions could be answered by considering the grinding mechanism.

A grinding wheel consists of a relatively soft, often porous matrix with hard abrasive particles embedded and anchored in it. In a new or freshly dressed wheel,

Surface Preparation for PVD Hard Coatings

Surface cleanliness, a prerequisite for high coating quality, can be achieved by observing the following guidelines:

- Dress grinding wheels three or four times more frequently than for uncoated parts. Avoid "spark-out," which causes cold working of impurities into surfaces. Make sure there are no burrs on edges.
- Avoid rubberized or resinoid buffing wheels or diamond polish.
- Do not sand- or bead-blast or vapor-hone surfaces.
- Use good quality silicon carbide wet-and-dry paper for manual polishing. Start with a coarse grit and proceed in small steps with finer and finer paper until the desired finish is achieved. Use plenty of water, changing water and rinsing between steps. Change paper frequently and apply only light pressure to minimize rubbing and maximize cutting.
- Do not use peel or dip coat and/or hydrocarbon rust preventives, such as WD-40.
- Do not use chemical scale or rust removers/preventives.
- Remove screws, clean tools of shop soil in a mixture of one part machine oil (any kind will do) and 16 parts mineral spirit. Cleanliness of crevices and coolant ducts is especially important.
- Use cadmium-free braze for brazed tools; make sure there are no crevices and pinholes in the brazed joint.
- Do not attempt to coat black-oxided or electroplated surfaces.
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sharp abrasive particles protrude from the surface. During grinding, weakly bound particles are dislodged from the wheel matrix and lost. The remainder cuts the workpiece material and wears continuously; the average edge radius of the abrasive particles increases with time, causing an increase in the cutting forces and leading to plastic deformation of the workpiece surface.

With increasing forces on individual particles, an ever-increasing number are lost, and fewer particles with larger and larger edge radii come in contact with the workpiece. Consequently, the material removal rate decreases and the generated heat increases. This process is exacerbated by "loading" of the wheel with debris from its own surface and the workpiece. Eventually the material removal ceases, and the wheel only rubs the surface, causing intense heating and melting or "glazing."

During grinding, foreign matter from the grinding wheel and the coolant is deposited onto the workpiece. Furthermore, freshly exposed metallic surfaces are chemically reactive and quickly oxidize and/or react with constituents of the coolant. However, because of the high removal rate of a freshly dressed grinding wheel, these impurities are effectively removed, and the surface remains clean.

As the wheel wears and the removal rate decreases, a residual impurity layer is formed on the surface and cold-worked into the material, thus creating a mechanically burnished, chemically impure para-surface region. The impurity concentration is further enhanced by increased diffusional mass transport caused by the heat generated by the worn wheel.

With the increasing non-metallic impurity concentration, the coating adhesion monotonically decreases up to the point of spontaneous coating delamination from the surfaces. There can be noticeable deterioration well before the appearance of visible signs of surface loading, which makes it difficult to define the proper wheel dressing procedures and frequency.

From the preceding description, it is clear that incorrect grinding can cause coating failures. Well dressed, relatively soft, open wheels should be used for grinding surfaces intended for PVD coatings. Optimum wheel composition, grade and dressing conditions for a particular application are usually suggested by the suppliers or found by trial and error. A good rule of thumb is that the frequency of dressing of grinding wheels should be some three to four times higher for taps that are to be coated than for those remaining uncoated. ○

Dr. George Fischer
is the owner of Ion Vacuum Technologies Corporation, a provider of PVD coatings, production support, consulting services and production troubleshooting for the metal cutting and forming industries.

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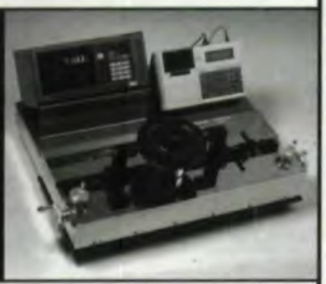

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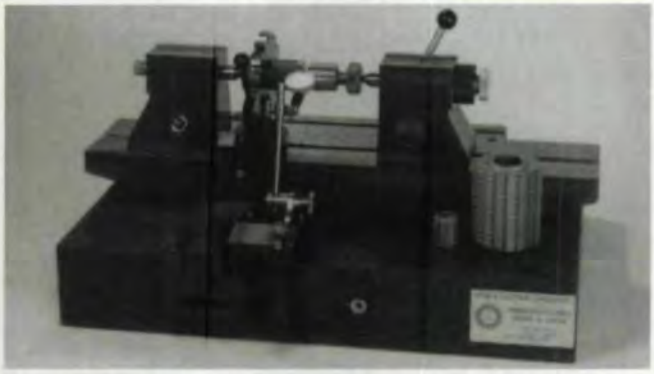

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Improved Ion Bond Recoating for the Gear Manufacturing Industry

Mark A. Pellman & Alan Stevenson

This article summarizes the development of an improved titanium nitride (TiN) recoating process, which has, when compared to conventional recoat methods, demonstrated tool life increases of up to three times in performance testing of hobs and shaper cutters. This new coating process, called Super TiN™, surpasses the performance of standard TiN recoating for machining gear components. Super TiN incorporates stripping, surface preparation, smooth coating techniques and polishing before and after recoating. The combination of these improvements to the recoating process is the key to its performance.

A primary objective of the development program was to improve the surface finish of recoated hobs and shaper cutters. To this end, research was conducted to study the effect of stripping prior to recoating, to quantify the effect of coating parameters on surface defect formation and to characterize the effect of polishing processes on recoated tool surface finish and edge condition. In addition, both laboratory and field testing were carried out over a period of two years to determine recoating performance on hobs and shaper cutters.

Introduction

The TiN coating studied was deposited by Multi-Arc's ION BOND® Physical Vapor Deposition (PVD) process. In this process, arc evaporation is used to create a highly ionized plasma that allows for deposition of adherent coating at temperatures as low as 400°C (752°F). In a standard coating cycle, tools to be recoated are first fixtured in a vacuum chamber. Following evacuation of the chamber, the tools are heated via one of several methods, dependent on the application. These include ion bombardment, glow discharge or radiant heating. After the tools reach temperature, an arc is struck on multiple titanium cathodes positioned inside the chamber. The arc flash evaporates and ionizes the titanium, which is attracted to the negatively biased components. Nitrogen or another reactive gas is then introduced to a small partial pressure and reacts with the metal to form a coating.

The advantages of the cathodic arc PVD process have been widely reported in the technical literature (Refs. 1–5). The cathodic arc process generates a high level of metal vapor ionization and high ion energy. These lead to exceptional coating adhesion even at low deposition temperatures. The multiple arc sources also provide coating uniformity and allow the deposition of alloy coatings such as TiAlN (Ref. 6). The low deposition temperature allows the coating of tool steels, powder metal alloys, cermets and cemented carbides without affecting their mechanical properties.

The one disadvantage of cathodic arc PVD is the emission of unreacted titanium droplets from the cathodes (Refs. 7–8). These droplets, often referred to as "macro-particles," can lead to growth defects and rough coatings (Ref. 8). Rough coatings, in turn, can lead to a high coefficient of friction, metal pickup and reduced tool performance. The negative effects of rough coating are particularly troublesome when tools are

Newer coatings with TiAlN and TiCN, as well as TiN are now being used for gear cutting tools.

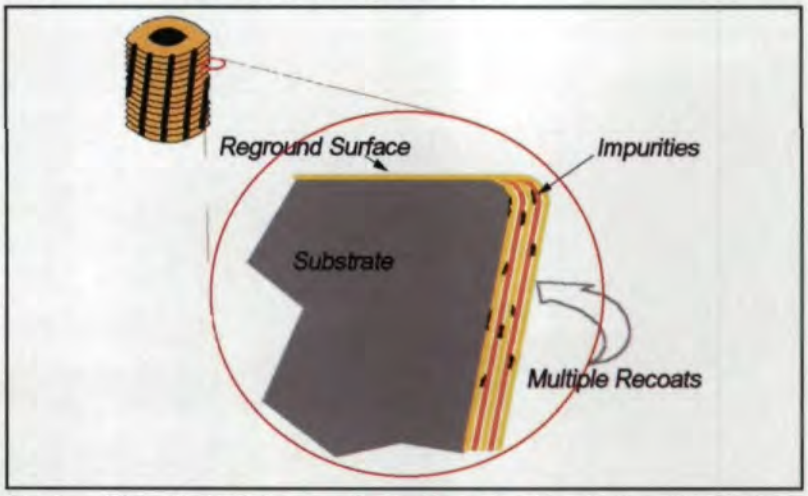

Fig. 1 — Contaminants between coating layers can compromise the adhesion of the coating.

recoated multiple times, as in the case of gear cutting tools. Hobs and shapers are often reground and recoated as many as 20 times. This can lead to excessive roughening on the flanks of hob teeth.

Recoating

PVD TiN coating has become widely used on metal cutting tools since its introduction in the early 1980s. Numerous technical papers have been written confirming the advantages of TiN coating and recoating (Refs. 9–12). In the early 1980s, when recoating was a new concept, users of expensive TiN coated tools, such as hobs, broaches and shaper cutters, noticed that tool performance decreased after sharpening. Sharpened tools cut fewer parts than the original coated tool. Furthermore speeds and feeds often had to be reduced.

Recoating was developed as a program to restore the performance of a sharpened tool to that of the original coated tool. Recoating replaces the TiN coating on the cutting face of a tool each time it is sharpened. The renewed coating allows tools to run at their optimum performance levels. Recoating is a proven process that can cut tooling and production costs by as much as 20–40% (Ref. 10).

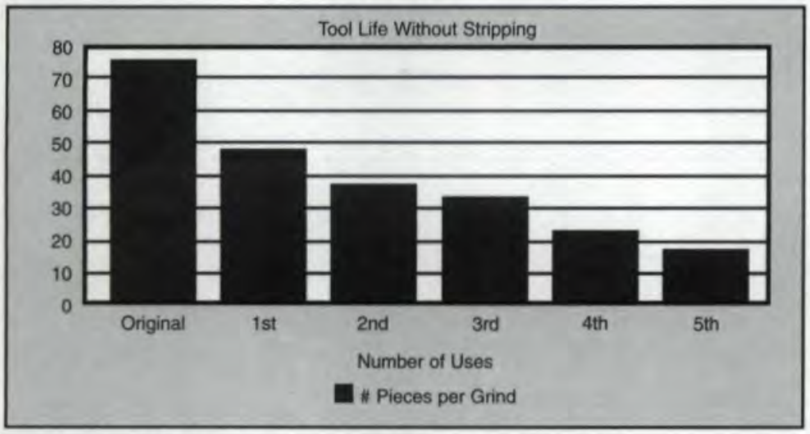

Fig. 2 — Number of pieces produced with recoated TiN shaper cutters.

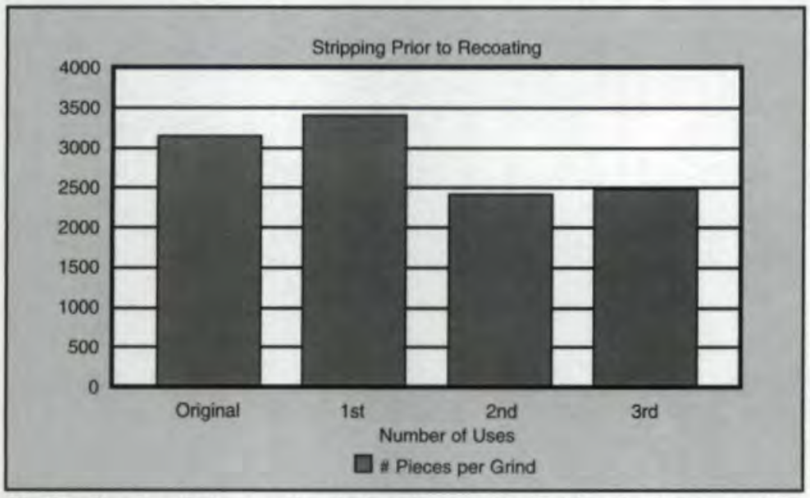

Fig. 3 — Number of pieces produced when shaper cutter is stripped prior to recoating.

In 1993 Multi-Arc initiated a development program to further improve recoated tool performance. As mentioned above, the scope of this program included

- Study of the effect of stripping prior to recoating,
- Study of the effect of coating parameters on defect formation and growth,
- Characterization of the effect of the polishing processes on tool surface finish and edge condition,
- Determination of the performance of Super TiN recoated hobs and shaper cutters.

Stripping

Stripping prior to recoating was investigated to determine if it could reduce or eliminate peel-back on the tooth flank on recoated hobs. Peel-back occurs when the TiN coating delaminates from the surface of the tool or between coating layers. With a recoated hob, as shown in Fig. 1, the adhesion between the successive layers of coating can be compromised by contaminants such as glass bead particles, metal build-up and flakes of old coating. Poor adhesion adjacent to contaminants, in turn, provides an initiation site for coating delamination under the loads experienced during cutting.

The stripping technique studied involved immersing the coated hobs in a hydrogen peroxide based solution at room temperature. The solution chemically reacts with titanium nitride, removing it and leaving a thin oxide on the hob.

The effect of coating build-up on tool performance is illustrated in Fig. 2. Shaper cutters were used to machine 4140 steel gears at a manufacturer of automotive transmissions. After each sharpening the cutters were liquid honed, cleaned and recoated with 2–3 microns of TiN. Fig. 2 shows the number of pieces produced with these cutters during six successive uses of the tool, which represents the average life span. Each point is the average of the results produced by 10 tools. The results show that the number of pieces machined decreased to less than half the original coated tool performance after six recoatings. The drop in performance is attributed in part to changes in tool geometry and clearance angles and in part to coating build-up.

Most of the tool wear was isolated to one or two teeth on the cutter. The majority of the teeth had only .005" (0.13 mm) of wear, but some had peeled back on the tip. Once the coating wore through to the substrate, the deterioration rapidly progressed to a peel-back state. The first teeth to wear through the coating often progressed to peel-back before the machine cycle was finished, resulting in wear as high as .095" (2.4 mm).

When shaper cutters are stripped prior to recoating with TiN, the number of pieces produced decreases, but much less dramatically.

Data from Land Rover, which is illustrated in Fig. 3, shows that an ASP 23 shaper cutter, when stripped prior to every recoating, had a decrease of only around 20% after sharpening and recoating 3 times. These cutters were 5" (127 mm) in diameter and 1.5" (38 mm) high operating at 35 sfm and a .012" (0.3 mm)/stroke.

The results show that the number of pieces machined actually increased to an average of 3,659 pieces following the first recoating when compared to the original TiN coated hob, which machined an average of 3,363 pieces. After subsequent sharpening, stripping and recoating cycles, the life dropped into the range of 2,700-2,800 pieces/grind.

Based on results like these, stripping of old TiN coating prior to recoating has become a standard Super TiN practice.

Defect Formation and Growth

It is well known that hard compound coatings produced using cathodic arc deposition exhibit higher roughness when compared with sputtered and E-beam deposited coatings. Many researchers have connected this problem to the droplet emission during arcing on the target. The protruding features from the coating surface are often called "macros," "macro-particles" or "droplets." Based on Multi-Arc's research, the term "growth defect" would be more appropriate. This conclusion is based on the observation that macro-particles deposited during the conditioning phase of a coating cycle can either grow as the cycle proceeds or be covered over as coating material is deposited. Both growth and macro-particle generation are dependent on process conditions.

Coating process conditions, in particular bias voltage and bias voltage waveform, were studied to determine their effect on defect formation and growth. In order to determine the effect of waveform on defect growth and propagation, several different power supplies were used to deposit TiN coatings on high speed steel coupons in a commercial ION BOND® PVD system. The coating process protocol is listed in Table 1.

Test coupons were fixtured in a rotating fixture facing the cathodes during the conditioning and coating cycles. The typical SEM micrographs of the TiN coating deposited with the best and worst power supplies are shown in Fig. 4. It is obvious from these pictures that the size and

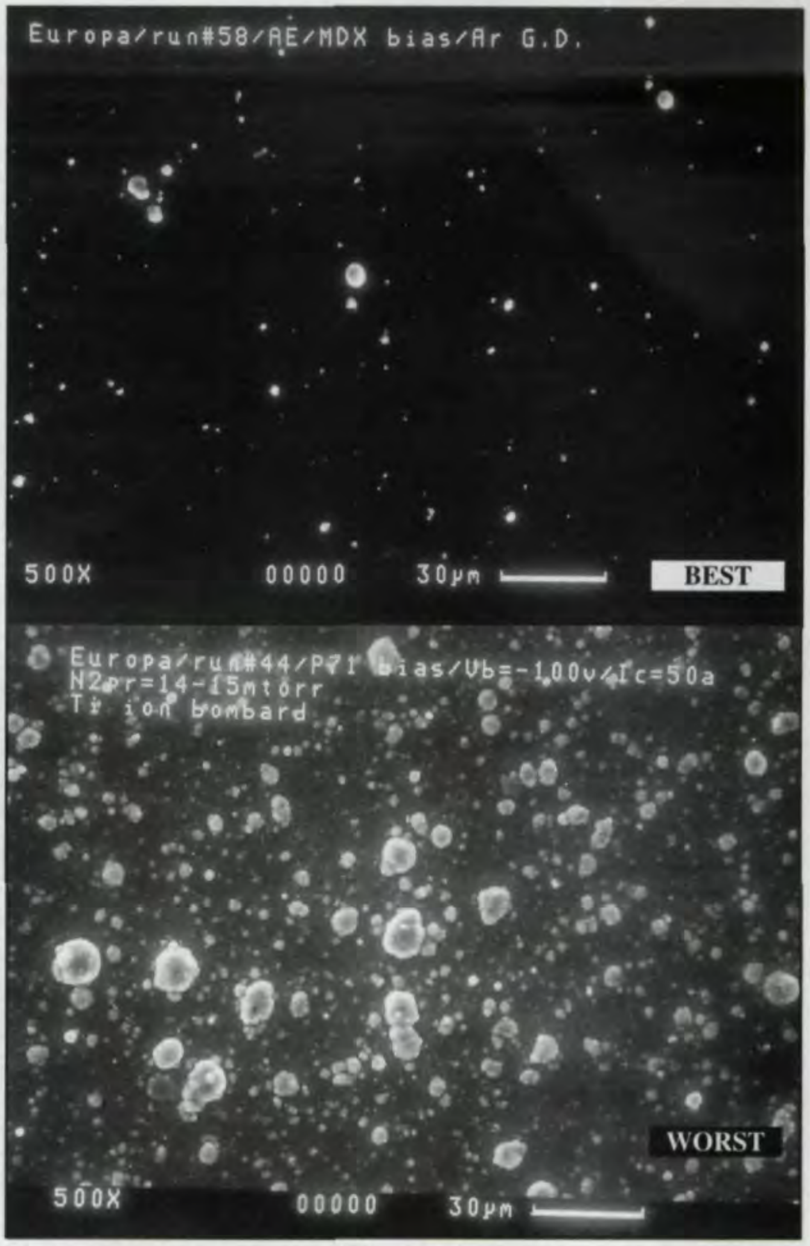

Fig. 4 — SEM photomicrographs of TiN surface for the different bias power supplies.

Table 1 — ION BOND® Coating Protocol

Conditioning Cycle	**5 minutes Ti ion bombardment in vacuum**
Number of Evaporators	4
Bias Voltage	-1000V
Coating Cycle	**45 minutes w/15m Torr N_2 pressure**
Number of Evaporators	4
Bias Voltage	-100V
Deposition Temperature	900–1000°F
Coating Thickness	~7 microns

Table 2 — Surface Properties of Deposited TiN

Bias Power Supply	Ra, Angstrom	Defect Density (mm^{-2})	Area Covered by Defects (%)
Best	3,000	10,000	3
Worst	7,000	20,000	20

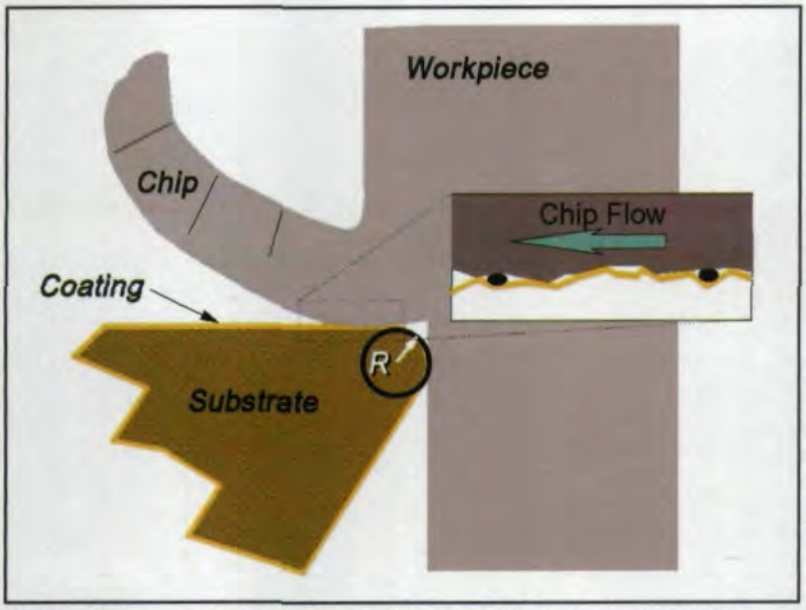

Fig. 5 — Optimum surface and edge conditions for a hob tooth prior to recoating.

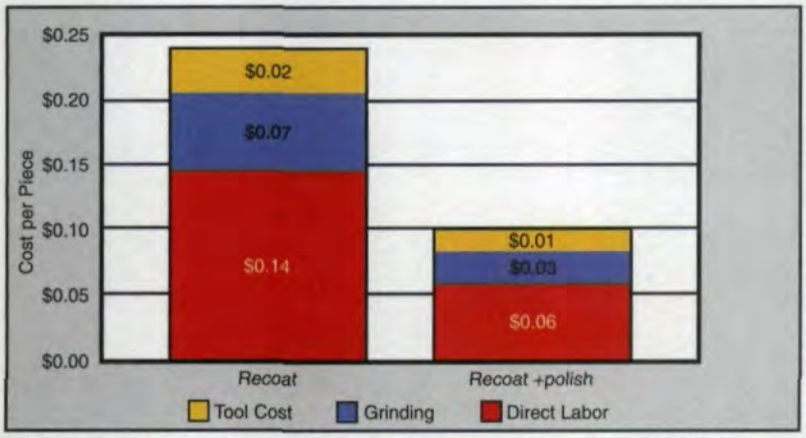

Fig. 6 — Comparative cost savings of recoating alone vs. recoating and polishing.

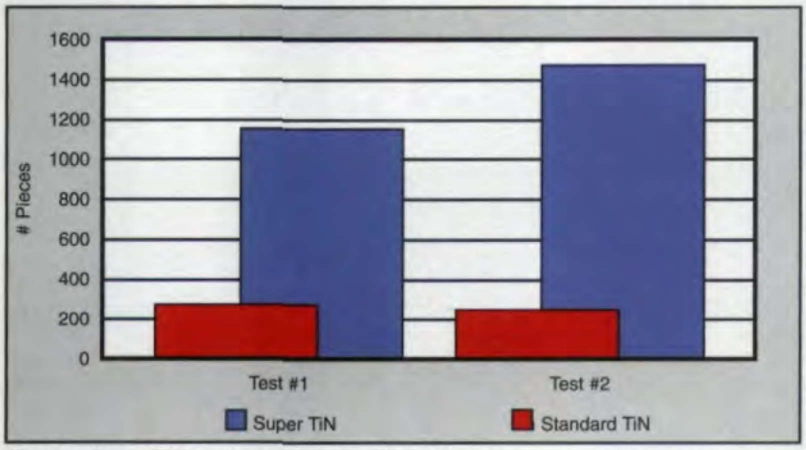

Fig. 7 — Super TiN performance tests at Land Rover.

quantity of defects is quite different. The only difference between the two deposition conditions is the waveform of the bias power supply used.

Some of the surface properties of the deposited TiN are summarized in Table 2.

The improved surface finish and reduced defect density observed with the best power supply tested is the result of its flat DC waveform, which minimizes the growth of macro-particles deposited on the surface. However, the waveform does little to eliminate the original source of macro-particles—the use of titanium ion bombardment to heat and condition tools prior to coating.

To eliminate this source of macro-particles, Multi-Arc developed and tested two alternative heating techniques: radiant heating and glow discharge heating. Radiant heating requires the installation of electric heating elements inside a coating chamber. These are used to heat tools to just below the desired coating temperature. Glow discharge involves the use of gas ion bombardment to heat tools. Typically, mixtures of argon and hydrogen gas are ionized and attracted to the tools by a pulsed bias power supply. This is similar to the process used for ion nitriding of tools, with the exception that ion nitriding uses nitrogen gas.

Laboratory and production testing of radiant and glow discharge heating indicates that both techniques can reduce the macro-particles and improve the surface finish of polished samples to less than 1,500 angstroms (6 micro-inches). More significantly, a practice which incorporates radiant heating followed by glow discharge heating and then a brief titanium ion bombardment can produce surface finishes of 500 angstroms (2 micro-inches). This best practice for smooth, defect-free coating is a key component of the Super TiN process.

Polishing and Edge Conditioning

Several polishing processes were investigated, including harperizing, mikrofinishing and hand polishing. Both harperizing and mikrofinishing are centrifugal polishing processes. Harperizing uses wet Al_2O_3 media, while mikrofinishing uses a dry media consisting of Al_2O_3 or SiC impregnated walnut shells.

Preliminary testing indicated that both harperizing and mikrofinishing hone the cutting edges of hobs and polish the flank and face. The honed radius of the cutting edge was dependent on the polishing time with both processes. The radius varied from .0005–.0007" (0.013–0.018 mm) with the harperizing process. The hone produced with the mikrofinishing process was typically .0003–.0005" (0.008–.013 mm) by comparison. The optimum surface and edge conditions for a hob tooth prior to recoating are shown in Fig. 5.

Field testing was carried out at a manufacturer of marine and industrial transmissions. The objective of the field testing was to produce more pieces between resharpenings, translating into more machine up time. The protocol called for testing of TiN recoated hobs versus polished and TiN recoated hobs. TiN recoated hobs were processed according to Multi-Arc's standard process path. The nominal TiN coating thickness was 2–4 microns. Polished and recoated hobs were polished in a mikrofinish centrifugal polisher both before and after recoating.

A Liebherr LC255 CNC hobber was selected for the test. Test tools were 3.25" (83 mm) diameter TiN coated M2 hobs with 33 teeth and D.P.s of 11.3937. The material machined was 4047 steel with a hardness of 180–210 BHN. Hobs were run at 430 rpm and feed rate of 0.115" (3 mm) per revolution. Hobs were sharpened in-house on a Star CNC grinder with a borazon wheel. The material removal on both TiN recoated and polished and recoated hobs was 0.012" (0.3 mm).

Test results showed that polishing improved the hobs' as-ground surface finish from 11–12 micro-inches (Ra) to 6–7 micro-inches (Ra). A similar improvement was observed when the hobs were polished after recoating. The polishing also honed the cutting edge and removed a burr that was normally observed on as-ground hobs. This was a subtle, but significant benefit. Burrs can be problematic when they are coated with TiN. Forces encountered during cutting cause the burr to break off, exposing uncoated substrate and a possible initiation site for peel-back.

The most significant result was the reduction of the shift rate from 0.007" (0.18 mm) per piece to 0.003" (0.08 mm) per piece. This more than doubled the life of polished and recoated hobs compared to those that were only recoated. The cost savings achieved are illustrated in Fig. 6.

Similar results were obtained at a Big Three automotive manufacturer when TiN recoating was replaced with recoating plus polishing. Flank wear was reduced from 0.008" to 0.004" (0.20 to 0.10 mm) when hobbing with normal operating parameters and a shift of 0.0016" (0.040 mm) per piece. This allowed the shift rate to be reduced to 0.001" (0.025 mm) while still obtaining the normal 0.008" (0.20 mm) flank wear on hobs. The net result: The recoated and polished hobs had almost twice the tool life compared to recoated only hobs.

Pre-coat and post-coat polishing techniques were combined with improvements in stripping practice, surface preparation and coating process in the United Kingdom around 18 months ago, thereby establishing the Super TiN recoating process.

The process specification for Super TiN encompasses the following improvements:

• Strip any old coating prior to recoating.

• Microhone or liquid hone with alumina to remove residual oxides from the stripping process. This dulls the surface, but actually achieves an improvement in surface roughness.

• Mikrofinish to further smooth the uncoated substrate and achieve a controlled hone on the cutting edge, thereby eliminating microscopic burrs, strengthening the cutting edge and providing a better coating growth site.

• Heat tools to coating temperature using radiant heaters and/or glow discharge.

• Coat/recoat to a minimum thickness of 4 microns.

• Finish polish to remove droplets and surface defects.

Land Rover began testing Super TiN in late 1994. The high surface finish and excellent adhesion of Super TiN allowed an increase in the number of passes per grind on some of the hobs used in the transmission manufacturing department. The results of testing at Land Rover are illustrated in Figs. 7 and 8.

Results for a 4" (102 mm) diameter x 6" (152 mm) long solid ASP 23 hob with 16 gashes appear in Figure 7. This hob machined helical gears (7 DP, 40 Teeth, 20° pressure angle, 168 mm diameter) on a Hurth WF10 hobber at 200 rpm and a feed of 0.120" (3 mm) per revolution.

Standard TiN coated hobs ran for 1 pass with a shift rate of .010" (0.3 mm). Super TiN coated hobs ran for 3–5 passes with the same shift rate. This increased the number of pieces per grind from 400 to over 1,200 on average.

Fig. 8 shows the results for a 4" (102 mm) diameter x 8" (203 mm) long solid ASP 23 hob with 15 gashes. The test was run on a Gleason 777 CNC hobber machining 590 Mi7 steel gears.

With Super TiN, it was possible to increase the spindle speed from 300 to 345 rpm while maintaining a feed rate of .090" (2.3 mm) per revolution. This resulted in a cycle time reduction of over 10%. In addition, the number of passes was increased from two with standard TiN recoating to four with Super TiN. This doubled the hob life from 400 to 800 pieces per grind.

TiN-coated shaper cutters.

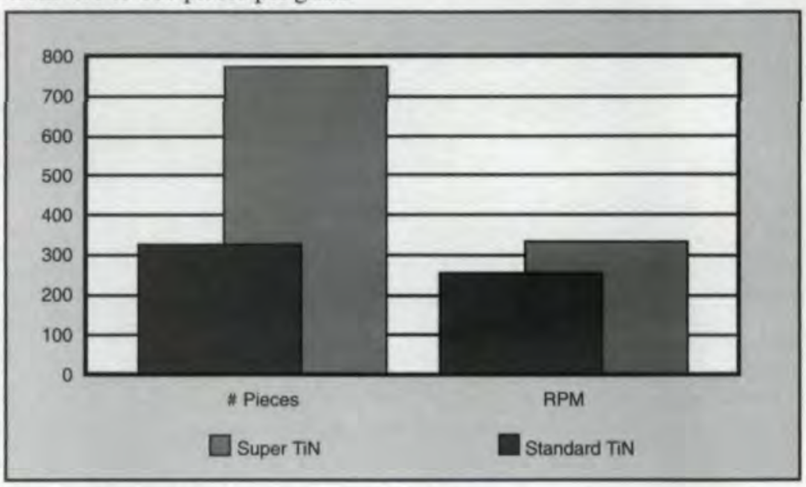

Fig. 8 — Super TiN performance tests at Land Rover.

Table 3 — The Effect of Super Surface Finish	
Super TiN Process Step	**Surface Finish (micro-inch, Ra)**
As Received	~35
Micro-Polish (6 minute cycle)	~35
Vapor Blast + Micro-Polish	18–20
TiN Coat	15–20
Post-Coat Micro-Polish (5 minute cycle)	12–15

The improvement in hob performance with Super TiN is directly related to the improved surface finish created by the combination of surface preparation, coating and post-coat polishing. Data obtained at Eaton, another U.K. account, illustrates this point. A 5" (127 mm) x 7" (178 mm) hob was evaluated for surface finish at each step of the Super TiN recoating process. The surface finish measurements, which are summarized in Table 3 above, show that this hob was quite rough as received. Micro-polishing alone had no significant effect on the rough surface finish. Vapor blasting followed by micro-polishing, however, improved the surface finish from 35 micro-inches to 18–20 micro-inches. Following coating, the surface finish was still in the range of 15–20 micro-inches. This was further improved to 12–15 micro-inches by post-coat micro-polishing.

Looking Forward

Based on the successful test results, Multi-Arc has upgraded its coating systems and installed polishing equipment at multiple coating centers in North America and the United Kingdom. Surface preparation and polishing are now a routine part of the recoating service provided by these centers. With Super TiN now available to customers in the gear cutting industry, Multi-Arc is looking at new ways of making recoating even more cost effective.

Titanium aluminun nitride (TiAlN), titanium carbonitride (TiCN), molybdenum disulfide (MoS_2) and multilayers of these coatings offer advantages over TiN in specific gear cutting applications. Further in the future, research and development projects are focusing on optimizing coating properties for high speed machining and dry hobbing.

Conclusion

• Polishing before and after recoating improves the surface finish and hones the cutting edge of hobs, shaper cutters, broaches and other tools.

• Super TiN, which combines pre-coat and post-coat polishing techniques with improvements in stripping practice, surface preparation and coating process path, further improves the life of gear cutting tools. Tool life increases of 200–500% are possible.

• Super TiN can reduce cost per component by over 50%.

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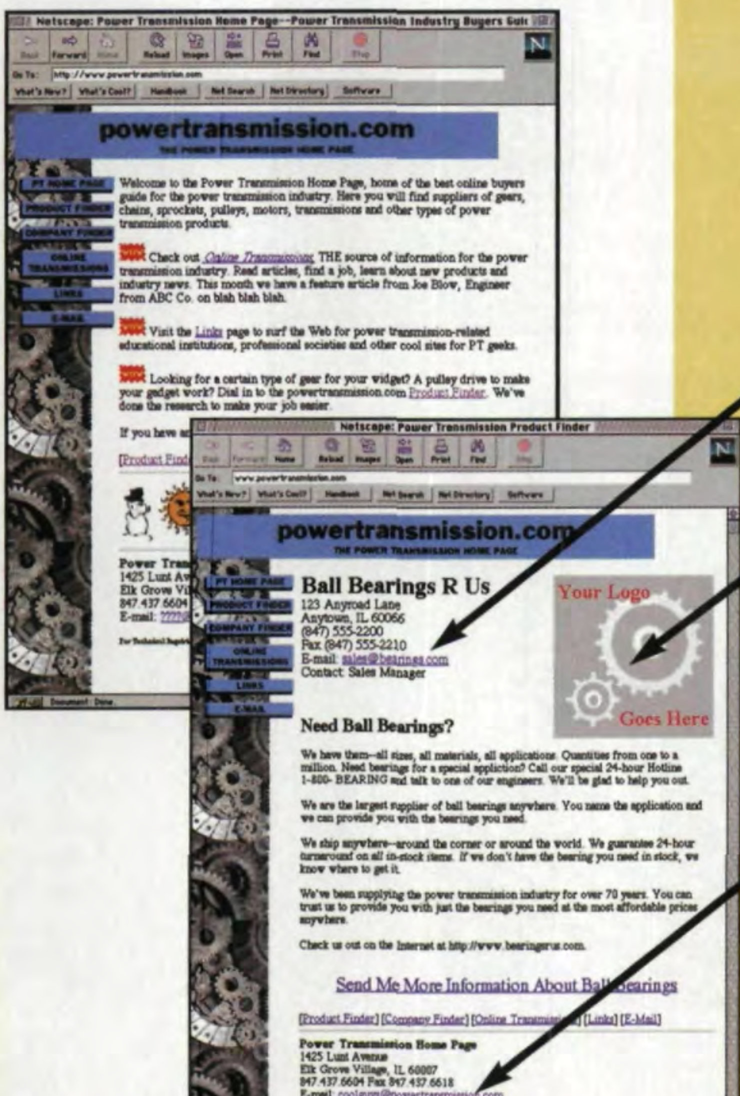

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February 3–4. Basic Gear Design & Manufacturing. The Ambassador West Hotel, Chicago, IL. This clinic will cover the basic concepts of gear design and manufacturing processes, including the preliminary design process, gear design optimization, design as related to tool life, gear inspection and more. For beginning designers, technicians, project and process control engineers and other professionals for whom a basic understanding of gear design is vital.

February 5–6. Heat Treating & Hardening of Gears. The Ambassador West Hotel, Chicago, IL. This clinic will discuss the basics of induction hardening and alternative heat treating methods, how to evaluate various methods, how to better control and monitor the process and hardness during heat treatment. The clinic is designed for any professional involved in any aspect of heat treating processes, quality control, materials development or industrial operations in gear manufacturing.

For information about these clinics, contact Cherrie Bacon at 313-271-1500, x358 or e-mail her at *bacoche@sme.org*.

ESD—THE ENGINEERING SOCIETY COMBINED CONFERENCE & EXHIBITION

April 7–10. United New Generation Vehicles Conference & Exhibition—Composites, Coatings & Concepts. The Westin Hotel, Detroit, MI. These combined conferences and exhibitions will provide a forum and act as a catalyst to promote global commercialization of vehicles with improved materials, design, manufacturing, safety and environmental compatibility. The Advanced Composites Conference & Exhibition will present an overview of the latest developments in advanced composites technologies for the transportation industry. The Advanced Coatings Technology Conference & Exhibition will cover current coatings technologies, and the Environmental Vehicles Conference & Exhibition will address the multiple challenges in the alternative fuels and advanced vehicle technology arenas.

For more information, contact Kristin Karschnia, 810-355-2910.

AGMA GEAR SCHOOLS & CLINICS

April 7–11. AGMA Gear School. Daley College, Chicago, IL. This one-week course is designed for employees with at least six months' experience in setup or machine operation, and it covers setup, gear inspection, gear calculations and basic gear manufacturing principles.

April 24–25. Hob Sharpening Clinic. This day-and-a-half clinic covers the basics of hob sharpening.

For more information, contact Susan Fentress at AGMA. Phone 703-684-0211 or fax 703-684-0242.

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Gear Software You Didn't Know About

William R. Stott

Designing and manufacturing gears requires the skills of a mathematician, the knowledge of an engineer and the experience of a precision machinist. For good measure, you might even include the art of a magician, because the formulas and calculations involved in gear manufacturing are so obscure and the processes so little known that only members of an elite cadre of professionals can perform them.

While it may seem like magic to the rest of us, no gear engineer can pull an involute out of his hat. The fact is that most of gear design and manufacturing is hard work, attention to detail and trial and error.

But wouldn't it be nice if someone invented a magic wand to take away some of the drudgery?

The computer revolution promised calculations at the touch of a button and design by menu. For many applications, that promise has been fulfilled. However, if you've ever gone shopping for gear software, you've probably found that there isn't much to choose from.

The gear market is so small that mainstream software developers have largely ignored it. But gear software is out there, if you know where to look. Most of it has been designed by gear shops, research institutions, independent consultants and universities for their own use. We suspect that many more shops have designed their own software but don't offer it for sale.

What we found comes in a variety of price ranges and performs a variety of functions. Some packages use text-only displays, while others have very detailed graphics and animation. We make no judgments about how useful any of this software is. We leave that to you.

For the Shop Floor

Sometimes the simplest programs can save time and make employees more productive. Calculating a gear's correct measurement over wires with a calculator and involute charts is a tedious project that no one enjoys.

Worrall Grinding Company, Anderson, CA, created a program called *WireSize (Version 1.0)* to make the calculation fast and simple.

"We wrote it out of necessity," says George Worrall, president. "It's really handy to use in the shop. If you do it on a calculator, it takes about an hour and a half. With this program, you could have the secretary do it."

WireSize uses the Zahorski long method to calculate wire sizes for spur or helical gears using information that can be taken directly from specifications on a drawing.

For example, after you enter the number of teeth, diametral pitch, pressure angle and amount of backlash, the program will give you values for involute check, pitch diameter and wire size, as well as theoretical measurement over wires and measurement over wires with backlash.

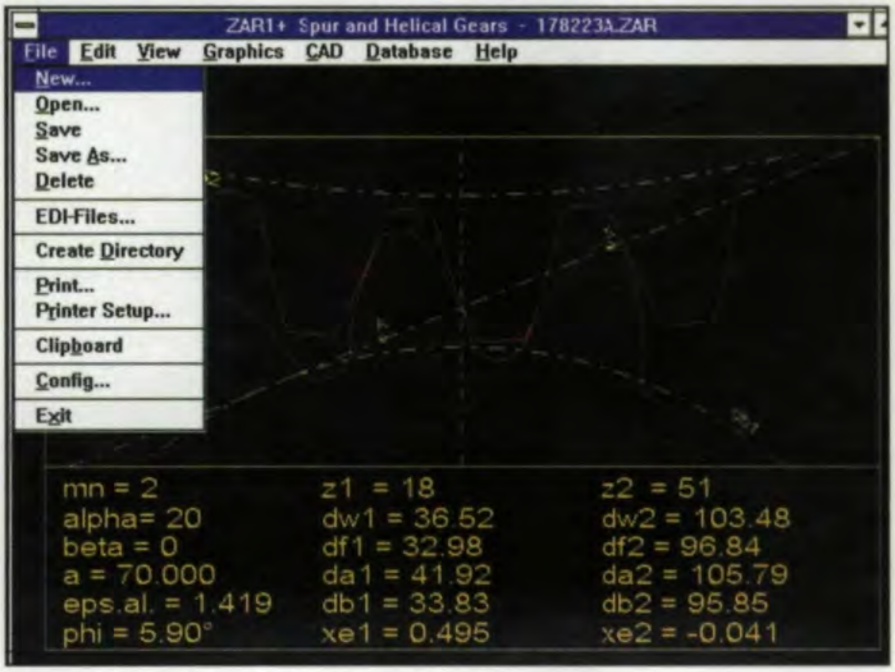
WireSize has limited error-detecting capabilities. For example, it will tell you if the calculated measurement over wires is larger than the outside diameter of the gear.

In addition, the program gives instructions to enable the person on the shop floor to make a second cut if the initial measurement over wires is bigger than the computed value. Simply enter the actual measured value, and the program will return the required depth of cut to achieve the correct measurement.

WireSize is a DOS-based program for IBM-compatible PCs, available on either 3.5" or 5.25" diskettes. It costs $25. According to the Worrall Grinding Co. Internet page, found at *http://www.snowcrest.net/wgc/software.htm*, the Windows version should be available around the time of this printing.

Gear Shareware

It seems everyone has a Web page these days. In fact, most of the software packages in this article were found by



The graphic display of *ZAR1* shows gear teeth in mesh.

WHERE TO GET THE SOFTWARE

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/software.htm

***GearCAD* includes modules for cutter design and measurement over rollers.**

doing research on the Internet. However, we were able to find only one piece of gear shareware.

GEARGEN, from ATS Software, Gouverneur, NY, was created as an aid for designing and manufacturing electrodes to cut the molds for die-cast gears. It has developed into software that can be useful in designing the gears as well.

The user can enter the number of teeth, diametral pitch and pressure angle to specify the gear he or she wants. Pressing the "Generate Gear" button causes the program to mathematically hob the gear form using the values entered. The program will return values based on ANSI B6.1-1968 and other standards for pitch diameter, outside diameter, root diameter, fillet radius and normal circular tooth thickness.

After the gear form is generated, the user can plot it on a printer or view it on screen to see the effects of changing the root radius, pressure angle or addendum. In addition, the form can be saved to disk in XY format or DXF format, which can be read by most CAD programs. Also available is a G-Code format, which can be used as toolpath instructions for a machine tool.

GEARGEN can also calculate the measurement over wires and wire sizes to be used for a given gear.

After calculating a gear form, the user can generate a second form, which corresponds to a mold cavity to be used to create the gear. This step includes an option that allows the user to compensate for shrinkage. From the mold cavity, you can generate a "cut plot," which can be used to create the EDM electrodes that will cut the cavity of the mold.

GEARGEN assumes a working knowledge of gear forms and machining operations. In many cases, the user is required to perform calculations and enter appropriate values. For example, the program offers pressure angles of 14.5, 20 and 25 degrees from the menu. While you can enter other values for the pressure angle, you have to calculate the responses yourself. However, from there, you can still have the program calculate wire sizes and mold and electrode forms.

GEARGEN is shareware, which means you can download the program in its entirety from the Internet. We found it at *http://www.shareware.com*. If you try the program and like it, a licensed version is available from ATS Software for $79.

Engineering Aids

While software can certainly help gear manufacturers by performing routine calculations on the shop floor, it can also save time and improve accuracy by helping the gear engineer perform some of the more complex calculations involved in design.

The Engineering Toolbox, from UNIK Associates, Brookfield, WI, is an electronic library of 101 programs for engineers.

The gear-related calculation modules included in the package are for helical, bevel and worm gear forces, involute spur gears, gear outside diameter, three-gear drives and worm lead.

For the helical gear force program, the user enters the input torque, pitch radius, helix angle and pressure angle. The program gives tangential force, radial force and force parallel to the axis. The results can be printed.

In addition users can view help screens that show the formulas used as well as sample input and output.

Also in the package are many generic engineering modules, including frustrum of a cone, fluid pressure on a piston, torsional stress on a shaft and Ohm's Law.

Engineering Toolbox costs $295. You can download a free demonstration version at *http://www.unik.com/unikeng.html*.

Beyond Calculation

At some point, a gear engineer needs more than a program that plugs values into formulas and spits out results. He or she needs something that will help design stronger, quieter or longer lasting gears.

One source of such gear design software is ESDU International plc in London. The company's "Data Items" are comprehensive handbooks on a variety of engineering disciplines, which are compiled from the latest standards and field data. Most of the data items are presented as printed handbooks, but many are supplemented by computer programs. The data items are available on an annual subscription basis.

Part of the company's sub-series on tribology, "Dimensions, Deflections and Stresses for Hertzian Contacts under Combined Normal and Tangential Loading" is the title of one computerized Data Item that would be of interest to gear engineers. The program locates critical stress points on rolling bearings, cams and gears for failure prediction.

The cost of the data item is $875 per volume per year, with a minimum order of $2625, which is the equivalent of three volumes for one year or one volume for three years.

ESDU also offers third-party software for the design of spur and helical gears according to AGMA, ISO/DIN or British standards. These programs are sold outright for £950 each.

Mechanical & Structural Design & Software has about a dozen gear and spline design programs that will provide complete manufacturing and inspection data, stress analysis and life ratings.

The company started writing gear software about 25 years ago, says Laszlo Keves, director of engineering. Originally programmed in FORTRAN, all programs are now written in BASIC and can be run on IBM-compatible computers.

Gear-related programs include packages for spur, helical, straight bevel, spiral bevel and hypoid gears. In addition, MSDS offers programs for simple epicyclic spur and helical gear trains, involute splines, roller bearings, threaded fasteners and helical compression springs.

The programs have very limited graphics capabilities, but the company plans to put more graphics into its software, Keves says.

MSDS software costs between $500 and $1000 per module, depending on the exact modules the customer requires.

Space Age Gears

For almost 30 years, the U.S. government has released computer software to the public through COSMIC, NASA's Software Technology Trans-fer Center located at the University of Georgia.

Software developed for use in the space program and software written at the NASA-run armed forces research centers around the country have been released over the years. In the past five years or so, some gear-related software has become available.

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OTHER GEAR SOFTWARE AVAILABLE:

For a full discussion of software not mentioned in this article see "How Many Mice Does it Take To Design a Gear" in the January/February 1995 issue.

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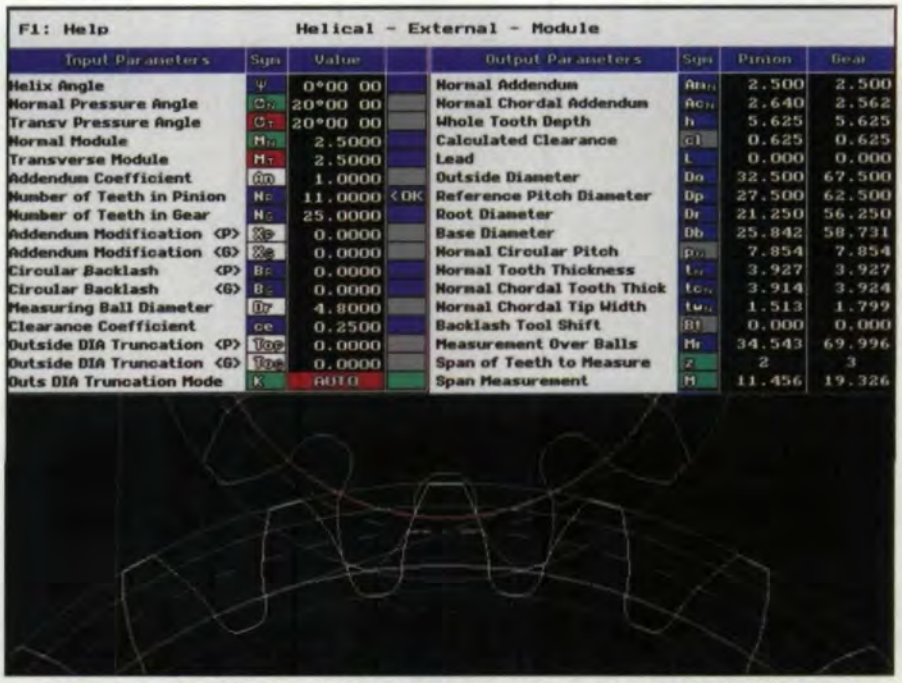
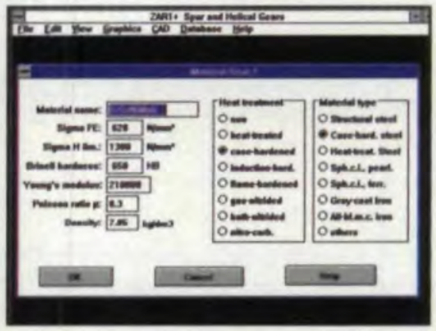


Screens from *GearCAD* (above and below, left) show gear geometry elements in different colors. *ZAR1+* comes with a materials database (below, right).



enabling optimization of transmissions during the design stage.

The analysis provided by the program is based on the two-parameter Weibull distribution lives of the component gears and bearings. Input and results can be formatted in either metric or English measurement units.

You can analyze spur, helical and spiral bevel reductions, as well as combinations of these reductions. Basic spur and helical reductions included in the program are single mesh, compound mesh and planetary gear trains. A variety of reduction types is also available for spiral bevel gear sets.

TLIFE was just released for public purchase in 1996. It is available for a variety of platforms and systems. It has been successfully implemented on IBM-compatible PCs and UNIX workstations. Cost is $500.00. Documentation, including user instructions and method of solution, can be purchased separately for $40 for evaluation purposes.

DANST (Dynamic Analysis of Spur Gear Transmissions), another NASA release, was developed in 1993. It can be used for parametric studies to predict the effect on dynamic load and tooth bending stress for spur gears due to operating speed, torque, stiffness, damping, inertia and tooth profile.

DANST calculates the properties of system components and substitutes them into the governing equations to solve for dynamic tooth loads and tooth bending stresses. The model includes driving and driven gears, connecting shafts, motor and load. The equations of motion were derived from basic gear geometry and elementary vibration principles. The dynamic solution is found by integrating the equations of motion.

DANST allows users to choose from a variety of gear materials, basic gear geometries and operating conditions. Users can also choose from a number of combinations of tooth profile variations and user-digitized profile modifications.

Three standard forms of tip relief are included among the tooth profile options.

The program is available from COSMIC for $500. It is provided in source code format so you can make changes. It runs on workstation-level computers. You may purchase the program documentation separately for $18. This will give you user instructions and an overview of the method of solution, as well as sample input and output.

Information about the NASA programs is available on the Internet at the COSMIC web site, *http://www.cosmic.uga.edu.*

Gear Design Systems

If you're looking for a complete gear design package, it might pay to extend your search outside the United States. We turned to Australia and Germany for two fairly comprehensive gear design packages.

GearCAD, by GearSoft Design, Lane Cove, NSW, Australia, is a complete gear design system written for IBM-compatible PCs. It includes calculations associated with the geometry of involute gears for the design of spur and helical gearsets. Some of the advanced features of the program include adjustable addendum, nonstandard center distance, selectable backlash, tooth sizing and load checking.

When designing spur gears, *GearCAD* allows the user to choose module, Fellows stub tooth or diametral pitch formats in external, internal or planetary configurations. The gears are graphically displayed on screen, and changing one or more basic parameters will cause the gear to be redrawn instantly.

Users can also use the zoom command to check for interference. Pressing a key will cause the gears to rotate in mesh. The display identifies each of the following by a different color: pinion, gear, pitch circle, outside/inside diameter circles, root circle, base circle, trochoidal fillet, line of action, start of involute profile circle, undercut circle, start of active profile and maximum allowable outside diameter.

"Our goal in developing GearCAD was to adopt the visual design concept," says Stan Koci, manager of GearSoft Design. "We wanted an easy-to-use program, simple enough for the occasional gear designer, but with the power for the very experienced designer."

Sub-windows include cutter selection, preliminary estimation of tooth size, center distance & gear ratio approximation, permissible load approximation, measuring roller calculation and AGMA geometry factors J and I.

The visual design concept makes the program an ideal teaching aid, says Koci. For example, if the user changes from a hob cutter to a 15-tooth pinion-type cutter, the designer can visually examine the effects on the SIP, root diameter, fillet radius and interference.

GearCAD includes many warning messages in case certain geometry parameters go outside permissible ranges. For example, if interference exists between the tips of the pinion teeth and the internal gear teeth as the teeth go out of mesh, the program will bring up a warning message that tip interference is present. Likewise, *GearCAD* will let you know if the operating pressure angle or the backlash is too large or too small.

Designs created can be printed or saved to disk in DXF or XY file format for use in CAD/CAM programs. The software comes with a detailed manual, including gear terminology, formulas used for calculations and examples of specific design problems and how they are solved with the software.

GearCAD Release 2.8 sells for approximately $1100. It is written for DOS but can be run under Windows 3.1, Windows 95 or Windows NT. A module for spiral gears is not yet completed.

Another comprehensive gear design package, *ZAR1 Gearing Calculation Software*, comes from Hexagon Mechanical Engineering Software in Germany. The program calculates geometry and strength of external and internal spur and helical gears with involute teeth in conformance with DIN 3960, 3961, 3967 and 3990.

Once the user has entered the pressure angle, helix angle, normal module, number of teeth, face width, addendum modification and center distance, *ZAR1* calculates complete gear geometry, tool dimensions and contact ratio factors.

After the basic gear design has been calculated, the user can enter a gear quality level and tolerance zone to determine the final gear data, tooth thickness, backlash and measurements over balls or pins. In addition, *ZAR1* will calculate the load-bearing capacity with respect to tooth root fatigue, fracture and pitting.

ZAR1 comes with special windows for designing planetary gear trains and special profiles. It comes with a database interface that allows the user to select materials used for making the gears. The extended version, *ZAR1+*, comes with a materials database built in. Otherwise, users can develop their own dBase-style database of materials.

The graphic display of *ZAR1* draws the gear form on screen. Users can see the tooth form as generated by a simulation of the cutting tool action. In addition, the gears in mesh can be shown in animation.

ZAR1 can be integrated with most CAD/CAM programs through its DXF and IGES interfaces. The program generates drawings of the front and side elevations of the gears calculated, as well as tables containing the gear data and dimensions.

ZAR1 runs on IBM-compatible PCs using MS-DOS 3.1 or higher. The price is $1306 for *ZAR1 or* $1450 for *ZAR1+* with the materials database included. A demo version can be downloaded on the Internet at *http://www.hexagon.de/zar1_e.htm.* There you can also find information about distributors of the software and additional programs available, including *ZAR2*, a similar program for bevel gears that sells for $1033. ✪

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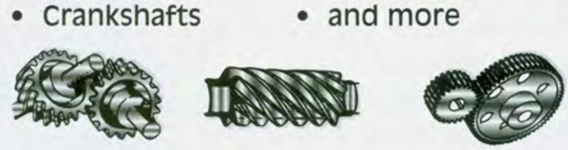

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Shifting Gears – Exploiting the Potential of Plastics

Zan Smith & Maribeth Fletcher

Injection molded plastic gears have come a long way. Historically, they were limited to very low power transmissions such as those found in as clocks, printers and lawn sprinklers. More consistent engineering polymers and better control of the molding process now make it possible to produce larger, more precise gears which are compatible with higher horsepower. Whirlpool enhanced a 3/4 hp drive for a washing machine with a spin gear molded in fiberglass-reinforced acetal copol-ymer. The molded plastic gear cost about a fifth of what the original machined metal gear cost and made the drive lighter.

As the experience base with plastic gears has grown, computer-aided design tools have advanced. For instance, CAD software can now optimize plastic gear designs based on temperature, moisture pickup and other factors.

Payoff and Potential

Typically, gears are a means of positively transmitting uniform motion with constant drive ratios. Thermoplastic and thermosetting polymers have long provided alternatives to metals in low-powered, unlubricated gear trains. Gears machined from phenolics and other thermosets can be used at higher operating temperatures, and they are more resistant to the lubricants which are generally required. However, injection-molded thermoplastic gears have better fatigue performance, and unlike those manufactured from thermosets, can cut manufacturing costs significantly compared with metal gears. Thermoplastics are now finding their way into applications demanding lubricated drives, higher horsepower and higher AGMA quality standards.

For the drive designer, thermoplastic gears offer powerful advantages over metal and thermosets. They enabled the maker of a gearmotor drive for a convalescent bed to eliminate powder metal gears and reduce the part count from three to two. The acetal gears reduced noise, improved durability and cut total drive costs by one-third compared to the original design.

Injection molding is fast and economical compared with hobbing teeth in metal blanks. Plastic gears usually can be used as-molded and require no finishing. Consequently, they have a significant cost advantage in production quantities. The cost of plastic alternatives can be one-half to one-tenth that of stamped, machined or powder metal gears, depending on the manufacturing technique. For example, the manufacturer of a damper actuator for heating, ventilating and air-conditioning systems calculated that 14 acetal copolymer gears in the gear train cost half as much as comparable metal gearing.

Fig. 1 — Hewlett-Packard took plastic gears to AGMA class Q9 to give its new color printer precise paper motion. For gears of this size, 1.25" in diameter and 48 pitch, the AGMA Class Q9 denotes gears with a Total Cumulative Error (TCE) of just 0.0015" and Tooth-To-Tooth (TTT) error of 0.00071".

Plastic gears are also inherently lighter than metal. The specific gravity of steel is 7.85, while the specific gravities of glass-filled nylon 6/6 and low-wear acetal copolymer are close to 1.4. Differences in specific gravity alone, however, are not direct indicators of weight saving, among other reasons, because to transmit the same power, plastic gears must usually be larger than metal gears. Yet once trade-offs in size and power are made, plastics lend themselves to innovative gear designs and smaller, lighter drivetrains. For example, compact, split-path planetary drives, which are rarely considered by designers because they demand greater numbers of expensive metal gears, can be made at lower cost than multi-stage spur drives.

Quiet and Smooth

Low coefficients of friction further help to minimize wear. Lower friction also means less horsepower wasted in heat. Plastic gears consequently lend themselves to gear trains where the use of grease must be avoided, such as laser printers or motorized toys.

Unlubricated gears can simplify drive design, but plastic gears can also operate with and benefit from lubricants when necessary. A major automotive supplier, for instance, eliminated squeaks and wear in motorized car seats by replacing metal seat adjuster gears with those molded in acetal

Fig. 2 — In the "World Washer," manufactured in several countries, Whirlpool Corporation introduced a splined clutch or "splutch," containing a spline and gears molded in acetal copolymer. The low-wear epicyclic gear assembly lasts four times normal washing machine life and reduces the number of moving parts by 20%.

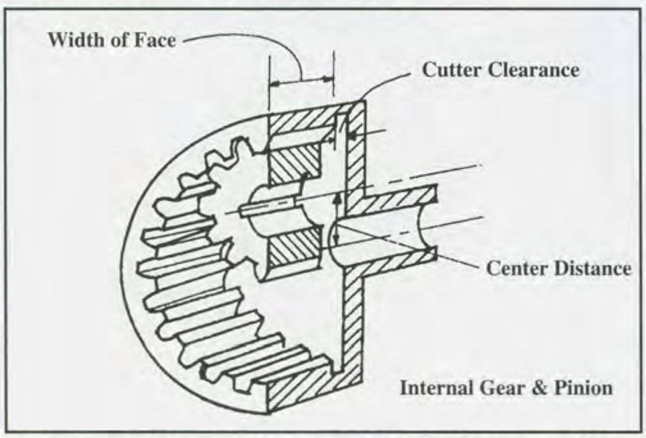

Fig. 3 — Internal gears are as easy to mold in plastic as external gears. They provide a means to reduce center distances and pack high power densities in a small space.

copolymer compatible with lubricants. Oil bath lubrication also enables designers to exploit the added strength of glass-filled plastic gears without excessive wear.

Plastic gears provide the opportunity to cut drive noise by reducing dynamic loading. Gear misalignment and small tooth errors create tiny impacts resulting in running noise. However, lower modulus plastic gear teeth deform to compensate for the inaccuracies and their softer material absorbs impacts, making plastic gears quieter than metal. Depending on the application, plastic gears can be quieter than expensive metal gears which are one or two AGMA classes higher in quality.

Powerful Potential

The most powerful advantages of plastic gears may be the design opportunities they afford. Gear geometries overlooked by designers accustomed to metal are easy to mold in plastic, and they can reduce drive size, weight and cost. For example, a common arrangement of two external spur gears with a large ratio demands a wide center distance. The same ratio can be achieved in a smaller space by replacing an external gear with an internal gear (Fig. 3). Internal gears, tough to machine in metal, are easy to mold in plastic.

Low cost, low wear plastic gears may also allow designers to reconsider the old axiom: The fewer parts, the better. Split-power paths in parallel or non-parallel axis drives can indeed have more parts, but they afford advantages in space, weight, efficiency and cost. Plastic gears impose no special restrictions on gear ratios, and the required accuracy can be achieved with today's molding machines and materials.

The more powerful the drive, the more complicated will be the up-front design effort required to make plastic gears work. The state of the gear art has advanced to where plastic gears are now in drives from 1/4 to 3/4 hp. Future applications may take them between 1 and 10 hp in the near-term and up to 30 hp in the long term. Horsepower limits for plastic gears vary with the polymer, depending upon the modulus, strength and creep characteristics which all change with temperature. Nevertheless, plastic gear limits can be defined broadly by K-factors and unit loads at ambient temperature. Depending on the polymer, reinforcement and lubrication, plastic gears are broadly compatible with K-factors of 30–200 psi and unit loads of 400–2,000 psi.

Plastic gear trains are generally built around involute gear technology. This system is very forgiving of the center distance shifts inherent in plastic gears but non-involute systems, which are center-distance sensitive, are not good candidates for plastic gears. In particular, many non-parallel axis systems are not based on involute technology and are difficult to manufacture with plastic gears.

Bevel gears are an exception. They are non-involute, but often made of plastics. The low modulus of plastics makes them relatively forgiving of the alignment errors inherent in mass-produced bevel gears. Crossed-axis helical worm gears which make point-contact when new are good candidates for plastic at low loads. Their capacity is increased by initial wear, which produces a line contact. Involute face gears have a line contact and are preferred to worm drives at higher power levels.

To Lubricate Or Not

As engineering resins now move into drives with higher horsepower and greater precision, the drive designer faces the choice of oil- or grease-lubricated or unlubricated gearboxes. This decision and the choice of a lubricant are key factors for the drive designer to consider.

For plastic gears running in an oil bath, the oil facilitates removal of frictional heat and allows higher load capacity. Unlubricated and greased gears are aerodynamically cooled and therefore run hotter with lower load capacity. Unlubricated gear sets are often molded in different materials for reduced coefficient of friction (COF). Acetal copolymer gears are often mated with those made of nylon 6/6 or polyutylene terphthalate, as these combinations have much lower COFs than sets of any of these materials working alone. Unlubricated plastic gears often have lubricants such as PTFE, silicone or graphite compounded into the polymer. While these additives reduce the coefficient of friction (COF), the COF is still higher than that of greased gears.

Generally, the load capacity and life of lubricated plastic gears is governed by bending fatigue at the tooth root. Unlubricated gears, which run hottest with the lowest load capacity, often fail by wear or overheating on the tooth flanks. Greased gears will occasionally fail by wear if the grease does not stay in the mesh.

While engineering resins can resist oils and greases, lubricants must be carefully chosen because some can cause dramatic changes in gear properties and dimensions. For example, extreme pressure oils are unnecessary with the low contact pressures found in plastic gearing, and some can attack plastics chemically. Likewise, the choice of resin for the application is important. PTFE and other low-friction additives compounded in the material of plastic gears may have little value or negative value if the gears are oiled or greased.

In The Know

Plastics are naturally more prone to dimensional creep than metal, and creep in plastic gears depends on their duty cycle and temperature. Consequently, molded gears are best used in applications without static loads. If static loads cannot be avoided, plastic gears must be designed to operate properly after teeth have deflected due to creep.

The operating speed of plastic gears obviously impacts operating temperature. However, rapid loading rates can also affect material properties. For some materials, the faster a tooth is loaded, the higher the effective modulus and strength. Higher temperature reduces the modulus and strength of most plastics and accelerates creep. These effects must be considered in the design process, and studies to quantify them are just beginning.

Gears also usually demand more precision than commonly molded parts, so their tooling can be expensive. A good plastic gear design, however, saves money by reducing trial-and-error mold iterations. For the project engineer, building a drive with plastic gears ideally should start with a team including a designer, molder, tool builder and resin supplier, all experienced with gears.

The team needs the most complete application information available to create the most detailed gear specification possible. Ambient temperature, lubrication and duty cycle all impact gear life and drive performance. A housing material which matches the thermal and moisture expansion of plastic gears can help maintain precise center distances. However, plastic housings cannot dissipate heat as well as metal. Gear swelling due to moisture absorption in some resins can also stall tight-meshed gears. Computer-aided design tools can help designers allow for worst-case tolerances.

Driving Design

Plastics also change the rules of gear and drive design. The designer of a metal pinion gear would normally limit the aspect ratio to one or less. With plastics, an aspect ratio of two or three may be acceptable as full tooth contact may be achieved. Plastic gears can require tip relief unnecessary in metal gears. The lower mesh stiffness of plastic teeth

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requires more backlash than found in metal gears. A hunting ratio considered desirable in many metal gear trains to equalize wear may accelerate wear with plastic gears. The guidelines for metal gear design must be examined carefully before applying them to plastic gears.

The rack tooth form remains a convenient way to define and generate gear teeth in metal or plastic. Standard metal gear profiles can provide a starting point for plastic gears, although there are some plastic profiles which are preferred.

Most profiles are based on a 20° pressure angle and a working depth of two over the diametral pitch or two times the module. However, the profile needs to be optimized for a material with a lower modulus, greater temperature sensitivity and different coefficients of friction and wear than metal.

Plastic gears commonly have greater working depths than metal gears, sometimes up to 35% greater. This allows for variations in effective center distance caused by thermal, chemical and moisture expansion. The designer of plastic gears should strive for a full root radius not only to reduce stresses at the root, but also to enhance resin flow into the teeth during injection molding, which reduces molded-in stresses and removes heat more uniformly from the plastic during solidification. A more stable geometry results.

The designer of plastic gears also should pay special attention to shaft attachment. Bore tolerances naturally impact true center distances, sometimes resulting in loss of proper gear action. A simple press-fit demands extra molding precision for a secure mount without over-stressing the plastic. A press-fit knurled or splined shaft can transfer more torque, but also puts more stress on the gear hub. Insert-molded hubs grip better, but during molding, as the plastic shrinks onto the shaft, they can induce residual stresses. Ultrasonic insertion of a knurled shaft produces the lowest residual stresses. A single- or double-D keyed shaft prevents slippage and minimizes distortion with assembly in some cases. However, if torque is high, these can become loose. For high torque applications, splined assemblies are preferred.

Table 1 — Typical Print Data for A Molded Spur Gear

Part No.	
Mating Gear Part No.	
Material	Inspection Data
	AGMA Quality No.
Number of Teeth	Measured Tooth Thickness W/Pins
Diametral Pitch	Size over X Pins of 0.X" Diameter
Module	Radial Runout (TIR)
Pressure Angle	Pitch Variation
Base Ptich	Tooth Alignment
Reference Pitch Diameter	
Effective Tooth Thickness @ Ref PD	Master Gear No.
Face Width	xx Teeth—Class 1A
	Gear Test Radius
Outside Diameter	Test Load
Effective Outside Diameter	Tooth-to-Tooth Composite
Roll Angle @ Effective OD	Composite Minimum Fillet Radius
Normal Tooth Tip Radius	
True Involute Form Diameter	Basic Generating Rack
Roll Angle @ TIP	Flank Angle
	Tip to Reference Line
Root Diameter	Tooth Thickness at Reference
Base Diameter	Tip Radius

Molded In What?

The choice of a gear resin also demands careful study. Less expensive commodity resins generally lack the fatigue life, temperature resistance, lubricant resistance and dimensional stability required for quality plastic gears in all but the most primitive applications. However, many of today's engineering resins provide the necessary performance for working gear trains.

It is generally easier to mold high-quality gears with resins containing minimal additives than with highly filled blends. The specifier should call for only as much glass or mineral filler or lubricant additives as are actually needed. If external lubrication is required, the drive designer, resin supplier and lubricant supplier should work together to select an appropriate lubrication system.

Most gear applications use the crystalline resins nylon and acetal because they have better fatigue resistance than amorphous plastics. Nylon, both with and without glass reinforcement, continues to serve in many gear and housing applications. However, it is moisture absorption prone, and consequent shifts in properties and dimensions have pushed many designers to acetal. Acetal copolymer does not absorb moisture and therefore provides long-term dimensional stability and exceptional fatigue and chemical resistance over a broad temperature range.

Other resins have found limited gear success. ABS has good dimensional stability and low shrink out of the mold, but its fatigue characteristics make it suitable only for light loads and short service life. Liquid Crystal Polymer (LCP) has exceptional dimensional stability and fills the most intricate molds. To date, LCP has been used for only small precision gears under light loads, such as tiny wristwatch gears. Linear polyphenylene sulfide (PPS) has exceptional temperature and chemical resistance and good fatigue life. It has been effective in other highly loaded parts molded with fine details and should prove to be a high-performance gear material. As plastic gears move into higher loads with larger gears in lubricated environments, the improved fatigue resistance and dimensional stability of long fiber-reinforced plastics should make these materials leading gear candidates.

Specify and Mold

Gear resin selection requires the designer to focus on resin performance at the high end of the operating temperature range planned for the drive. Heat deflection temperatures for engineering resins range from 170°F for unfilled nylon and 230°F for acetal copolymer to 500°F for reinforced linear PPS at 264 psi. However, higher temperatures lower both the modulus and strength of gear resins. They increase creep rate and introduce thermal expansion into precision parts. Fortunately the temperature response of engineering resins is well understood, allowing designers to predict the effect on their gears.

For the gear molder, uniform mold flow and cooling is essential to the fabrication of accurate gears. Uniform cooling from cavity to cavity is also critical for consistent quality gears. The best approach for precision gears is a single-cavity mold, but it is rarely cost-effective for production. Multi-cavity molds can create minor differences in flow patterns and major variations from part to part. The more mold cavities, the greater the potential variation. Four cavities is generally the maximum allowable for molding precision gears.

Three-plate tooling with small pin gates on the gear web is common for molding most small gears. However, larger gears with heavier teeth can require center diaphragm gating for better dimensional control and higher quality.

Whatever the mold, gear teeth should be cut in an insert, not integral to the mold cavity. Gear designers and molders are almost guaranteed to replace the tooth profile once or twice in the gear prototyping evolution to get it right. Interchangeable ring inserts make refining the tooth profile faster and less expensive.

Smooth Mesh

The initial engineering effort to design plastic gears is greater than that required with metals, if only to cope with changing properties and dimensions. The most common errors of plastic gear designers start with insufficient application specifications. The specifics of the application must be factored into detailed drawings before prototyping. The drawings must contain sufficient information to manufacture the gear. (See Table 1.)

Problems with prototypes can also tempt gear designers to change resins, a costly mistake, given the different shrink characteristics of various plastics. It is better to rework the tooth profile than switch the material unless it is clear that the wrong material was chosen.

Expertise to avoid the pitfalls of plastic gears is available from gear consultants, software and resin suppliers. With careful design and material selection, the power transmitted by plastic gears can be significant, and the potential savings enormous. ○

Acetal copolymer gears in a dual drive washer transmission developed by Maytag.

Zan Smith *is a staff engineer with Hoechst Technical Polymers, working with customers to develop gear applications with the company's resins. He holds a doctorate in mechanical engineering and is the author of numerous books and articles on plastics and gearing.*

Maribeth Fletcher *is a Celcon® market program development executive with HTP. She is responsible for bringing new acetal copolymer applications to market.*

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IN MEMORIAM

Dr.-Ing. Karl Stölzle of Munich, Germany, in April of this year. Dr. Stölze's career in gear engineering spanned more than 50 years. He worked for companies such as RENK AG, Höfler Maschinenbau, where he served as managing director, and SSS Clutches. He was also one of the partners in AG Consulting, Munich, which specializes in gears and power transmission systems.

Chris Haeni, a sales engineer with **Koepfer America**, South Elgin, IL. Mr. Haeni served his apprenticeship with Mikron Corp. of Biel, Switzerland. He came to the U.S. in 1974, where he has worked for ITW and Reishauer. He earned a Bachelor of Science degree from Elmhurst College, Elmhurst, IL and joined Koepfer in 1993.

NEW AGMA PUBLICATION

The AGMA Foundation has a directory of gear schools, seminars, and courses for the gear industry called "Education & Training for the Gear Industry." Programs offered by both technical organizations and individual companies are included. Available from AGMA headquarters, the book describes courses and seminars on basic and advanced manufacturing, cutting, finishing, inspection and testing, lubrication, metallurgy, corrosion and quality control.

THE WINNER'S CIRCLE

Liebherr-Verzahntechnik of Kempton, Germany, is the first European machine tool manufacturer to earn the Ford Q1 Preferred Quality status from Ford Motor Company. The company also recently has been ISO-9000 certified in Germany . . . **Welduction Corporation**, Farmington Hills, MI, was granted ISO 9001 certification in September of 1996. . . . **Brown & Sharpe** has been included in *World Trade* magazine's list of the top 100 high-technology exporting companies in the U.S. . . . **Regal-Beloit Corp.** was recently ranked 130th in *Forbes* magazine's list of the 200 Best Small Companies in America . . . **National Broach** has been named Supplier of the Quarter by **New Venture Gear**. The company is the first perishable tooling supplier to be chosen for this award. National Broach supplies shaving cutters, broach tools and related machines.

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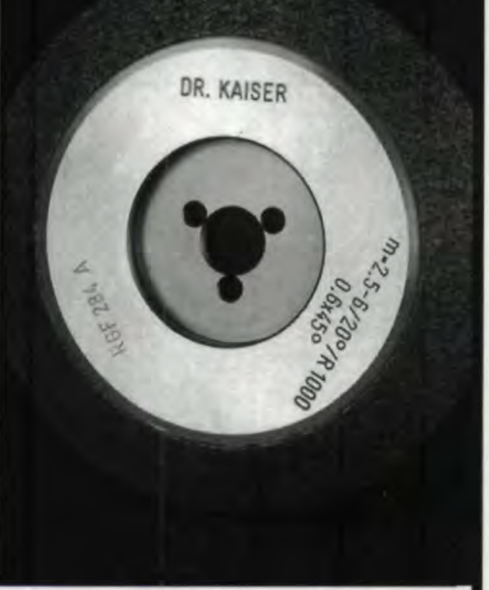

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Costimator Version 5.1

Manufacturers Technologies Inc. has released Version 5.1 of the Costimator® computer-aided cost estimating system, which simultaneously produces estimates and process plans for virtually any part or assembly. The latest version is designed for Windows 95 and Windows NT and can operate on Windows 3.1. The system is in 32-bit architecture compliance with Open Database Connectivity Standards, permitting implementation of a client/server database and easy integration with other manufacturing management systems. Version 5.1 offers a variety of new features, including an expanded materials database, a customer database and a purchased parts database.

Circle 306

Fatigue Calculation Program

NASA's Software Technology Transfer Center announces the availability of FATPLUS, an automated fatigue calculation program, which makes it possible to cross-check fatigue life calculations based on proprietary methodology and to locate parts, components and subassemblies where fatigue problems may occur. Written in Microsoft FORTRAN for IBM PC-compatible computers running MS-DOS.

Circle 307

Software for CMMs

Measure Manager DCC from Starrett is a software package for direct computer-controlled coordinate measuring machines. It is a 32-bit software system with an operating environment that satisfies all skill levels. Operators may choose from three levels of operation, depending on the complexity of the application and user preference. It is possible to work with all three levels simultaneously. The system also contains a CAD Viewer, which allows CAD files to be directly imported in a variety of formats.

Circle 308

MasterControl™ Version 3.0

MasterControl 3.0 from Document Control Systems is document control software that helps organizations achieve ISO/QS 9000 certification. This newest release also includes complete e-mail interfaces for MS Mail, cc:Mail and Novell's Groupwise. It also offers improved reporting and new electronic release capabilities. It is designed to meet all document control requirements of ISO 9000, QS-9000 and FDA GMP standards. Among its other capabilities are electronic routing and approval, viewing and comment, automated document release and distribution and in-process tracking of approval documents.

Circle 309

To get more information on these items, please circle the Reader Service Number shown. Send your new product releases to: *Gear Technology*, 1425 Lunt Ave., Elk Grove Village, IL 60007, Fax: 847-437-6618.

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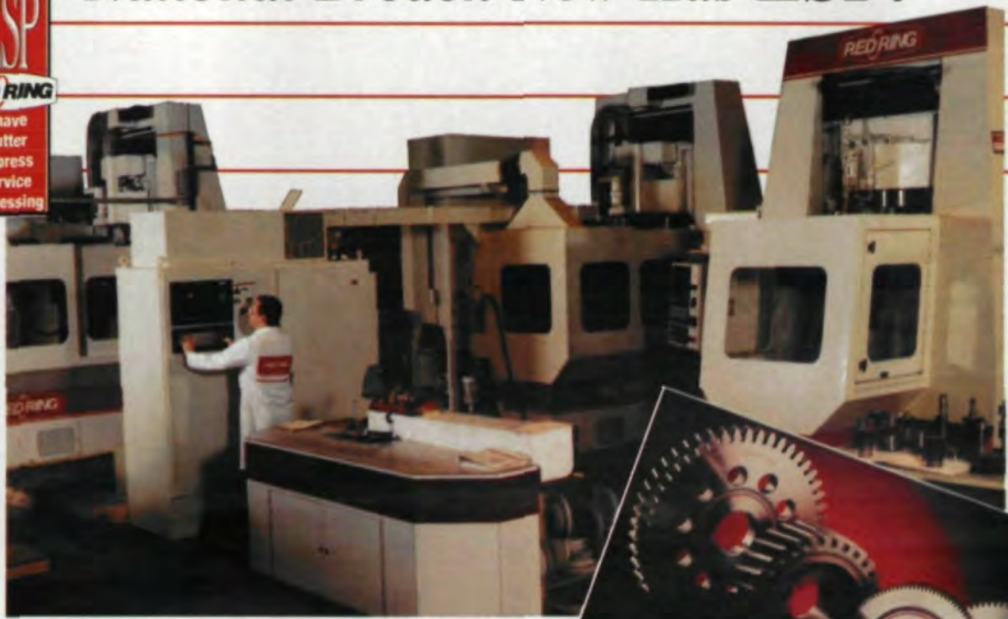

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CIRCLE 148

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LITERATURE MART

ADVERTISING SECTION

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Calculating Gears

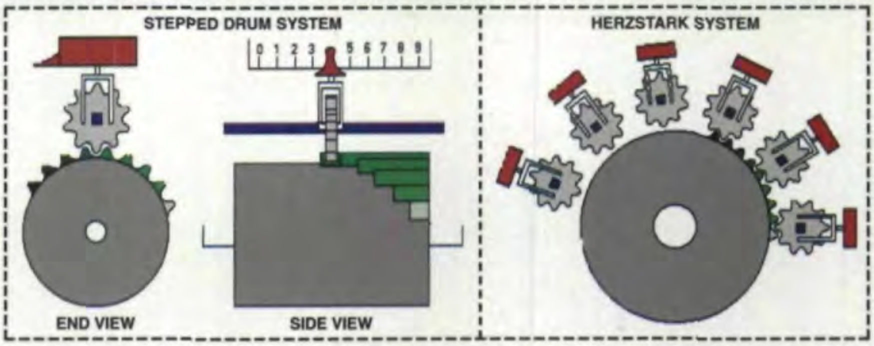
Gear Technology's bimonthly aberration — gear trivia, humor, weirdness and oddments for the edification and amusement of our readers. Contributions are welcome.

Interesting gear factoids discovered wasting time on the Net while pretending to be working . . . The first four-function mechanical calculator was built by the mathematician Gottfried Leibniz in 1694. While not commercially available for nearly 200 years, the design was the basis of many such calculators until well into this century.

What caught the Addendum staff's attention was the gear problem presented by the mechanical calculator: How to move the gear an amount proportional to the number to be added. A number of solutions were tried at various times.

The first was the use of rocking segments. This system is a kind of curved rack and pinion arrangement. The rocker (rack) had nine teeth that meshed with a pinion. The operator would strike a key and turn a crank, engaging the pinion, which would move the rocker segment up until it hit the key's stop. When the crank was returned to its original position, so was the rocker, and the pinion disengaged so the return stroke wouldn't subtract the digit just added.

The second system was the stepped drum approach developed by Leibniz, although a man named Charles X. Thomas was the one who made it commercially viable. It solved the problem by using a drum on which cogs of varying length (one for each number between one and nine) were attached. A gear was attached to a pointer, which the user could move to the desired digit on a numbered dial. The gear would move along the drum's length and engage the appropriate cog. For example, if the user set the point to four, the gear would miss all the cogs shorter than the fifth one.



A refinement of this system was developed by Curt Herzstark. He used a counter gear, which rotated based on its position along the length of the drum for each number. This led to a design that was simpler, smaller and less likely to jam.

(The Addendum staff thanks David Hicks, who provided this information and lots more on his Web page, The Museum of HP Calculators at *www.teleport .com/~dgh/mechwork.htm.*)

The Entertainment Section

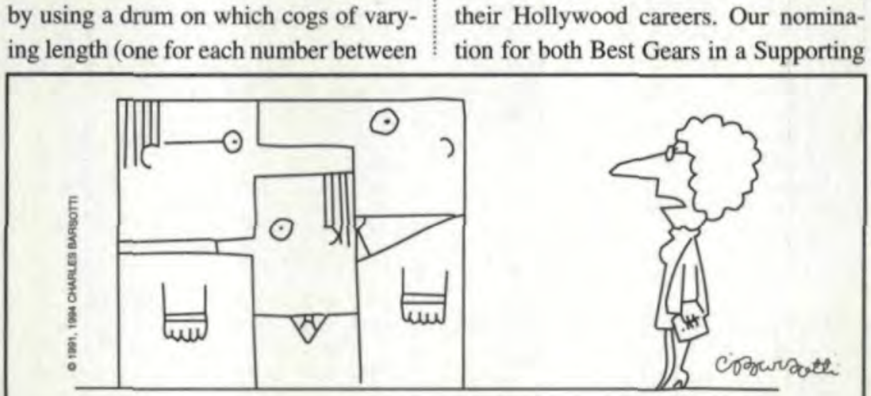
When we're not surfing the Net in search of gears, we're still following their Hollywood careers. Our nomination for both Best Gears in a Supporting Role and Best Gears in a Family Movie goes to "Beauty and the Beast" (1991). For those of you who have been a) living on another planet, or b) have no children, grandchildren, nieces, nephews, or young friends of any variety, we're referring to the animated version of the story from the folks at Disney.

In the first 10 minutes of the film, there are at least three scenes with gears in them.

First are the almost inconspicuous gears attached to the weathervane on top of Belle's father's house. This clever contraption appears to be some sort of windmill generator, and its artistic placement here in the opening scenes provides subtle clues about the mad inventor (a gear engineer?) who lives inside.

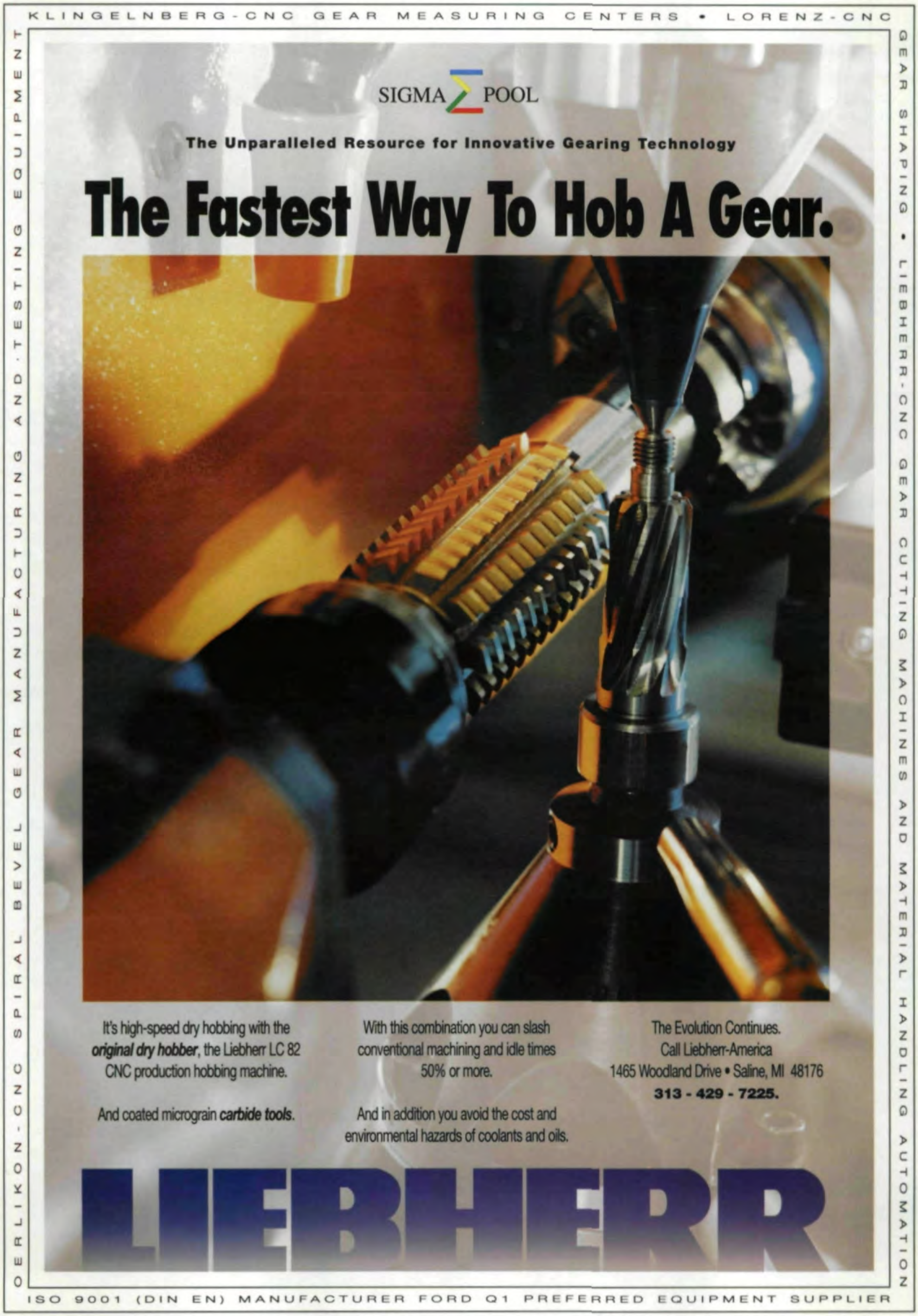
The gear motif continues inside the inventor's house, when we see his latest contraption, an automatic wood chopping machine, which has a spur gear set prominently placed on the outside of the machine.

Finally, in a very dramatic scene, Cogsworth (an animated clock) is knocked down the staircase by his angry master, the Beast. All sorts of spare parts pop out of Cogsworth's case when he hits the floor. Never before has a gear demonstrated such anguish, such pain, such frustration. . . Rating: OOO.



"Gentleman, can we stop networking long enough to get some of the work done around here?"

The Addendometer: If you've read this far on the page and enjoyed it, please **circle 225.**



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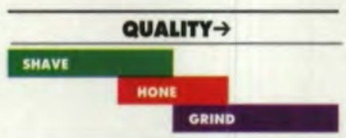

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