GEAR TECHNOLOGY

NOVEMBER/DECEMBER 2006

The Journal of Gear Manufacturing

www.geartechnology.com

STATE OF THE GEAR INDUSTRY

- Results of our Research

TECHNICAL ARTICLES

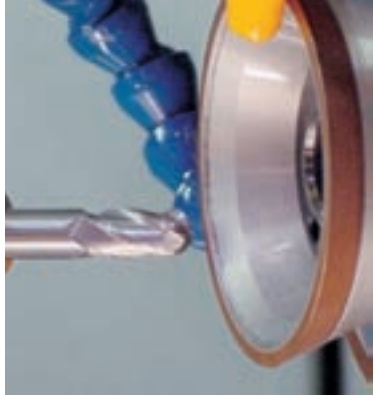
- Characteristics of Master Gears
- Optimization of Profile Grinding
- Selecting Thermoplastic Materials

THE GEAR INDUSTRY'S INFORMATION SOURCE

Grind with the experts







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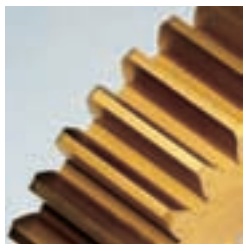
Shave with the experts











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NOVEMBER/DECEMBER 2006

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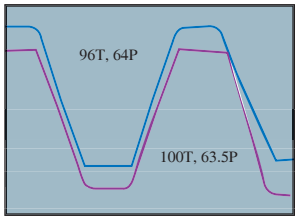

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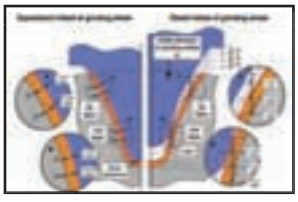

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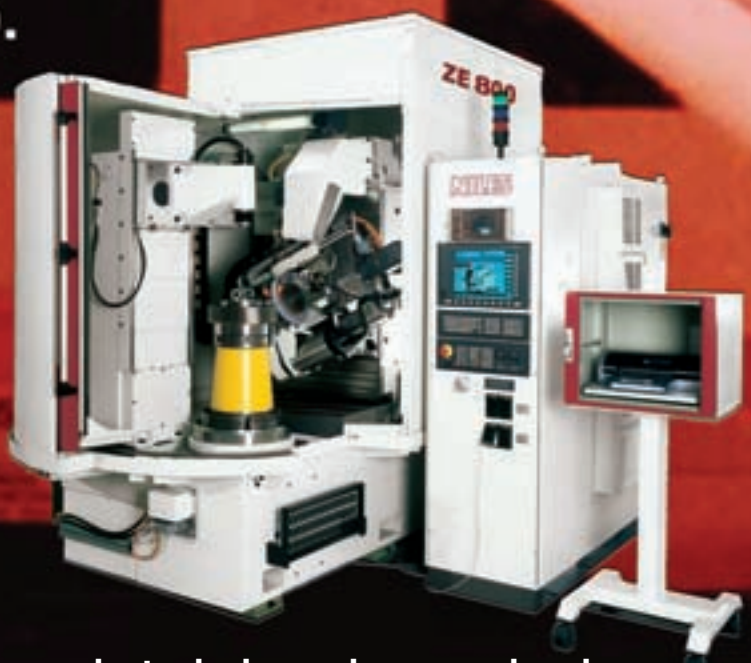

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The Journal of Gear Manufacturing

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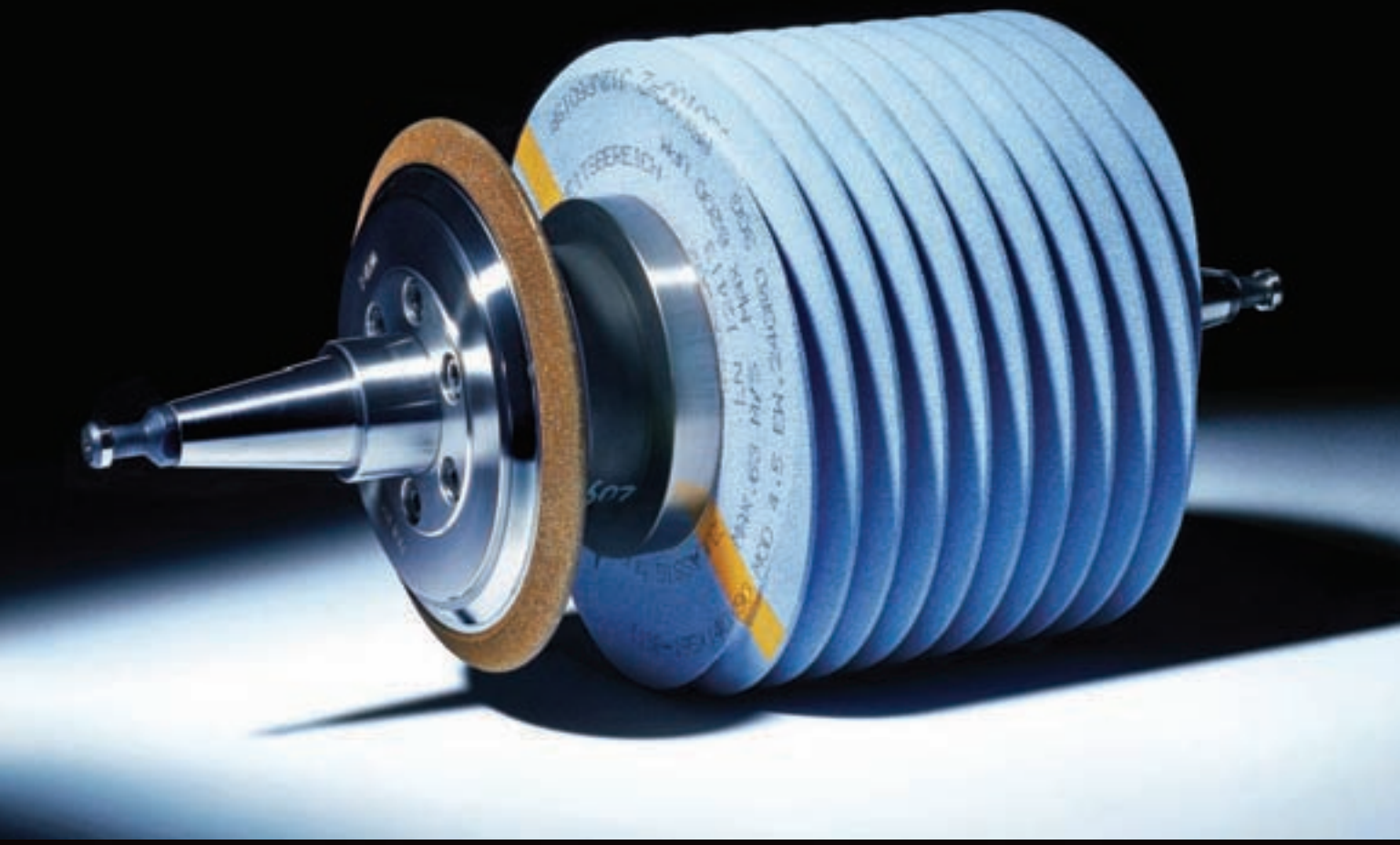

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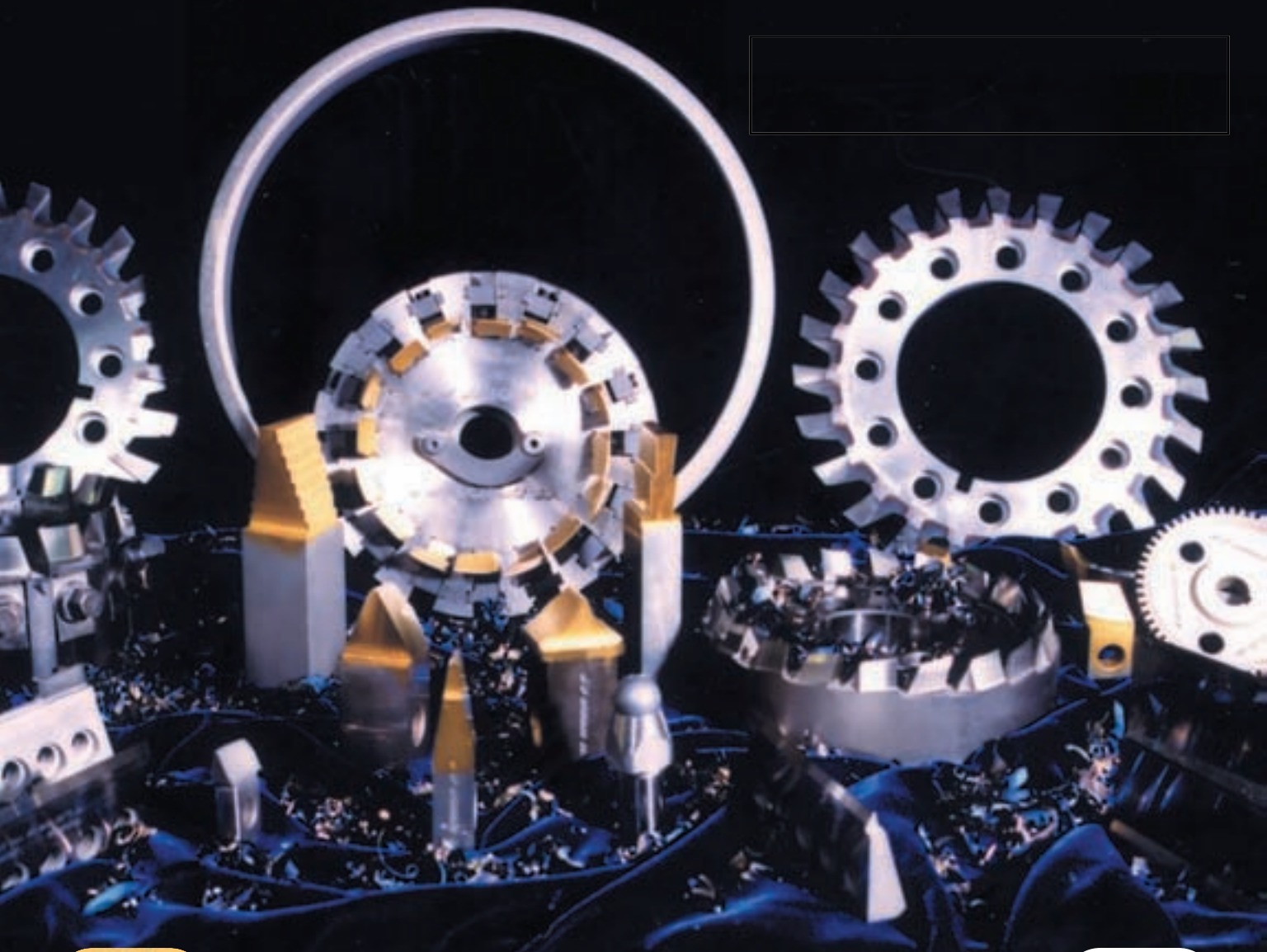

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Coming Soon!

The New Gear Technology–Bigger! Better! More Often!

Psst! Hey buddy, can you keep a secret?

For some time there've been rumors coming out of the Randall Publishing skunkworks. People have been curious about the lights being on at all hours of the night. Until now, only hints have escaped the locked doors and closed blinds about what's going on over there.

Well, I've been inside, and I know what they're up to. Don't tell anyone, but the folks at *Gear Technology* are planning all kinds of changes, including a major redesign—the first in more than 10 years and only the third in the magazine's 23-year history.

I'm not supposed to be telling you this yet, but I can't keep it a secret any more. They've kept it pretty well under wraps, what with all the clandestine meetings and such, but just between you and me, this project is much further along than anyone has let on. In fact, *Gear Technology's* redesign is scheduled to launch with the January/February 2007 issue.

The staff at *Gear Technology* is doing its best to keep this thing quiet, but the excitement about this new project is obvious. The whole place is abuzz with redesign fever, and the buzz words seem to be "BIGGER," "BETTER" and "MORE OFTEN."

Everyone's talking about bigger ideas, bigger photos, and a bigger presence than the magazine already has. The editors mean to bring readers more in-depth features, more quality technical articles and more relevant news and product information than ever before.

Now, remember, you didn't hear this from me. But those of you who advertise in *Gear Technology* will be interested to learn that the magazine's staff is also talking about bigger and better circulation. They're saying that the electronic version of the magazine has really taken off (nearly 3,000 electronic subscribers*), and they're planning to do even more international mailing in 2007. In fact, they're planning to blanket China and India with bonus distribution of the January/February and May 2007 issues, respectively.

But bigger isn't good enough for *Gear Technology*. The editors and staff want to make the magazine "better" as well. They're working on everything, including the cover design, the layout, the content and the subjects covered. They're doing everything they can to make the best magazine even better.

Fans of the old version need not worry, though. These people haven't forgotten where they came from—far from it! They're working on improving all the things that have set *Gear Technology* apart over the years, like the top-notch, peer-reviewed, unbiased technical articles; the timely, relevant, well-researched feature articles; the best news sections in the business; and a qualified and audited circulation of subscribers who request the magazine.

The secret's also out on what the *Gear Technology* staffers mean by "more often." *Gear Technology* will be published eight times in 2007 instead of just six. The schedule will run something like this: January/February, March/April, May, June, July, August, September/October and November/December.

* Statistics based on publisher's own data.

I wanted to smuggle out a mock-up of the first issue so you could see *Gear Technology's* new look, but the staff has been very protective about the redesign, and I didn't want them to know who leaked this information. But I've seen it, and I have to tell you that the new look is inspiring. The new *Gear Technology* is going to be sleek, clean and professional. Its powerful presentation will be easy to read and pleasing to the eye, with great photography and graphics.

All of these changes will also be reflected online at *www.geartechnology.com*, where they're getting more than 30,000 unique visits per month.

Many of you may be wondering what's happening with the second magazine, *Gear Product News*. It was announced at IMTS that *Gear Product News* would publish its last issue in December 2006. Strangely, though, there's been an awful lot of activity in that section of the building as well.

This next part was supposed to be a surprise, but as long you've got me spilling secrets, I might as well tell you that the *powertransmission.com* people have taken over the space that used to be occupied by *Gear Product News*, and they're planning to launch a *powertransmission.com* printed magazine in the Spring. It makes sense, if you think about it. *powertransmission.com* will celebrate its 10th anniversary in January, and we've been getting loads of traffic—75,000 unique visits per month—including buyers of gears, bearings, motors and other power transmission products all that time. The new magazine will take the same unbiased, educational approach that has served *Gear Technology* so well all these years.

The target audience for *powertransmission.com* magazine will be design engineers, maintenance and facility managers and purchasing professionals, just like the website. If you're a gear manufacturer looking for new customers, *powertransmission.com*—in print or online—is just the right vehicle for you.

By the time you read this, there will even be a space on the website where you can sign up to receive the new magazine. Just go to *www.powertransmission.com*. The link will be right there on the home page. You can't miss it.

I hope you're as excited about these new changes as I am. I'd love to be able to tell you more, but I'm afraid someone might find out about our little conversation here. Besides, you'll see it for yourself next issue.

If anybody asks, you never saw me here.

Michael Goldstein
Publisher & Editor-in-Chief

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Affolter Introduces Gear Machines for Watches & Medical Instruments

Affolter Technologies SA of Malleray, Switzerland, has introduced a new line of gear hobbing and micro-milling machines for the manufacture of small gears, worms and similar parts used in watches and medical and dental instruments.

The Gear AF100 gear cutting center, introduced a year ago at EMO, is an eight-axis CNC gear hobbing machine for cutting parts up to 36 mm diameter and 50 mm length. The machine can cut spur, helical, tapered or convex teeth on gears, shafts and pinions, either by hobbing or tooth-by-tooth using an indexed milling cutter.

Parts are held between centers and are direct-driven by two independent motor spindles. The cutting tool is driven by a third motor spindle. All three spindles are electronically synchronized, with rotation speeds of up to 16,000 rpm.

The Gear AF110 micro-milling center, introduced in September at the AMB show in Stuttgart, Germany, is designed for gear hobbing, screw cutting and micro-milling.

The AF110 is also capable of hobbing gears up to 36 mm diameter and 50 mm length. However, unlike the AF100, the AF110 has no tailstock motor spindle, which allows the cutting spindle to be inclined up to 90° for machining worms, straight bevel or face gears, bone screws and other medical or dental tools and parts. With the AF110, the part is collet-clamped and may be supported by a tailstock center, steady rest or guide bushing.

Both machines have mineral-cast frames, designed to provide thermal stability and vibration absorption. All linear axes have direct measurement scales for positive feedback, with system resolution less than 1 µm.

Affolter has developed and built machine tools for more than 10 years, says Raymond Graf, sales and marketing manager. But until recently, those machines were manufactured for the use of sister company Affolter Pignons SA, a manufacturer primarily serving the Swiss watch industry.

Affolter Pignons, which today manufactures more than 30 million gear trains per year, created its own demand for new and updated machine tools. So, in 1991, Affolter Pignons started up a new, separate company to develop its machine tool capabilities. That company is now Affolter Technologies SA. In the beginning, Affolter Technologies worked mainly on machine retrofits, working with lathes and gear hobbing machines.

In 1996, Affolter entered into a partnership with Wahli to develop an eight-axis CNC hobbing machine. That machine was the Wahli W100. However, about two years ago, Affolter decided to redesign the machine and begin marketing it under its own name, Graf says.

Over time, Affolter Technologies has developed expertise in a number of areas of machine tool manufacture. The company makes its own CNC controls—including both hardware and software development—as well as its own spindles, "the most important mechanical component of the machine," Graf says.

"We wanted to master the whole technology," Graf says. "First we only did retrofits of existing machines, and finally, we got all the know-how to develop the machine completely."

The company has two more gear machine models in the works. The Gear AF90 will be a high-productivity gear hobbing machine. The first AF90 is scheduled to be completed and presented to a customer by the end of 2006, Graf says.

In addition, Affolter is working on the Gear AF120, an eight-axis CNC micro-grinding

machine, equipped with an 80,000-rpm grinding head motor spindle. The AF120 is designed for grinding gears, tools and parts for the medical sector. The machine will be available early in 2007, Graf says.

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Fax: (201) 489-0048
E-mail: *cdeastech@mindspring.com*

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Internet: *www.affelec.ch*

SPV Spintec's Automatic Deburring Machine Designed Especially for Gear Wheels

The new D-Burro-Mat 68 2006 automatic deburring machine from SPV Spintec is designed for deburring of gear wheels, flanges and other circular symmetrical components.

The machine allows variable settings in length, height and machining angle between the spindle and rotating table for machining various workpieces. Other features include six programmable presettings of machining time, a signal input for controlled start from robot manipulator, and a signal output for custom requirements, such as maneuver signals for pneumatic chucks.

According to the company's press release, the speed of rotation of the grinding spindle ranges from 15,000 to 36,000 rpm. The maximum weight of the workpiece is 12 kg.

Accessories include an enclosure in acrylic, pneumatic or servo gripping chuck. The deburring machine can be

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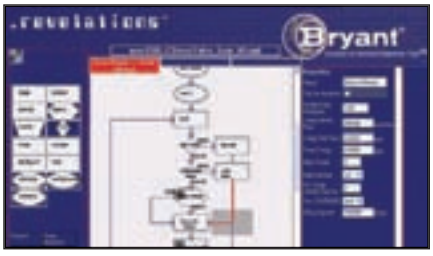
Bryant Grinder's New Software Enables Lean Production for any Machine Tool



Bryant Grinder, a division of Vermont Machine Tool, released the *Revelations* software, a Microsoft Windows-based, CNC control software designed to make machine tools more efficient, more flexible, and easier to operate.

"*Revelations* software reduces operator training, programming time, cycle and setup time, and scrap," says Craig Barrett, president of Bryant Grinder. He adds that, with optional online Ethernet support, Bryant Grinder engineers in Vermont can troubleshoot and solve a software, electrical, hydraulic or pneumatic issue with a machine that is anywhere in the world.

"Using *Revelations* software increases a shop's flexibility on many levels," Barrett added. "The software can run on any grinder, lathe, machining center, hobber, gear shaper, or special machine that uses a PC-based controller."

Operator training on *Revelations* software takes only a couple of hours. Training is simplified because operators use only one screen to run the entire machine, and programmers use only one screen for flowchart programming. Online documentation, such as help screens and links via help text, is available at the machine, too, guiding the operator through each step in the process. All hydraulic, electrical, and pneumatic diagrams are available online. The software also graphically displays dressing forms and grinding profiles on grinding applications.

"*Revelations* software makes the machine shop flexible on several levels," says Barrett.

Engineers using browser-enabled workstations on a company's network can easily program one or more machines on the shop floor using *Revelations* software visual flowcharts. The programming automatically generates the G-code and downloads it into the control.

Engineers can also generate production estimates from their workstations without running machines, which allows them to reduce setup time and manipulate cycles to fit production requirements.

Revelations software can control multiple machines in a shop—so operators can run more machines and be more productive. Additionally, it has an unlimited range of speeds and feeds, not relying on typical canned cycles, and it helps engineers collect data and manage machines based on that data.

At present, *Revelation*s software is being used on machines grinding fuel systems components.

For more information:
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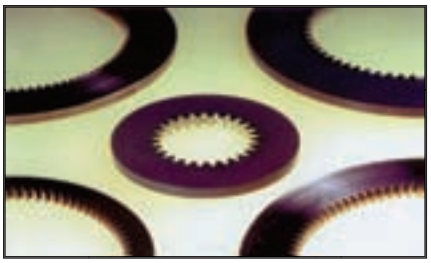

New precision internal gears from Sterling Instrument are available from stock in inch and metric sizes.

The 20° pressure angle inch gears, identified as the S1E62Z- Series, are offered in 303 stainless steel or 2024-T4 anodized aluminum. The metric gears, identified as the S1E05ZM, S1E08ZM and S1E10ZM Series, are supplied in 303 stainless steel.

The metric gears in Modules 0.5, 0.8, and 1 are ISO Class 7 and are stocked in 5, 8 and 10 mm face widths. They have from 60 to 120 teeth, and outside diam-

eters ranging from 50–150 mm. The inch gears are stocked in 24, 32, 48, 64, 72 and 96 pitch.

According to the company's press release, the metric gears are AGMA Q10 with a 1/8" face width. They have from 20–300 teeth and outside diameters ranging from 1.998–3.998".

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Phone: (516) 328-3300
Internet: *www.sdp-si.com*

New Potentiometer From Nireco Produces Dance Roll Position Feedback Signals

Nireco America Corp. introduces the Series 2699 geared dancer roll potentiometer. The heavy-duty, high-precision geared potentiometer is designed to produce dance roll position feedback signals.

According to the company's press release, the new control offers more than 700 gear ratios from 0.06–25 turns, which eliminates the need for external gearing or timing drives. The dual-bearing design and a 1/2" input shaft handles up to 80 lbs. of radial load.

Since it does not contain internal stops, the unit cannot be damaged by excessive dancer roll travel. It is rated to 1W and provides more than 1% linearity with essentially infinite resolution. Complete PID and tension control circuits are also available.

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Internet: *www.nirecoam.com*

Nitrex Develops New Small-Scale Furnaces

The new NX-400 series of nitriding and nitrocarburizing systems from Nitrex Metal is designed for use in small-scale processing, as well as for general laboratory and testing purposes.

According to the company's press release, the furnaces have a compact construction that makes efficient use of restricted floor space in a plant.

Available in three standard sizes, ranging in workload capacity from 440–880 lbs., the furnace, control system and auxiliary equipment are integrated and mounted on a platform for secure transport by forklift. Alternatively, the system may be physically separated back into individual components at the customer's request.

The NX-400 series comes plug-and-play ready, which simplifies installation.

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Canada
Phone: (514) 335-7191 ext. 151
E-mail: *paul.gofas@nitrex.com*

Rex-Cut's Fiber-Mounted Points Reveal Fresh Abrasives

New cotton fiber-mounted points from Rex-Cut Products expose fresh abrasives as they work to deburr and finish in one step with chatter-free performance.

According to the company's press release, the mounted points deburr and finish precision machined, cast and extruded parts. Providing smooth, controlled grinding with limited vibration, they come in various shapes, sizes, grits and bonds for use on all hard and soft

metals, and will not change their geometry.

Featuring multiple layers of non-woven cotton fiber and abrasive grains pressed and bonded together, the mounted points come in barrel, bullet, conical and round shapes with 1/8" and 1/4" shanks. They are suitable for deburring, blending, finishing and edge-breaking applications on stainless steel, Inconel, titanium and mild steel and are non-loading on aluminum.

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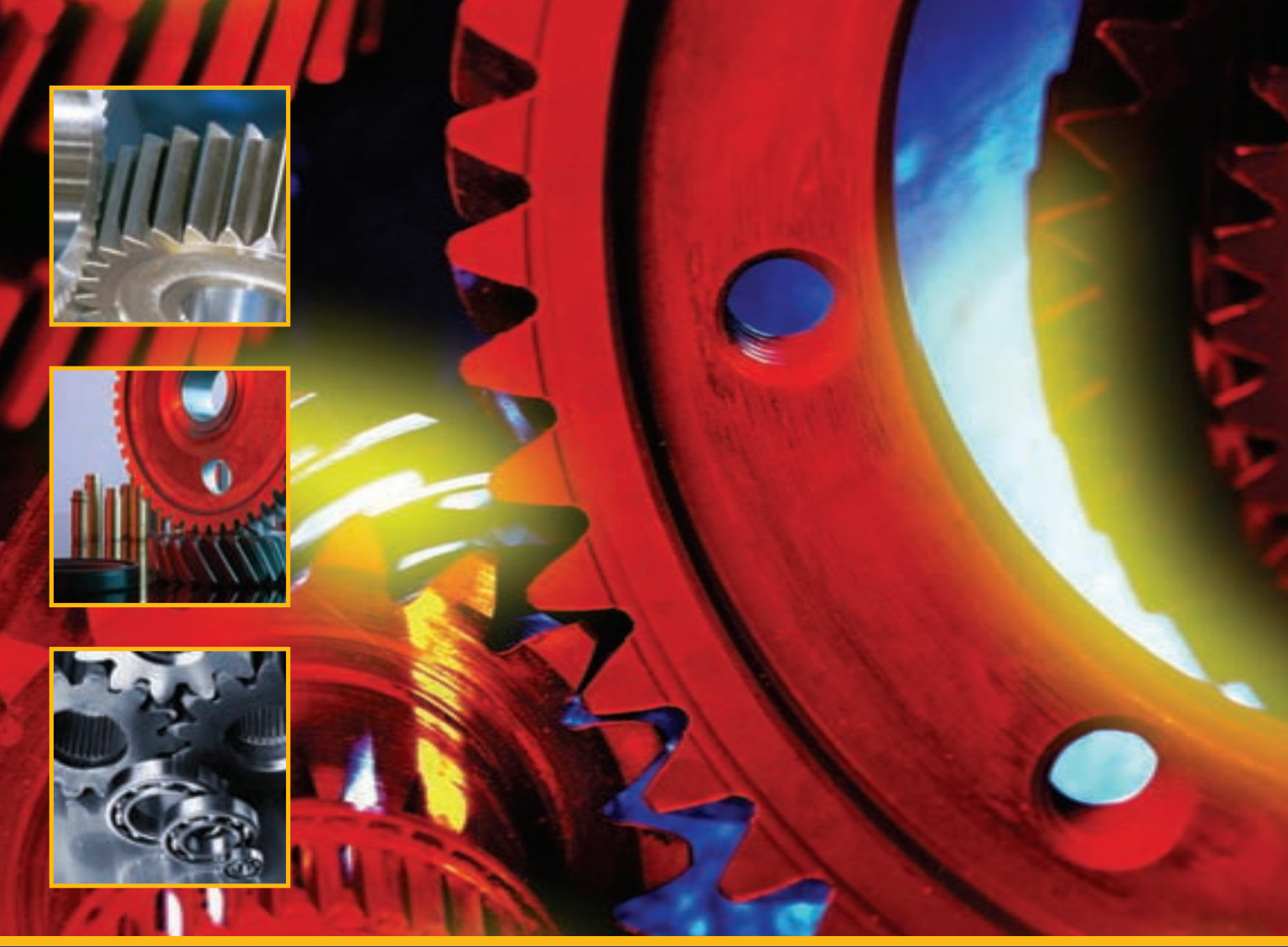

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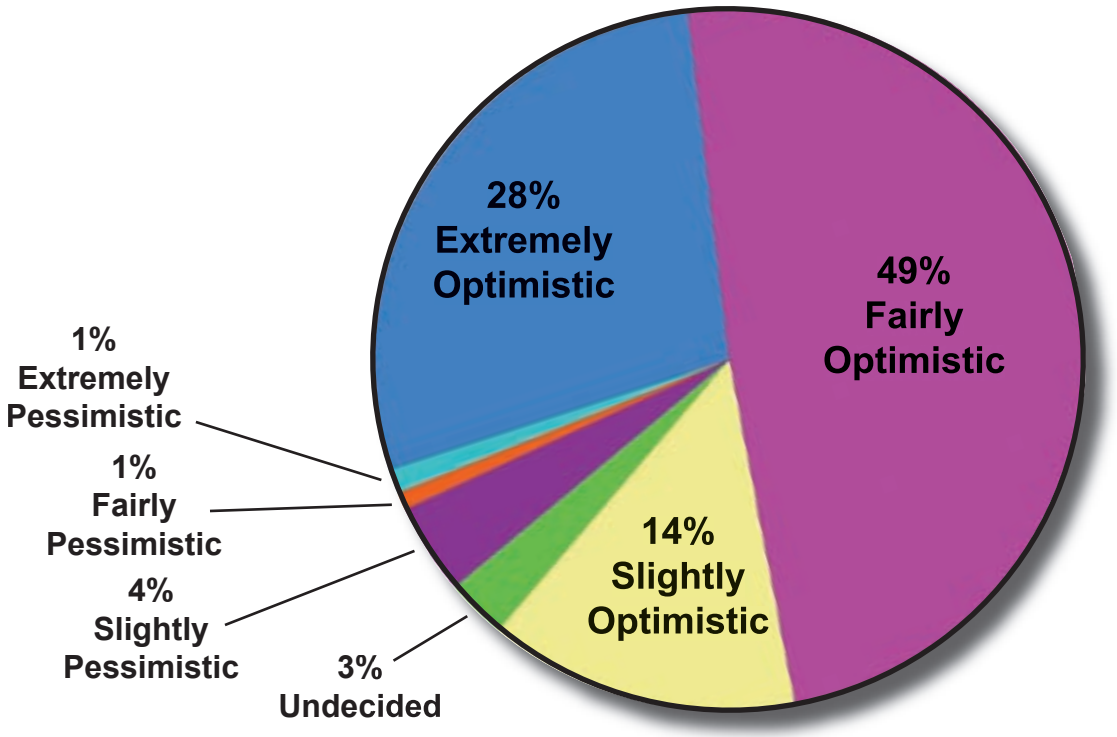
State of the Gear Industry

91% of Gear Industry Respondents are Optimistic About their Ability to Compete over the next 5 Years



Based on the chart above, gear manufacturers are clearly optimistic about 2007 and beyond. They've been riding a wave of increased employment, increased sales and increased production. Nearly all involved in gear manufacturing believe in their companies, their technology and their processes.

It's safe to say the gear industry has a positive outlook.

Of course, the optimism shown by these results reflects a worldwide gear manufacturing economy that has been strong over the last few years. If you make gears these days, chances are good that you're pretty busy.

But that doesn't mean that you aren't concerned.

The results presented here are biased. They aren't representative of the entire gear industry, nor are they representative of all of its facets. For example, this survey definitely underrepresents the thousands of Americans who manufacture gears for automotive transmissions and axles—and that industry, at least in America, continues to struggle.

"Our highest-volume products are tied to trucks and SUVs, which have fallen out of favor due to higher fuel prices," said a design engineer for a U.S. Tier One automotive supplier. "We either need new products, new customers or both."

Another automotive industry respondent said, "This facility is closing and production is being moved to low-cost countries, like India, Poland and China."

A number of other respondents mentioned that the automotive industry downturn was negatively affecting their businesses.

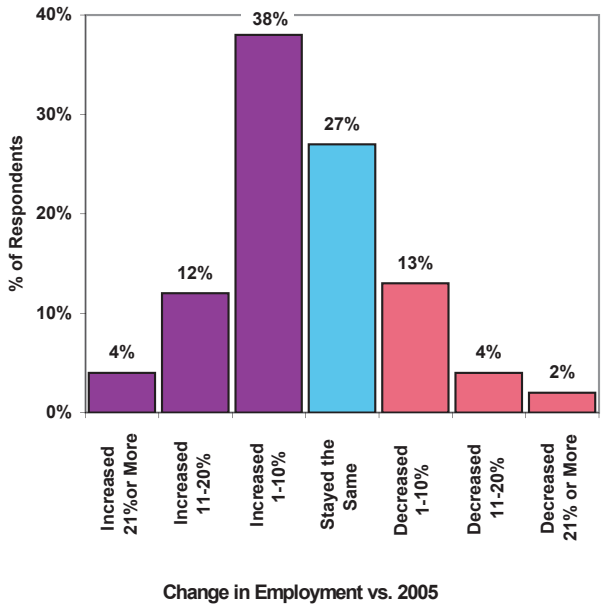
In October, Gear Technology *conducted an anonymous survey of gear manufacturers. Invitations were sent by e-mail to thousands of individuals around the world. More than 300 individuals at gear manufacturing locations responded to the online survey, answering questions about their manufacturing operations and current challenges facing their businesses.*

The respondents considered here all work at locations where gears, splines, sprockets, worms and similar products are manufactured. They work for gear manufacturing job shops (45%), captive shops at OEMs (53%) and shops manufacturing gears for maintenance, spares and their own use (2%).

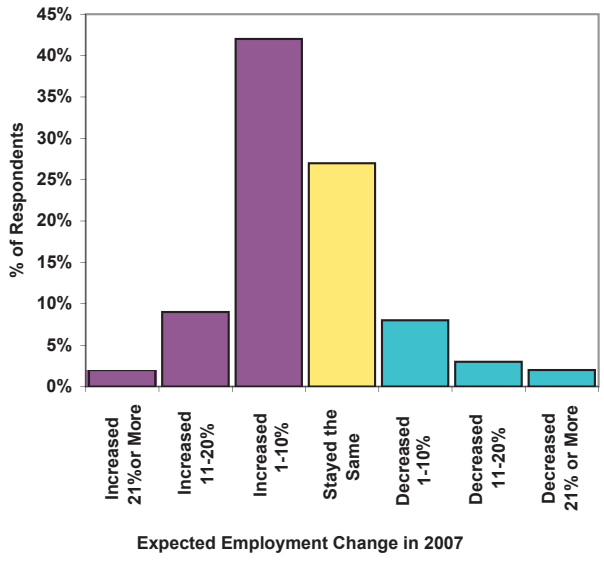
The survey covers gear manufacturing around the world, with 57% of respondents working in the United States, and 43% outside the United States.

A full breakdown of respondents can be found at the end of this article.

54% of Gear Industry Respondents Work at Locations Where Employment Increased in 2006



53% of Gear Industry Respondents Expect Employment at their Location to Increase in 2007

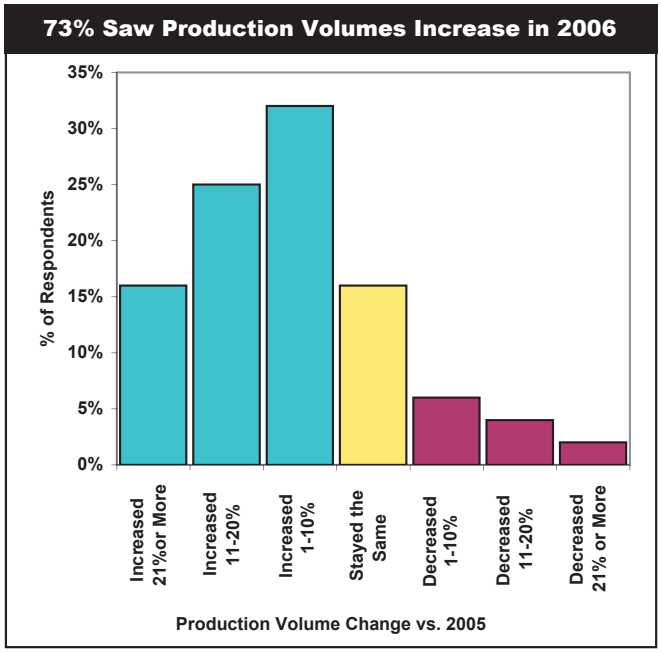


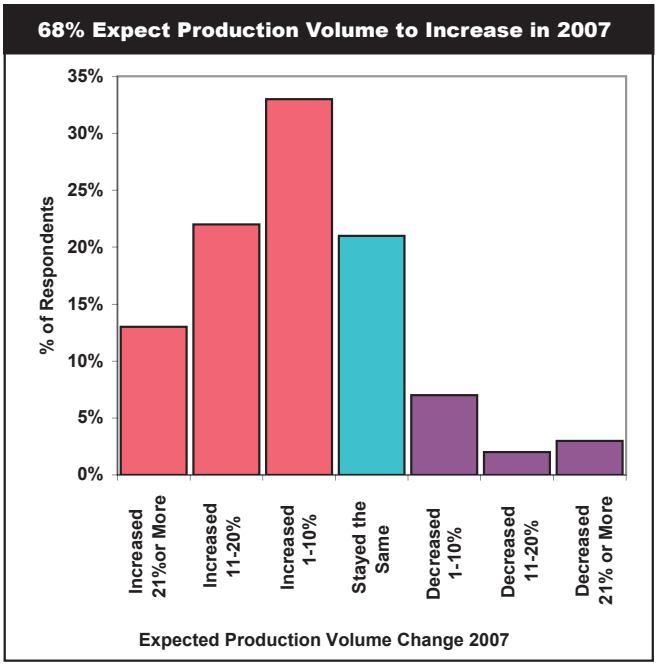
Surprisingly, only a few mentioned foreign competition, and some of those who did were outside the United States. In some cases, companies are being forced to set up manufacturing operations overseas in order to serve a major customer. A design engineer working for a major OEM in Wisconsin cited "unfair pricing by foreign competitors" as one of his company's most significant challenges.

Our audience seems less concerned with foreign competition than with competition in general. The respondents are worried about how they're going to be able to do more with less.

"Same as every year," one respondent said. "make it better, cheaper, and faster."

Most respondents work at locations that are increasing



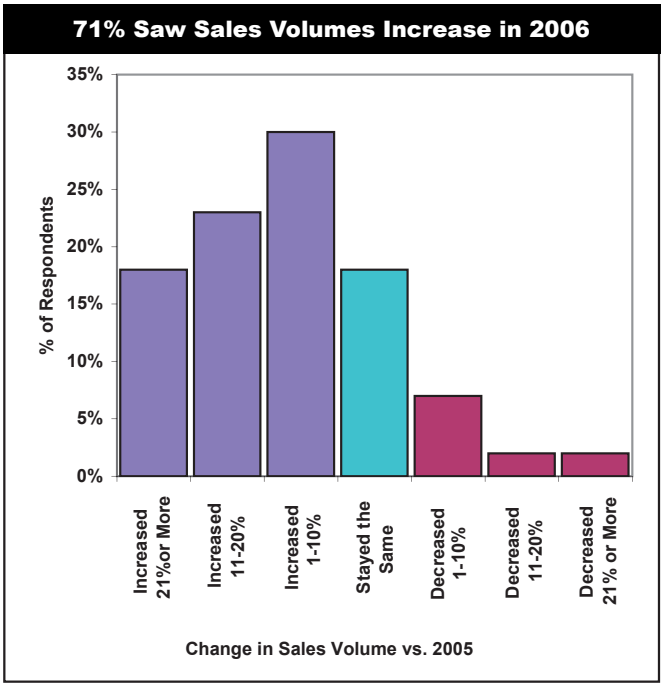


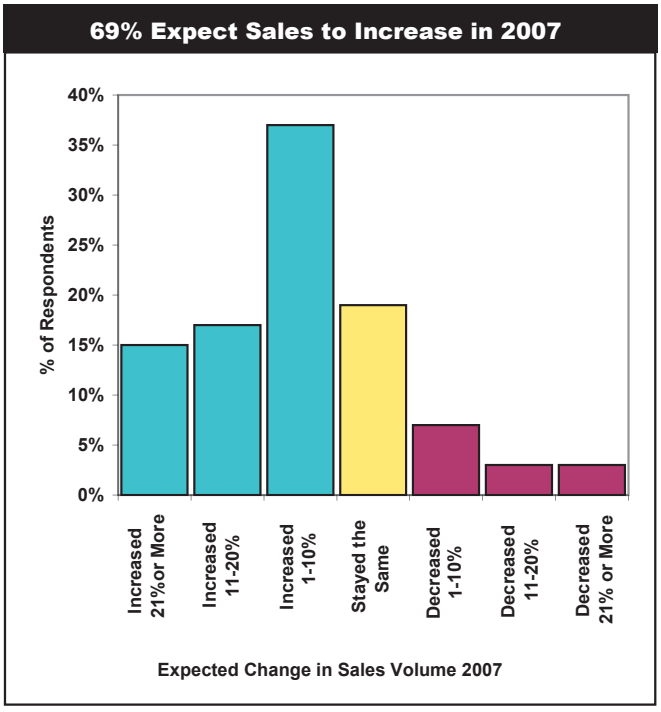
production, but they're also being asked to reduce costs and decrease delivery times, all while deliveries from their suppliers are taking longer, costing more and becoming less reliable.

Another theme common among respondents, especially in the United States, was the difficulty in finding skilled workers—not enough engineering talent, not enough machining talent, and not enough interest in manufacturing in general.

"Large corporate attrition programs will see experienced workers flow out, being replaced by inexperienced workers," said a manufacturing engineer at a major U.S. manufacturer of heavy-duty transmissions.

"For my small operation, the inability to find qualified or any other help will be a deterrent to the growth of this com-



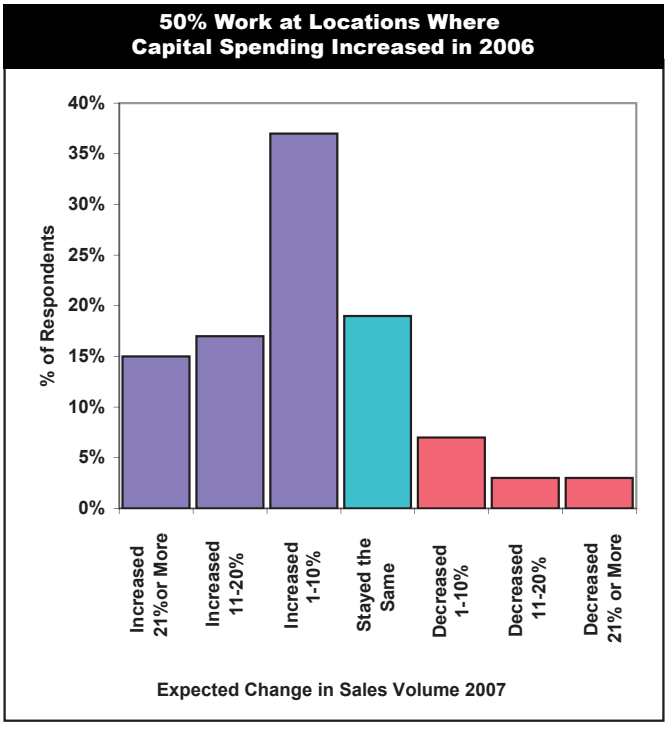


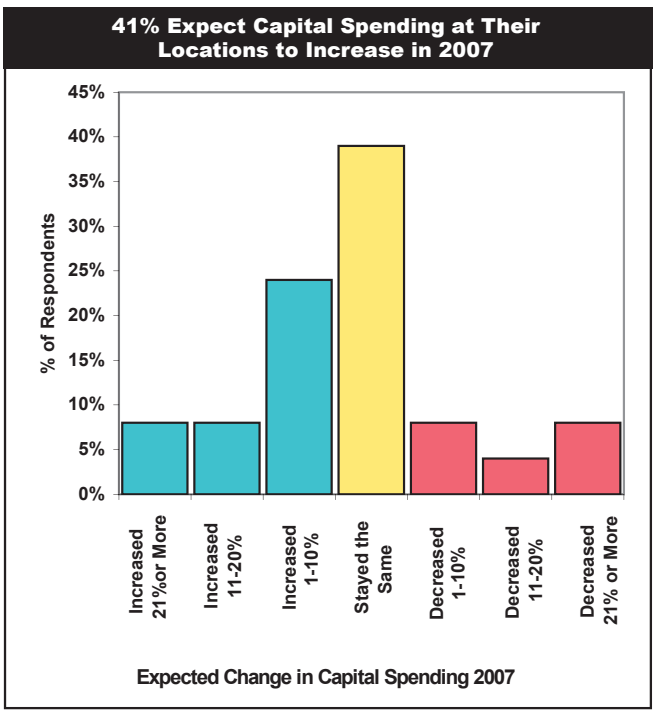
pany," said a production worker at a California job shop.

Other concerns were voiced as well, including issues like scheduling, finding raw materials, improving quality, increasing productivity and so forth. Others want to reduce their inventories and increase their flexibility through lean manufacturing.

Some are simply struggling with their own growth. "We are running out of space," said a manufacturing engineer at a mid-sized Canadian job shop.

We deliberately did not ask questions about profits in this survey. Many of the respondents wouldn't necessarily have access to that kind of information. Others work at large OEMs whose profits are largely dependent upon factors outside of their gear manufacturing operations. But it's clear from the



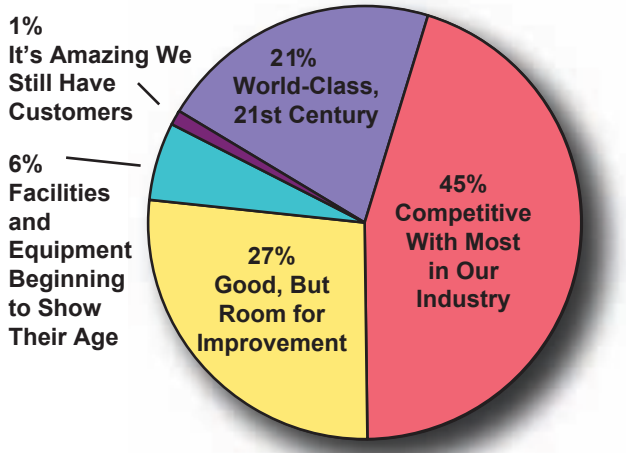


comments of many of the respondents that, although they are extremely busy, it doesn't necessarily follow that they're also extremely profitable.

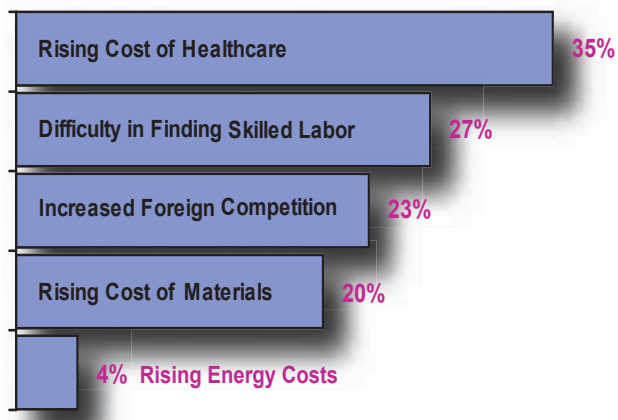
Reading through their comments, you get the sense that gear manufacturers are feeling squeezed, in more ways than one. Some are squeezed by space constraints. Others are squeezed by pricing. Still others are squeezed by their customers' demands for higher productivity, lower prices and improved quality.

But squeezing the most out of the least is the task of modern manufacturing. Despite the many challenges facing them, you also get the sense from reading their comments that the gear industry is not only up to the task, but also hopeful about its future.

How Do Respondents Describe Their Manufacturing Operations and Technology?

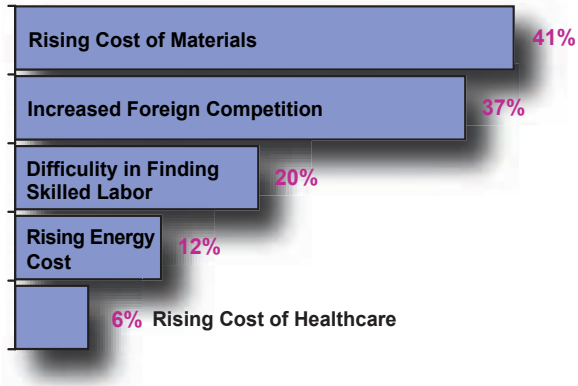


Ranked as #1 Concern in the USA



* % equals more than 100% because some respondents chose more than one option as their #1.

Ranked as #1 Concern Outside USA



* % equals more than 100% because some respondents chose more than one option as their #1.

What Other Factors are Presenting Significant Challenges to Your Business?

"Although we have experienced a nice increase in sales in the last 18 months, there is still a fear that the industry could go into a downturn again…The fun of what would be coming in the door next is being replaced by the dread of 'How can we meet these ridiculous deliveries on parts we quoted months ago and now are suddenly HOT because the customer waited so long to order.'"

—a manufacturing production worker at a Michigan job shop

"Coping with changing demands on products. Reducing stock levels with a view to becoming leaner."

—design engineer at a U.K. manufacturer of gear drives

"Failure of society/industry to shake negative perceptions about machining as a career, thus difficulty in finding and hiring excellent, intelligent help."

—corporate executive at a small U.S. manufacturer of automotive powertrain products

"Increased competition, but domestic."

—a manufacturing engineer at a major U.S. automotive transmission plant

"Keeping up with rapid growth and demand."

—a quality control worker at a U.S. manufacturer of mining equipment

"Meeting the ever-increasing demands for quicker deliveries and reducing lead times, coupled with price reduction requests. Many customers' expectations have gone beyond being unreasonable."

—corporate executive at a mid-sized Illinois job shop

"More and more companies which were not gear producers 10 years ago are now getting into the gear business."

—employee at a mid-sized Michigan job shop

"Not just the cost of gear steel, but availability; getting forgings into the plant."

—production worker at a large U.S. manufacturer of industrial gearboxes

"Suppliers being able to meet our scheduled ramp-up and our quality requirements."

—manufacturing engineer at a major U.S. automotive transmission plant

What are Your Company's Most Significant Manufacturing/ Engineering Challenges for 2007?

"Find people with enough skill on gears."

—manufacturing engineer at a small California job shop

"Bringing the best manufacturing practice to produce world-class gear products. Implementing six sigma and TQM culture into the organization."

—corporate executive at a small Indian job shop serving the construction market

"Cost reduction to compete with foreign products."

—production worker at a small U.S. manufacturer of motion control products

"Creating good scheduling for production, to create better on-time delivery."

—production worker at a large U.S. job shop serving the aerospace industries

"Design and prototype products in a shorter time period with the same resources."

—design engineer at a major U.S. manufacturer of construction/off-highway equipment

"Expansion: double production capacity without losing focus on cost optimization."

—corporate executive at a major European manufacturer of industrial gearboxes

"Finding and retaining skilled labor."

—corporate executive at a mid-sized New York job shop

"Increasing the production by at least 10% while reducing the manpower by 2-5%."

—manufacturing engineer at a major Indian automobile manufacturer

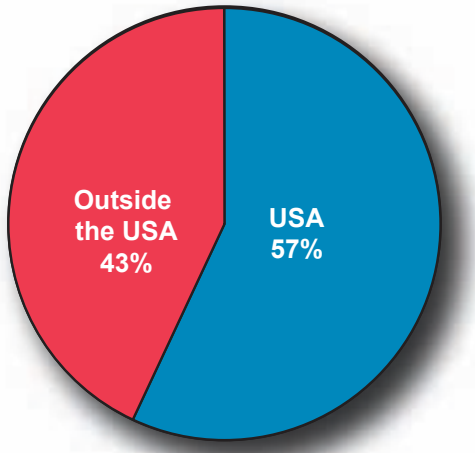
"Keeping production costs low and keeping our competitive edge against foreign competition."

—marketing & sales worker at a mid-sized job shop in Malaysia

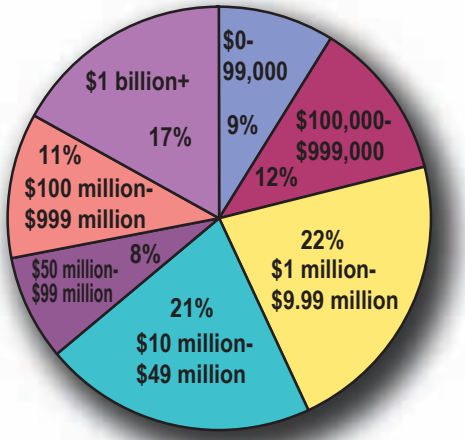
"To reduce price without affecting quality and delivery."

—quality control worker at a major U.S. aerospace job shop

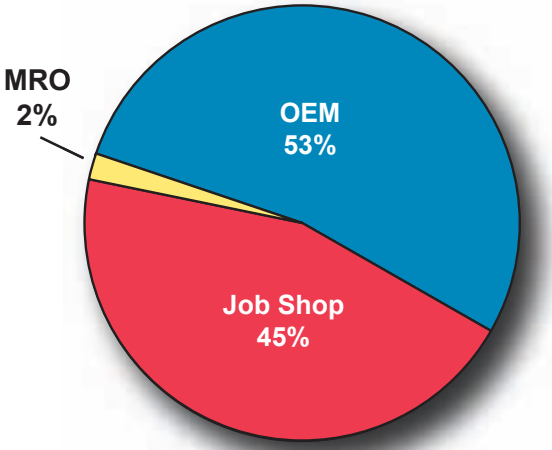
State of the Gear Industry: Who Responded



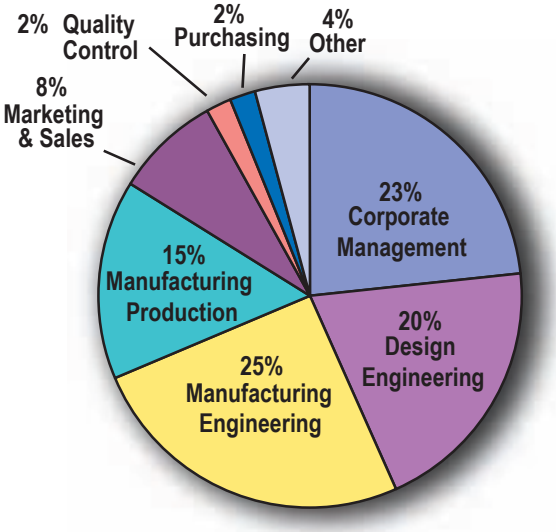
Sales Volume of Company



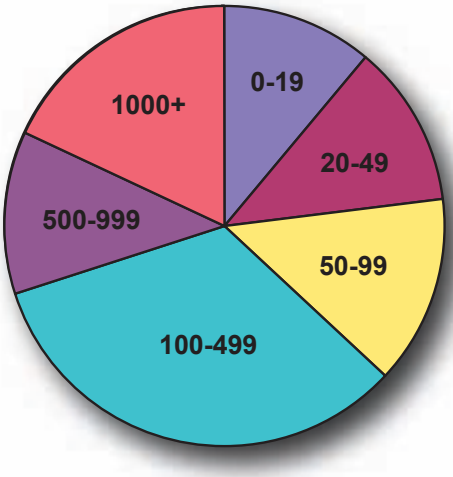
Type of Operation



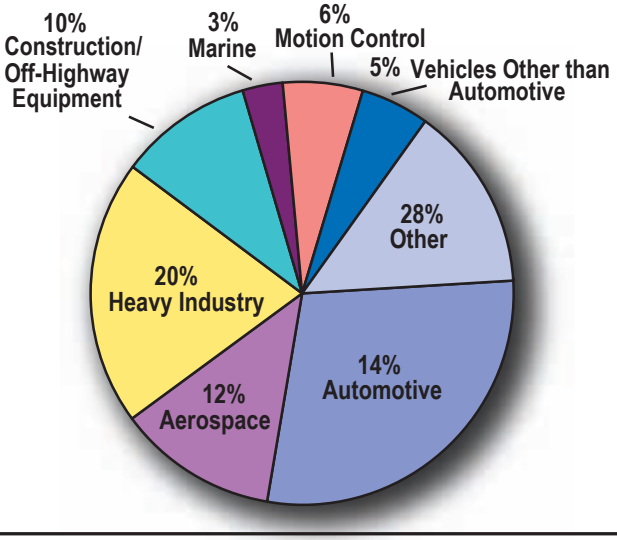
Job Title/Function of Respondent



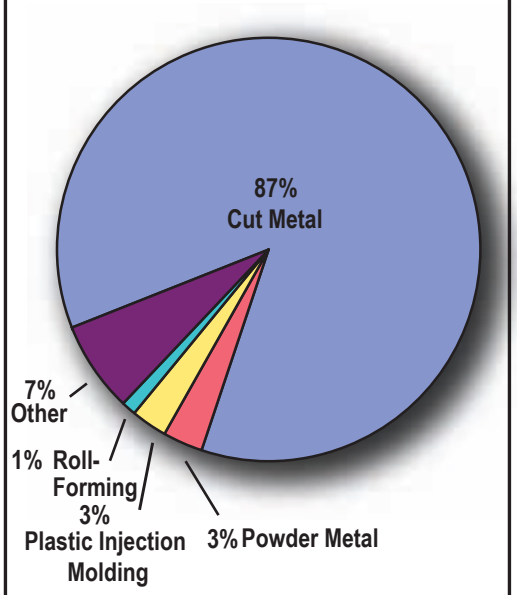
Size of Company



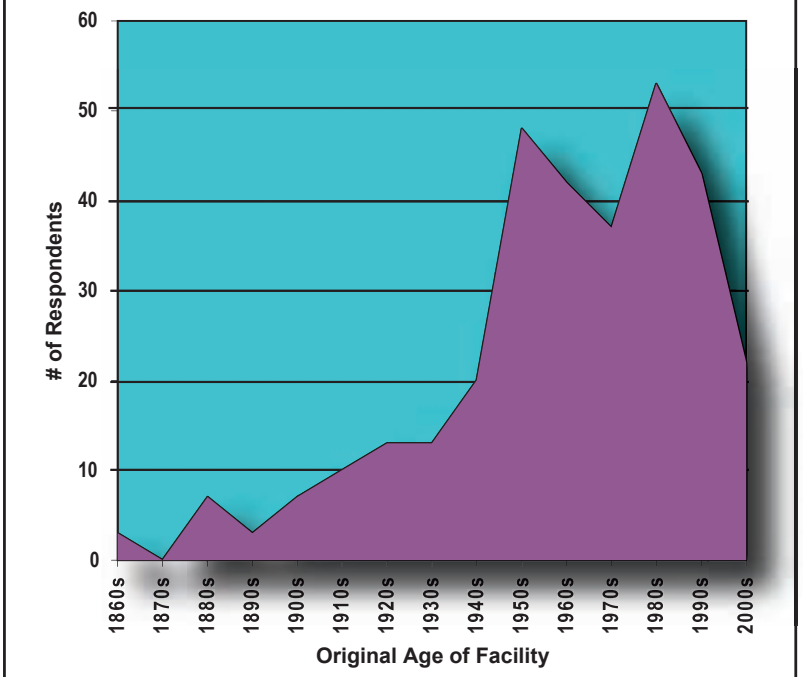
Prime Industry



Primary Method of Manufacture



Age of Manufacturing Location



Half of gear industry respondents work in facilities originally built before 1967

Dr. Suren Rao (left), GRI managing director, and graduate assistant Daniel MacNamara, setting up an RCF test machine.

It's All About the Science at Gear Research Institute

Jack McGuinn, Senior Editor

Experience counts, shared or otherwise, in most anything we do. But it sometimes falls short when trying to establish consistent gear design and standards definitions. That is why—despite racking up more than $2.5 million in R&D contracts this year with its member sponsors—the Gear Research Institute at Pennsylvania State University is not content. And Dr. Suren Rao, institute managing director, pulls no punches in explaining why.

"It is my opinion that too much of gear design and definition of standards is anecdotal, he says. "While analytical methods have been developed to establish a 'better' theoretical basis for these efforts, it has to go hand-in-hand with rigorous and robust experimental verification. The institute, in conjunction with the (school's Drivetrain Technology) Center, has the most comprehensive gear test capability in the nation. It can play a leading role in this experimental verification."

Asked to expand on those observations, Rao refers to how standards are typically arrived at, and two inherent disadvantages with that process.

"Right now, AGMA is writing standards in committees that bring together experts in their respective fields who bring their practices to the table and define a consensus that is acceptable to the group. This is purely experience-based, and while I have no quarrel with this process, it has two disadvantages. One, while experience is a great teacher, it is less able to define technological advances, both in terms of what, and when. Two, it also trends to the conservative side, as no one wants to be 'out on a limb.'"

Rao allows that the points he makes were less valid when the United States and Western Europe ruled a much smaller industrial universe. But he cautions that the advances of Asian and other emerging Third World countries are dictating the need for a new playbook.

"Both of these issues were irrelevant when we were 'king of the hill,'" he says. "Today, we face a host of competitors that are willing to take risks that we are not bold enough to do, and are losing the game as a result."

For Rao, it's a "no guts, no glory" call to arms.

"The only addition I would make to this process is devising experimental verification of the proposed standards to make sure we are not going overboard on the cautious side, and that we are exploiting the benefits of advanced technology. To implement this will cost money—money that needs to be justified to management."

An independent, not-for-profit corporation formally begun in 1986 by a group of Chicago area-based gear engineers, GRI then made its home at Northwestern University around 1994 before eventually establishing a permanent base at Penn State. The institute co-sponsors projects with the university's aforementioned Drivetrain Technology Center, a division of its Applied Research Laboratory. From its inception, the institute has made its mark in the industry by conducting collaborative, pre-competitive gear and applied research.

Asked to define "pre-competitive," Rao explains the distinction between the institute's work and that generally conducted in academic environments.

"In the academic environment, we generally characterize it as research which is publishable without any restrictions. At the institute, we follow a narrower concept. And the basis is research that several companies can jointly conduct without impacting their competitive advantage."

The institute boasts an "A" list of top companies with which it has partnered on gear research. Rao cites the institute's efforts in developing gear design allowables for AMS 6308 gear steel with a consortium including Avio (Italy), Boeing, Honeywell, Pratt &Whitney, Purdy Corp., Rolls-Royce, REM Chemicals, Sikorsky Aircraft and Timken. Rao also alludes to ongoing single-client projects sponsored by Rolls-Royce in support of the Joint Strike Fighter program, and to just-completed work for Boeing-Mesa evaluating the durability characteristics of several gear steels for Apache aircraft.

Rao explains how this concept played out in a recent aircraft project.

"The AMS 6308 Gear Design Allowables project is a typical example. All aircraft gearboxes are being designed with high hot hardness steels, such as AMS 6308. All of them need the material failure data.

"How they translate the material failure data we provide them into design allowables within their own organizations is proprietary, and impacts their competitive advantage. (The institute) allows several companies to work together without the fear of losing any competitive advantage."

The institute is overseen by a tri-partite, nine-member board of trustees. Three members are nominated by the American Gear Manufacturers Association (AGMA), three by the American

Society of Mechanical Engineers (ASME), and three are elected by the institute's membership for a three-year term. The board elects a president—currently Bill Bradley of the AGMA; treasurer—Al Swiglo of Northern Illinois University; and a secretary—Sam Haines of Gear Motions.

Other board trustees currently serving the institute are Michael Tinkleman (ASME), Terrell Hansen (Boeing-Mesa), Jack Masseth (American Axle), Neil Anderson (GM Gear Center), Bruce Boardman (John Deere) and Gary Kimmet (The Gleason Works).

Rao, completing his 10th year at the institute, (succeeding institute co-founder Dale Breen of International Harvester), is of course a firm believer in the institute and the work it does. For him, it's all about the science and protocols.

In addition to its corporate sponsors, the institute is also supported by nominal membership fees—$300 corporate, $50 individual and $10 for students. In return, members are welcomed to the institute's annual meeting and are able to access the institute's database to research past projects—contingent upon approval by the sponsoring entity—at reasonable cost. Members also receive mailings regarding institute workshops and symposiums which they can attend at a reduced rate.

In breaking down FY '06 (Oct., '05–Sept. '06) projects, Rao cited Rolls-Royce, Boeing, Distortion Control Technologies and LSP, Inc. as companies that combined sponsored more than one million dollars in institute projects. That work, along with that of the other companies previously mentioned, allowed the institute to repay its original 1986 founding grant provided by the ASME. In addition, another $1.5 million was realized from the aircraft-related work done at the affiliated Drivetrain Center. But, an unfortunate sign of the times, the U.S. automotive sector this year sponsored less than $100,000 for research by the institute. Too, GRI has attracted no interest or sponsorships from foreign automakers. Back on the plus side, Rao says possible programs with Boeing and Northrup Grumman Marine bode well for 2007.

Typical areas of research conducted by the institute include: high hot hardness gear steels; utilization of boron-toughened steels; technology surveys; gear durability testing; lubrication effects on durability; induction hardening of gears; effect of surface finish on durability; heat treat distortion; and finite element modeling.

To perform this work, the Gear Research Institute is empowered with an array of research capabilities, including rolling contact fatigue (RCF) testers for low- and high-temperature roller testing; modifiable power circulating (PC) gear testers for parallel axis gears with a 4" center distance; single-tooth fatigue (STF) testers for spur and helical gears; a gear tooth impact tester; and worm gear testers with 1.75" and 4" center distances. Metallurgical characterization facilities are also made available by Penn State to the institute.

Along with its research capabilities, the institute prides itself on its efforts—necessarily limited though they are—in educating and nurturing students seeking a career in gear design and related technologies. And yet, despite the shortage of upcoming wannabe gear engineers, the institute finds itself in a "Catch-22" dilemma, given the constraints and limited dollars they must work with.

"While there are plenty of students looking for work in my laboratory, funding them is always a challenge," says Rao. "Most of the industrial contracts have very tight intellectual property rights (IP) that, in most cases, preclude their publication as a thesis."

For Rao, and the gear industry in general, support for gear engineers of the future is a major concern with no apparent solution.

"While educating the next generation of gear engineers is a purpose we would like to fulfill, I have a very difficult time doing just that. Educating gear engineers is a major concern. If funding and IP rights were less stringent, education of students in gear technology would not be a problem."

For more information contact:
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Pennsylvania State University
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State College, PA 16804-0030
Phone: (814) 863-9749
Fax: (814) 863-6185
Internet: *www.gearresearch.org*

Aaron Isaacson (right), GRI research engineer, and engineering aide Joe Bitner, at a PC gear test machine.

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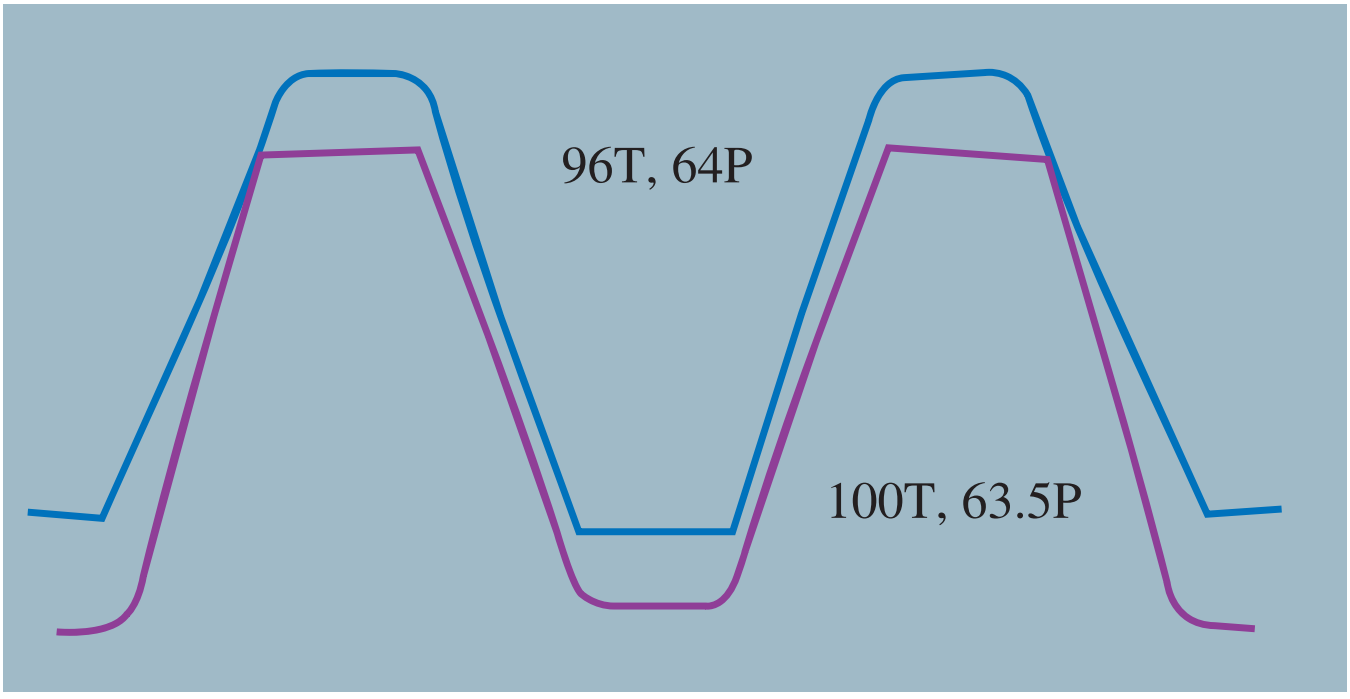

Figure 1—Computer plot for a master gear tooth on the line of centers.

Characteristics of Master Gears

Richard L. Thoen

Richard L. Thoen *is a consultant specializing in medium- and fine-pitch gearing. He has authored several articles and papers on measurement, involute mathematics, statistical tolerancing and other gearing subjects.*

Management Summary

The two-flank roll test (a work gear rolled in tight mesh against a master gear) measures kickout (also known as tooth-to-tooth composite error) and tooth thickness. In this article, it will be shown that the measured values for kickout and tooth thickness vary with the number of teeth on the master gear, and that the errors in measured values become greater with the number of teeth on the master gear.

Introduction

To show that the measured value for kickout varies with the number of teeth on the master gear, a work gear is meshed against master gears of various tooth numbers. For example, the author has a 100-tooth, 48 diametral pitch, 20° profile angle, molded plastic gear—drawn at random from a production line—that has kickouts of 0.0003". and 0.0010" against 96- and 30-tooth master gears, respectively. Another way to show the variation in kickout values is to mesh high grade work gears of various tooth numbers against a master gear of slightly different diametral pitch (Ref. 1).

For example, when a 180-tooth, 120 diametral pitch master gear is meshed against a 192-tooth, 127 diametral pitch (0.2 module) master gear, 20° profile angle on both, the kickout is only about 0.0002", despite the fact that the difference in base pitch is 0.0014". But when 120 diametral pitch high-grade work gears of various tooth numbers are meshed against the 127 diametral pitch master gear, the kickout increases as the tooth number decreases, to about 0.0019" for a 12-tooth work gear (Ref. 1).

It is pertinent to note that an error of 0.001" in base pitch is not uncommon in formed gearing (molded plastic, die cast, powder metal, stamped, cold drawn).

And to show that the measured value for tooth thickness varies with the number of teeth on the master gear, a work gear of slightly different diametral pitch is meshed against master gears of various tooth numbers.

The general way in which tooth thickness varies with the number of teeth on the master gear has been known for a long time (Ref. 2). Now, with the advent of the computer plot, it is feasible to calculate values for both the tooth thickness and the kickout.

Numerical Example

Given two master gears: 96- and 20-tooth, 64 diametral pitch, 20° profile angle, basic tooth thickness (π /128). Also given a work gear: 100-tooth, 63.5 diametral pitch (0.4 module), 20° profile angle, basic tooth thickness (π/127). Accordingly, the error in base pitch, relative to the 96- and 20-tooth master gears, is:

$$\left(\frac{\pi}{63.5}-\frac{\pi}{64}\right)\cos 20° = 0.00036"$$

Since only the effect of an error in base pitch is being investigated, the outside diameter of the 100-tooth work gear is (100 + 2)/64 = 1.5938", not (100 + 2)/63.5 = 1.6063".

When the 100-tooth work gear is meshed against the 96-tooth master gear on the computer plot, it is seen that the center distance is maximum for a master gear tooth on the line of centers and minimum for a work gear tooth on the line of centers. Also, it is seen that both center distances exceed the basic center distance of (96 + 100)/128 = 1.53125".

Thus, to bring the maximum center distance down to the basic center distance, it is seen (via trial and error) that the tooth thickness on the work gear must be 0.0498" less than the basic π/127".

From Figure 1, which is the computer plot for a master gear tooth on the line of centers, it is seen that the master gear tooth is not in contact with the adjacent work gear teeth and that contact is on the tips of the work gear teeth, not on the line of action.

For a work gear tooth on the line of centers, the center distance on the computer plot is 1.53092" for a tooth thickness of 0.00498" less than basic. Thus, the kickout is 1.53125–1.53092 = 0.0003".

Further, for two work gears with 0.00498" reduction in tooth thickness, their tight mesh center distance is 1.5606" (Refs. 3 and 4), not the (100 + 100)/128 = 1.5625" indicated by the 96-tooth master gear.

Conversely, when the work gear is meshed against the 20-tooth master gear on the computer plot, the reduction in tooth thickness is 0.00487" (versus 0.00498" for the 96-tooth master), the kickout is 0.0005" (versus 0.0003" for the 96-tooth master) and the tight mesh center distance between the two work gears is 1.5609" (versus 1.5606" for the 96-tooth master), not the 1.5625" indicated by the 20-tooth master gear.

Lacking the computer plot, nearly the same results can be obtained with gears made to the above dimensions, using 64 diametral pitch and 0.4 module hobs.

Excessive backlash (arising from unknown reductions in tooth thickness) can be avoided when both members of a gear pair are generated (hobbed, shaped). Specifically, all parts for one member of the gear pair are cut to mesh against a master gear. Then, these parts, drawn at random to simulate the assembly process, are used to cut parts for the other member of the gear pair to a specified center distance (Ref. 5).

Optimum Tooth Number

In the foregoing example, both kickouts were determined for a known error in base pitch. In practice, however, the gear defects are not known. Consequently, the optimum tooth number for a master gear (that for which the kickout is maximum) must be determined by experiment.

The optimum tooth number is likely to be determined by work gears with high tooth numbers and is likely to be lower for formed gearing than for generated gearing.

Measurements

It is imperative that the experimental measurements for optimum tooth number not be conducted by different companies. For example, Michalec and Karsch conducted a correlation study (Ref. 6), wherein an assortment of 100 fine-pitch precision gears were inspected at 20 different facilities for total composite error, tooth-to-tooth composite error (kickout) and testing radius. In their report, in addition to finding a "wide variation of measurements among companies," they decided to eliminate the study of kickout because "the readings contained considerable uncertainty."

It is interesting to note that the study was conducted during the heyday of the analog computer (Ref. 7), when the participants had a special interest in obtaining state-of-the-art gears.

If a similar correlation study were to be conducted today, the discrepancies probably would be similar since there have been no marked improvements in inspection practice and test equipment.

In short, it is imperative that the search for optimum tooth number be conducted at one location by personnel who are well acquainted with the measurement errors in gear roll testing (Refs. 8 and 9).

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Optimization of the Gear Profile Grinding Process Utilizing an Analogy Process

Christof Gorgels, Heiko Schlattmeier, and Fritz Klocke

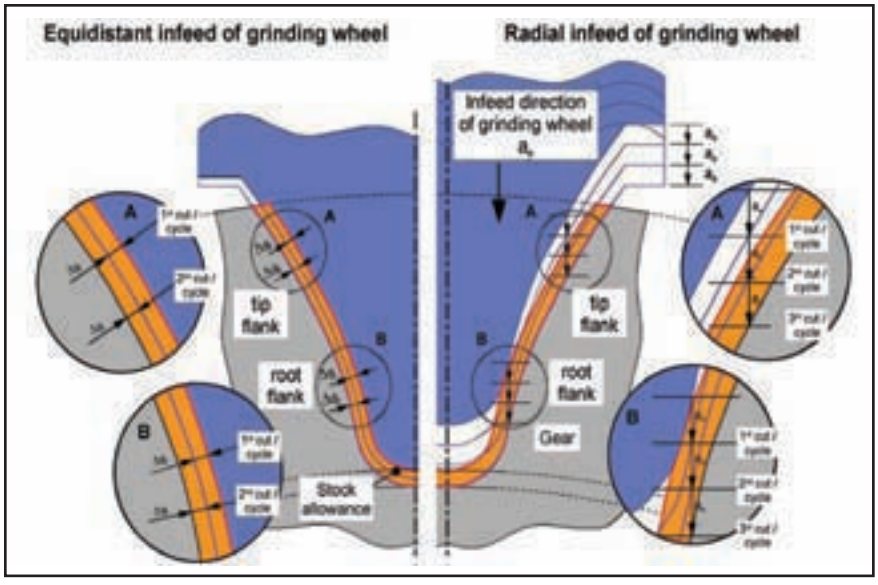

Figure 1—Local stock removal depending on the process strategy.

Management Summary

The requirements for transmission gears have continuously increased in past years, leading to the necessity for improvements in manufacturing processes. On the one hand, the material strength is increasing, while on the other there is a demand for higher manufacturing quality. For those reasons, increasing numbers of gears have to be hard-finished.

The appearance of grinding burn in gear profile grinding, especially when using dressable grinding wheels, seemed to increase over the past years. As we know, grinding burn reduces the load-carrying capacity of gears tremendously. Conversely, costs need to be cut in order to assure a company's competitive position in the global market. And yet, reducing the machining times in gear grinding still increases the risk of producing grinding burn (Ref. 1).

In order to grind gears burn-free and as productively as possible, a better understanding of the process is required. This is especially important for gear profile grinding, due to the complex contact conditions between workpiece and grinding wheel (Refs. 2–3). In this article, an analogy process and a process model will be presented in order to gain a closer look into the process. Finally, different process strategies will be analyzed using the presented process model in order to give examples for the use of the described calculations.

Introduction

Discontinuous gear profile grinding is commonly used in the manufacture of large-module gears. And because the batch sizes are typically small to medium, the process must be highly flexible. In order to achieve this flexibility, dressable—rather than CBN-plated—grinding wheels can be applied. But in using these tools, the process robustness can be compromised by local structural damage—such as grinding burn—to the external zone.

In tooth-flank profile grinding, due to the variation of contact conditions along the profile between grinding wheel and tooth flank, process optimization is difficult. And in comparison with other grinding processes, these conditions clearly lead to varying grinding conditions along the profile. Examination of the complex geometrical and contact conditions requires fundamental technological investigations in an analogy process. In this way, the relationship between various material removal conditions can be investigated as functions of the machining parameters and grinding wheel specifications.

The purpose of this article is to develop a better process understanding in order to use new potentials for process optimization. The knowledge gained in the analogy process is the basis for a new mathematical model, allowing that understanding to be transferred to the real

process. Finally, a process optimization for gear profile grinding using this mathematical model will be presented.

Local Stock Removal and Grinding Burn in Gear Profile Grinding

Local grinding conditions along the profile in gear profile grinding. Basically, there are two process strategies that are commonly used for gear profile grinding in industrial practice. The left side of Figure 1 shows a grinding process with the removal of an equidistant stock along the profile. These are typical contact conditions occurring in single-flank grinding, with an infeed realized by a rotation of the workpiece (Refs. 2, 4).

The right side of Figure 1 shows the removal of a constant stock in the radial direction, realized by a radial infeed of the grinding wheel in multiple steps. This is the process strategy most commonly used in industrial practice. It is obvious that the initial stock removal is not constant along the profile. In the first cut, stock is removed in the area of the root flank only. With further infeed, the area of stock removal is increasing. The whole stock in the tooth root is removed in the last cut only.

Appearance of grinding burn in gear profile grinding. Typically, grinding burn appears only locally along the tooth profile in gear profile grinding. This is due to either the chosen process strategy or heat distortions and centering defaults. In this article, two examples of local grinding burn—dependent upon the process strategy—will be shown. For these trials, a typical truck gear from the case-hardened steel 20MnCr5E has been ground using a dressable, white corundum grinding wheel and using different process strategies. The tooth gaps have all been pre-ground in order to remove the influence of heat distortions and to ensure a constant stock removal in either infeed or equidistant direction.

The results for a radial infeed of the grinding wheel without grinding the tooth root are shown in Figure 2. In the trials, a variation of the specific stock removal rate $Q'w$ has been realized by a variation of the axial feed speed f_a. The picture in the lower left shows the tooth flanks after nital etching. It is readily apparent that the grinding burn appears only in the area of the tip flank.

Additionally, technological trials have been conducted with a constant stock removal along the gear tooth profile (see results in Figure 3). The specific stock removal rate $Q'w$ varies in this operation along the tooth profile. The values shown in the chart are calculated at the indexing diameter in order to be comparable to the previous results. The picture in the lower-left

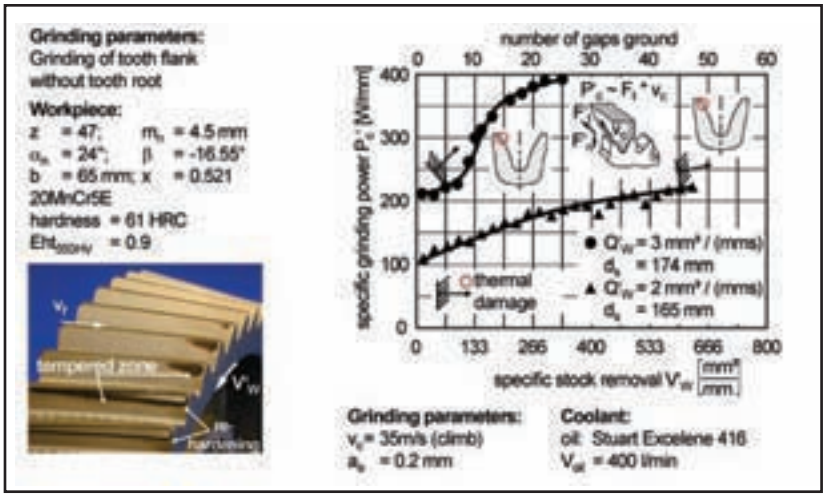

Figure 2—Typical grinding burn for radial infeed of the grinding wheel.

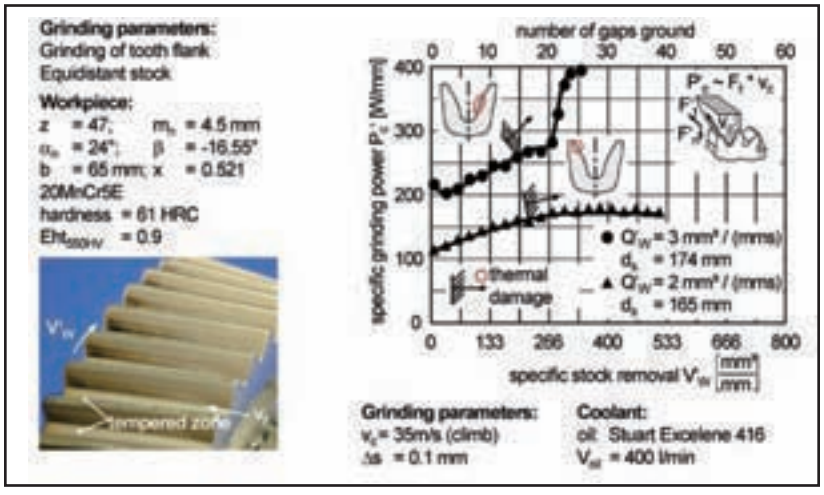

Figure 3—Typical grinding burn for equidistant infeed of the grinding wheel.

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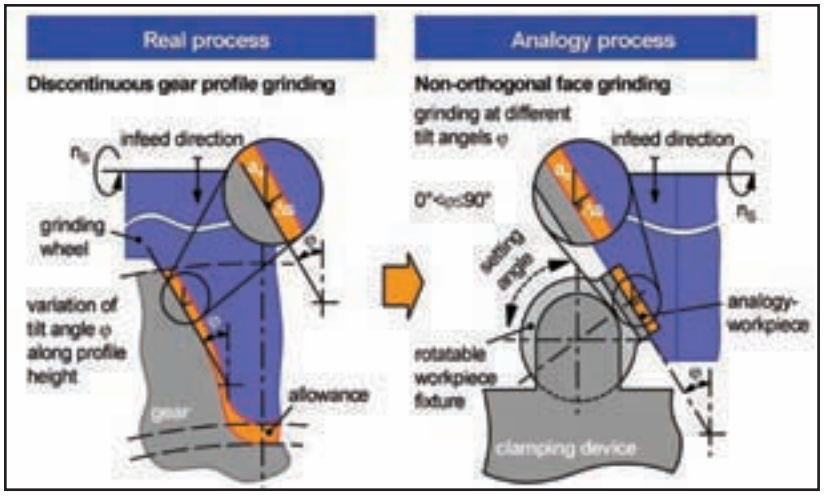

Figure 4—Analogy process for gear profile grinding.

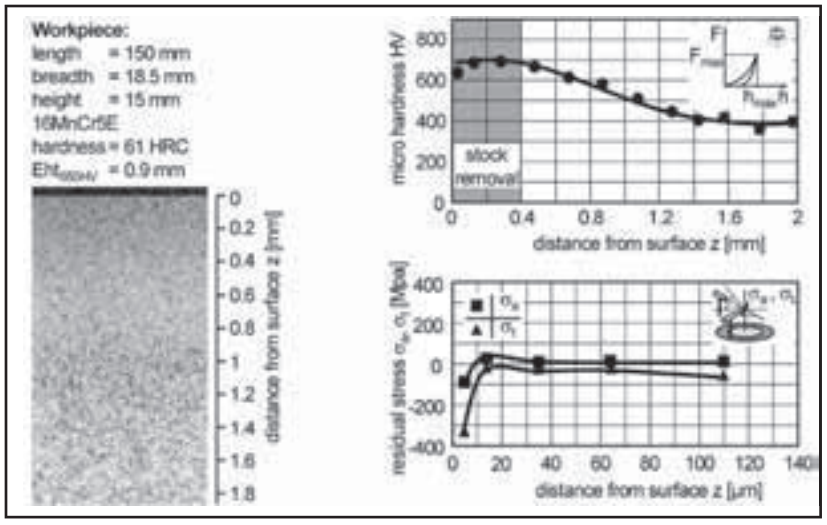

Figure 5—Workpiece data.

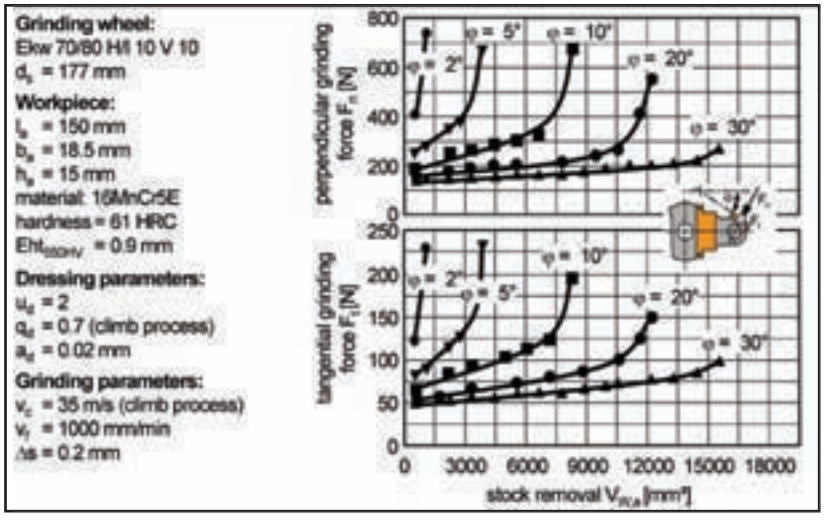

Figure 6—Grinding forces depending on the profile angle.

corner shows the gear after nital etching, and the tempered zone has moved from tip flank to root flank. Again, this is a typical phenomenon for this process strategy of removing a constant stock along the profile.

These results show that process strategy greatly influences local grinding conditions and, in turn, the area where grinding burn can appear. But why this area in particular shows thermal damage from grinding burn is not obvious. As the diagrams showing the specific spindle power $P'c$ clearly reveal, the grinding burn nearly always appears before the spindle power shows a disproportionate increase.

Analogy Process for Gear Profile Grinding

The main difference between gear profile grinding and standard grinding is the varying profile angle φ along the tooth flank. Investigations of gear profile grinding can only show total effects over the whole profile height and varying grinding conditions. This is a major reason why it is difficult to find out what leads to grinding burn occurring only locally on the tooth flank.

In order to investigate the technological conditions separately along the tooth flank, an analogy process has been developed at the WZL laboratory at RWTH Aachen University. The basic setup of this analogy process is shown in Figure 4. The left picture shows the varying contact conditions along the tooth flank for a radial infeed of the grinding wheel into a pre-ground tooth gap. The radial infeed a_e is constant along the profile height, while the stock in normal directions varies with the local profile angle φ.

On the right side of Figure 4, the analogy process is shown. The local contact conditions, infeed a_e, stock Δs and profile angle φ of one position of the gear tooth profile are transferred to the grinding of a rectangular workpiece. In this way, all possible grinding conditions occurring along the profile can be examined separately.

The first trials using the analogy process have been carried out using a corundum-white grinding wheel, commonly used in industrial practice for gear profile grinding. The machining parameters have also been adjusted to those common in gear profile grinding. The trials were conducted on a Kapp VAS55P gear grinding machine in order to keep the pre-conditions in the analogy process as close to gear profile grinding as possible.

The workpieces are rectangular parts of the case-hardened steel 16MnCr5E, with a hardening depth of 0.9 mm. In the trials, a maximum total stock of $\Delta s = 0.4$ mm was removed in the grinding process. The hardness of 61 HRC was nearly constant from the surface to this depth. The

workpieces were also ground before the trials in order to assure a constant surface quality and to remove the distortions from heat treatment. The material structure, the hardness and the residual stress profile are shown in Figure 5.

In Figure 6, the grinding forces in the normal direction (F_n) and in the tangential direction (F_t)—depending on the stock removal for different profile angles and a constant stock of $\Delta s = 0.2$ mm—are shown. It is obvious that, with a smaller profile angle, grinding forces increase and the possible stock removal is significantly lower. Especially in the steep areas, with a profile angle of $\varphi = 2°$, the initial grinding force is very high, and it increases rapidly, indicating that there is high wear of the grinding wheel.

However, for a large profile angle of $\varphi = 30°$, there is hardly any increase of the grinding forces with the stock removal. Thus, hardly any wear of the grinding wheel occurs. It can therefore be stated that the larger the local profile angle, the more material can be removed before a dressing operation of the grinding wheel is needed.

A reason for the tendency of the grinding wheel to wear earlier with a smaller profile angle can be attributed to the increasing contact length caused by a decreasing profile angle. The dependency of the grinding forces on the removed stock Δs is shown in Figure 7. The grinding forces in the tangential direction (F_t) and the direction normal to the surface (F_n) are displayed, depending on the stock removal for different Δs and a profile angle of $\varphi = 10°$. The grinding forces increase with the stock Δs, especially the maximum stock removal, until the super-proportional increase of grinding forces begins lowering significantly.

The results in the analogy process provide a better understanding of the effects occurring in gear profile grinding. It has been shown that gear geometries with a rather small profile angle lead to high grinding forces and to increased wear of the grinding wheel. And yet, it is rather difficult to transfer the results to the gear profile grinding process directly. At this point, one must analyze the local grinding conditions along the profile and attempt to find similar conditions in the analogy process. In order to more easily compare the profile grinding process to the analogy process, developing a process model is required. The model that has been developed is explained below.

Transfer of the Analogy Results to the Real Process of Gear Profile Grinding

Development of an empirical process model. As a first approach to the technological description of profile grinding processes, an empirical process model was developed to allow application of the results from the analogy process to profile grinding. In the analogy process, a large number of trials with profile angles varying from $\varphi = 2°$ to $\varphi = 90°$, and a stock varying from $\Delta s = 0.05$ mm to $\Delta s = 0.4$ mm, were conducted. A function shown in Figure 8 was chosen as an approach in order to calculate the grinding forces in profile grinding, based on the results of the analogy process. The coefficients were determined using the least-squares method. Grinding forces for conditions within the parameters tested in the analogy process are calculated using linear interpolation.

The graphs in Figure 8 show the correlation between the measured value and the calculated value for all three grinding forces in the different coordinate directions. A perfect result would be gained if all points were on the 45° line, meaning that the measured values are exactly the same as the calculated values. In this case, the graph shows quite clearly that the points are very

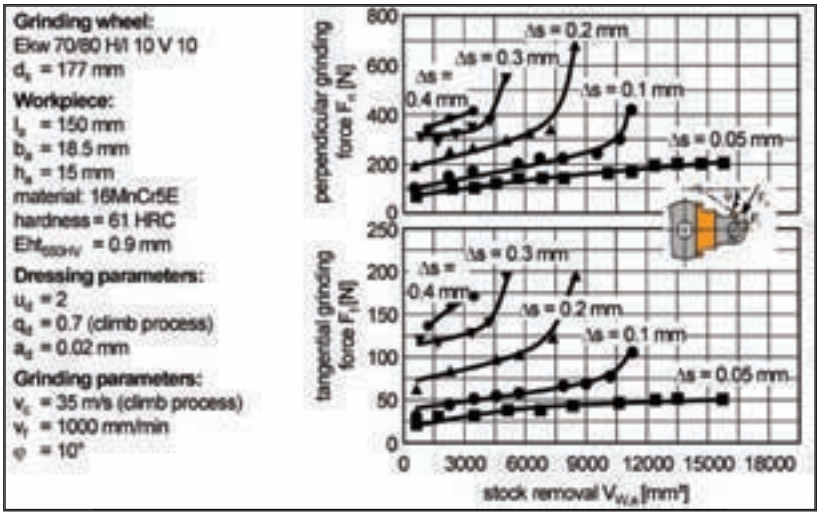

Figure 7—Grinding forces depending on the stock Δs.

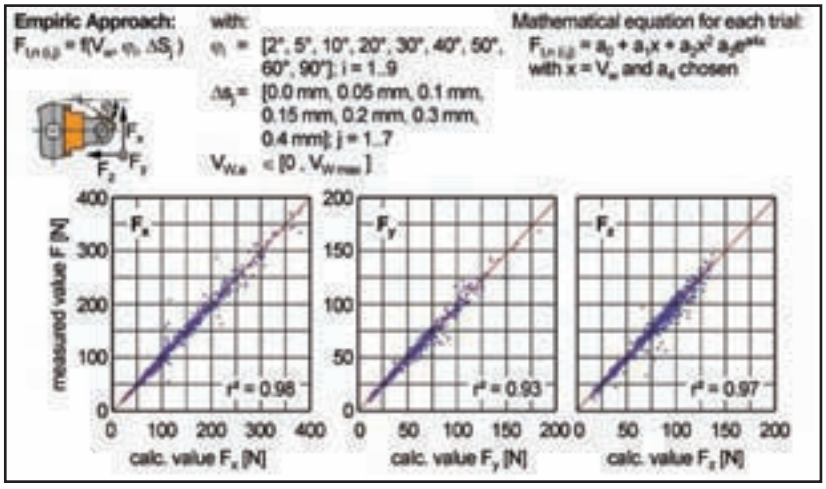

Figure 8—Development of an empirical process model.

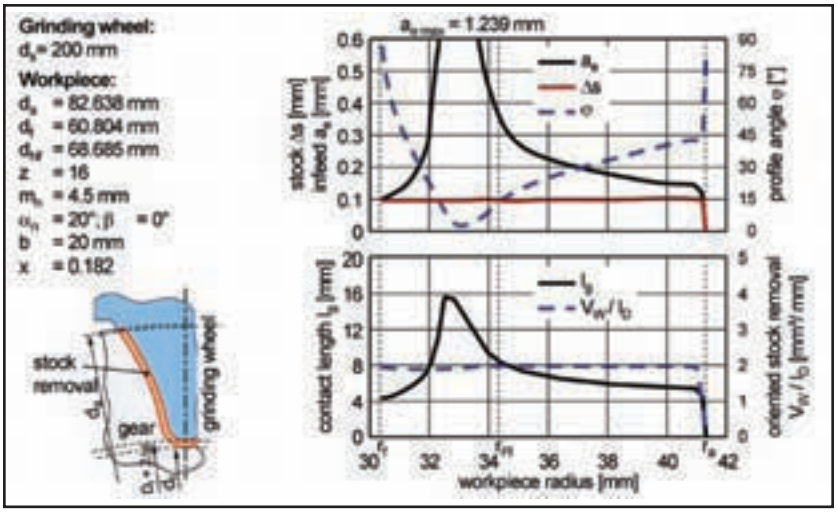

Figure 9—Local contact conditions in gear profile grinding with a constant stock Δs along the profile.

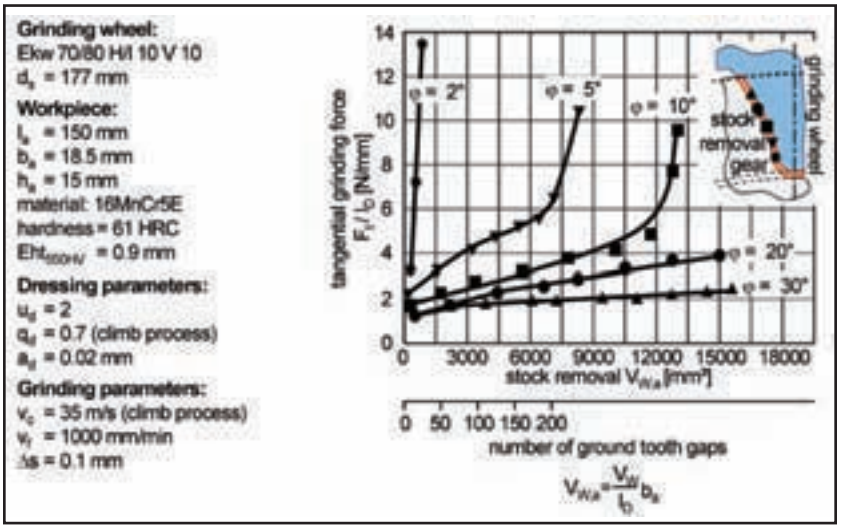

Figure 10—Transference of the analogy results to gear profile grinding.

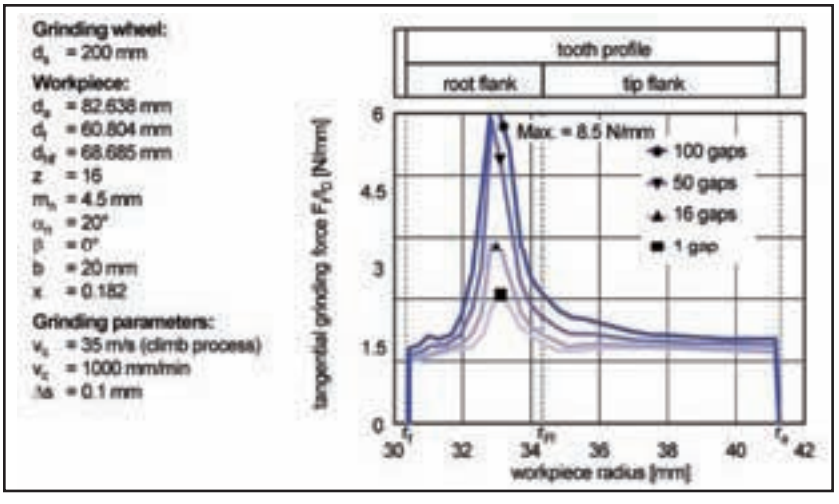

Figure 11—Local grinding forces when removing a constant stock Δs along the profile.

close to this line, and that there is a very good correlation between the measured and calculated values. Additionally, the stability index amounts to values between $r^2 = 0.93$ for the tangential grinding force, and $r^2 = 0.98$ for the grinding force in the direction of the x-axis—a good result in this case.

Calculation of local grinding forces in gear profile grinding. For the transfer of these results to the profile grinding process, a typical spur pinion with a gear geometry of the FZG-C gear was chosen. It has $z = 16$ teeth; a module of $m_n = 4.5$ mm; a pressure angle of $\alpha_n = 20°$; and an outside diameter of $d_a = 82.638$ mm. The grinding wheel diameter used to calculate the geometrical contact length l_g is $d_s = 200$ mm.

As a good first example, a grinding process with a constant stock Δs along the profile was chosen. This is a typical process occurring in single-flank grinding with an in-feed realized by the rotation of the workpiece. The stock amounts to $\Delta s = 0.1$ mm constantly along the profile geometry. The radial infeed a_e differs along the tooth flank due to the changing profile angle φ. It amounts to a maximum of $a_{e\ max} = 1.239$ mm in the area of the minimum profile angle $\varphi_{min} \approx 3°$ on the root flank. The distribution of the stock and the profile angle versus the local radius is shown in the upper diagram of Figure 9.

The lower diagram shows the calculated geometrical contact length along the profile, which varies from $l_g = 4$ mm in the tooth root, $l_{g\ max} = 16$ mm on the root flank, and $l_g = 5$ mm in the tip flank area. The stock removal related to the length of the considered contour element amounts to a constant value of $V_w/l_d = 2$ mm³/mm along the profile. So it can be concluded that, using this process strategy, the extreme values for the infeed a_e, as well as for the contact length l_g, can be found in the area of the root flank below the root form radius.

The grinding forces have been calculated for grinding 1, 16, 50 and 100 gaps. Even though the workpiece does not have more than 16 gaps, these calculations make sense in order to show the behavior of the grinding forces after a high stock removal, which can occur when grinding a similar gear with a much larger face width.

By knowing the local contact conditions, it is now possible to apply the results gained from the analogy trials to the gear profile grinding process. The first step is to transfer the analogy trials' contact conditions to each point of the gear profile. These calculated con-

tact conditions are shown in Figure 10.

The different curves showing the tangential grinding forces versus the stock removal are representative of contact conditions occurring in the gear profile grinding process. The x-axis has a second label indicating the number of gaps being ground after removing a certain amount of stock. This method is rather time consuming, and it is only possible to determine the grinding forces in areas of the profile, i.e., where the contact conditions (stock Δs and profile angle φ) are known from the analogy process. Therefore, the calculations of the local contact conditions are used in order to calculate local grinding forces, as opposed to using the process model. The results of the calculations of the tangential grinding forces related to the contour length of $l_d = 1$ mm versus the workpiece radius are shown in Figure 11.

Those results show that the lowest grinding forces of $F_{t\,\min}/l_d = 1.2$ N/mm can be found in the area of the largest profile angle, which is the tooth root. Along the profile geometry, the grinding forces are increasing up to a maximum of $F_{t\,\max}/l_d = 2.3$ N/mm in the area of the root flank just below the root form radius, where the minimum profile angle $\varphi_{\min}$ is found. The grinding forces are then observed decreasing again, to $F_t/l_d = 1.5$ N/mm in the area of the tip flank with a rather high profile angle. Furthermore, these calculations show that the grinding forces are increasing most when machining multiple gaps in the area with the maximum grinding forces. In this area, initial grinding burn can be expected for this process strategy. This has already been shown by Schlattmeier (Ref. 2).

The most common process strategy in industrial practice is the radial infeed of the grinding wheel. In this case, the local stock Δs varies along the profile geometry. For typical trials, as well as for these calculations, a pre-ground gap is used in order to make sure that infeed a_e is constant along the profile. The important geometric values for a radial in-feed of $a_e = 0.235$ mm versus the workpiece radius are shown in Figure 12.

The local stock shows a maximum of $\Delta s_{\max} = 0.235$ mm $= a_e$ in the area of the tooth root, and lowers to a minimum short below the root form diameter of $\Delta s_{\min} = 0.02$ mm. Towards the tip flank, it increases again—to a local maximum of $\Delta s = 0.2$ mm. The contact length l_g is constant along the profile, but the oriented stock removal shows an absolute maximum in the tooth root, a minimum short below the root form radius, and a local maximum in the area of the tip flank.

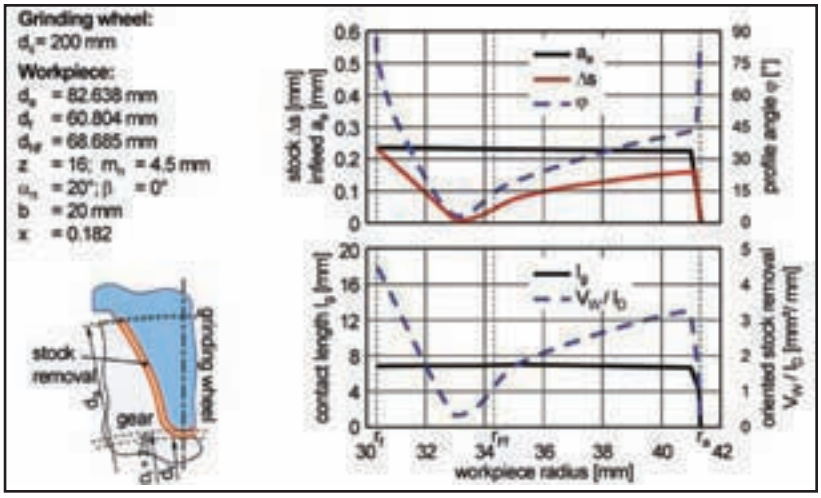

Figure 12—Local grinding conditions for a radial infeed of the grinding wheel.

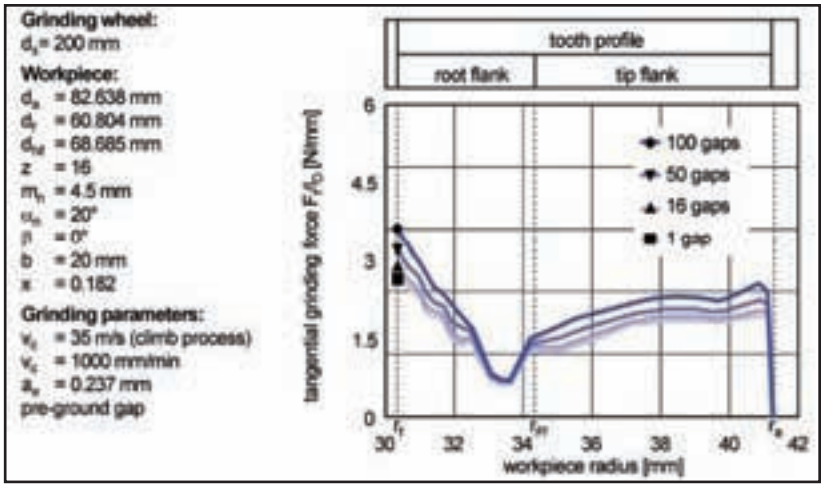

Figure 13—Tangential grinding forces for a radial infeed of the grinding wheel.

With this data, it is now possible to calculate the local grinding forces along the gear profile geometry. The calculations of the tangential grinding forces F_t versus the workpiece radius are shown in Figure 13.

The grinding force F_t shows a maximum in the tooth root and a minimum in the area of the root flank, just below the root form radius. Another local maximum can be observed in the area of the tip flank. After grinding multiple gaps in the area of the minimum forces, there is hardly any increase. But in the areas of the tooth root and the tip flank, grinding forces are increasing with the number of ground gaps. Increased grinding wheel wear can be expected, and grinding burn is most likely to occur in these areas.

With these calculations, it is known that in the areas found to be critical, grinding burn occurs when using a radial infeed strategy in gear profile grinding (Ref. 2). When grinding the gear with a radial infeed including the tooth root, a grinding burn occurs mostly at the tooth root. When grinding the gear with a radial infeed

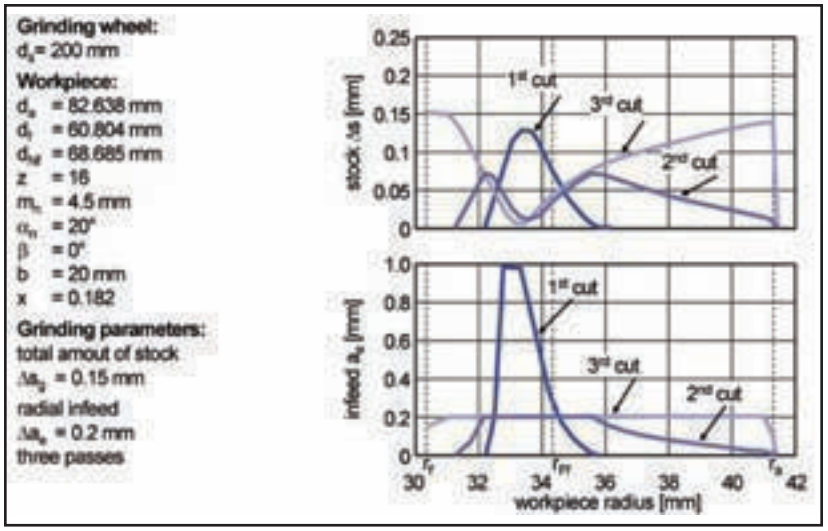

Figure 14—Local stock removal in infeed direction a_e and normal to the profile Δs.

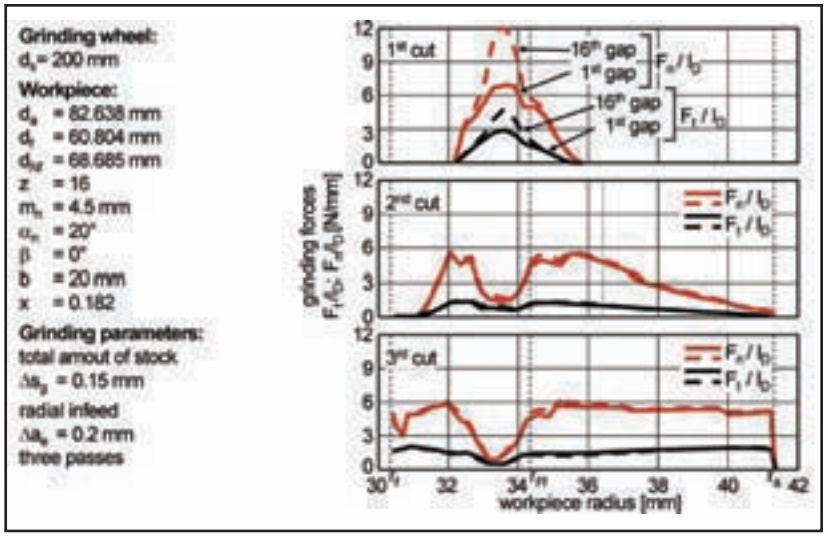

Figure 15—Tangential grinding forces for a radial infeed of the grinding wheel.

without the tooth root, the grinding burn is most likely to occur at the tip flank. These are the areas where, based on these calculations, the maximum grinding forces can be found.

Evaluation of Process Strategies Using the Process Model

Following is an example for the evaluation of process strategies, using the empirical process model to calculate local grinding forces. Grinding forces are calculated not only for one grinding step, but also for an infeed strategy using multiple steps, including deviations from the desired shape that can be due, for example, to centering deviations. It is only necessary to be able to calculate the local stock removed in the evaluated cut, as well as in the local profile angle. An example of this using the grinding of a test gear will be simulated with three radial infeed steps of 0.2 mm each. This means that the first cut takes place at a center distance between grinding wheel and gear which is increased by 0.4 mm, compared to the final center distance creating the final contour.

In Figure 14, the local stock in the direction normal to the tooth flank Δs and the stock in infeed direction a_e are shown. In the first grinding step, material is removed from the gear flank only in the area of the root flank. In the infeed direction, the infeed into the material is up to a_e = 1.0 mm, which means that a stock in normal direction of Δs = 0.13 mm is removed. The result is that, in the area of the root flank, nearly all the stock is removed by completion of the first step. In the last step, material is removed along the whole profile, and the radial infeed amounts to a_e = 0.2 mm.

This is because the whole profile height has been ground in the second step. In the area of the root flank, only a very small amount of stock is removed in the normal direction. While in the area of the root and tip flanks, nearly all stock is removed in the last cut.

The resulting grinding forces for these contact conditions are shown in Figure 15. The upper diagram shows the grinding forces in cutting and normal direction for the first cut. The drawn-through lines show the grinding forces when grinding the first gap with a newly-dressed grinding wheel. The broken lines show the grinding forces for grinding the sixteenth and last gap in order to gain an impression of the development of the grinding forces with the set-in time of the grinding wheel.

In the area of the root flank, very high local grinding forces can be seen, and those forces are increasing quite a lot with an increasing stock removal. This means that this area is susceptible to grinding burn in the first grinding step. To reduce that burn risk, the center distance between the grinding wheel and the workpiece must be increased. However, this will require more cuts and thus increase the manufacturing time on the machine tremendously.

In the last grinding step, the grinding forces are smaller than in the first. There is also a smaller increase of those forces, with an observed increase of material removal. It is nevertheless apparent that the grinding forces are increasing towards the tip flank and the tooth root. This means that these areas are very sensitive to grinding burn when using an infeed strategy for a radial infeed of the grinding wheel. These areas are known to be most critical towards grinding burn, which can be seen in the grinding forces (Ref. 2).

It can thus be concluded that the areas most critical to grinding burn can be evaluated by a calculation of the local grinding forces. While

the area of the root flank is most susceptible to grinding burn occurring in the first grinding step, the areas of the tooth root and the tip flank are most susceptible for burn in the last grinding step. Using this calculation of the grinding forces, it can be evaluated qualitatively how critical a gear geometry is in relation to grinding burn towards another, and if the chosen infeed strategy is critical as well.

Summary and Outlook

Gear profile grinding, especially using dressable grinding wheels, is a process rather sensitive to grinding burn. It therefore is important to understand the process well in order to either prevent grinding burn or, at minimum, if a grinding burn appears, to be able to change the process in a way that prevents it. This is especially important since grinding burn reduces the hardness of the external layer, and leads to tensile stresses which reduce the load-carrying capacity of the gear, thereby making gear failures more likely.

The main consideration when trying to better understand the process of gear profile grinding is the constantly changing contact conditions along the profile. In real process trials, only effects resulting from all those contact conditions along the profile can be observed. And since grinding burn, in most cases, occurs only locally, the effect on values like grinding power or grinding forces often cannot be seen initially.

In order to attain better knowledge of the effect of local grinding conditions on the process behavior, an analogy process was established to analyze them.

Rectangular workpieces were ground in a clamping fixture that can be turned in order to set the different profile angles occurring on a tooth flank. Particularly in this analogy process, grinding forces have been measured. The results reveal that grinding steep profile angles leads to a high risk of grinding burn, which can be due to the increasing contact length, and, in turn, can lead to a higher amount of energy conducted into the workpiece. The main goal of these tests is to facilitate an understanding of the real-time process.

Since the amount of heat conducted into the material is proportional to the cutting force, a process model has in fact been developed for calculation of local grinding forces. This model enables calculation of local grinding forces, provided local contact conditions and the set-in time of the grinding wheel are known.

With the aid of this process model and *CASTOR* software (with the ability to simulate different gear finishing processes), various process strategies in gear profile grinding can be considered and analyzed. Calculations show that in a radial infeed strategy of the grinding wheel in the first cut, maximum forces are calculated in the root flank area. In the last cut, the maximum is calculated in the tooth root and the tip flank—areas known to be most exposed to grinding burn. With these calculations, the reasons for this exposure can be demonstrated. They also demonstrate that for the removal of an equidistant stock along the profile, the maximum forces can be observed in the area of the root flank. This is also the area known from the real process of gear profile grinding to be most sensitive to grinding burn.

In order to evaluate the risk of grinding burn, both qualitatively and quantitatively, future research must focus on developing a specific value. Since the level of grinding forces observed depends very much on the ground profile angle, the goal in developing a specific value is finding a limit where, if the value exceeds the limit, grinding burn can be observed independent of the contact conditions.

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Gear Design:

Multipoint Properties are Key to Selecting Thermoplastic Materials

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Management Summary

The palette of thermoplastic materials for gears has grown rapidly, as have the applications themselves. Designers need to be aware of key properties and attributes in selecting the right material.

Introduction

Thermoplastic gear applications have expanded from low-power, precision motion into more demanding power transmission needs, even in such difficult environments as automotive engine compartments. Thermoplastics have supplanted metals in a number of applications, beginning historically (as might be expected) with the replacement of die cast metal gears. The range of applications has expanded as thermoplastics have proved their worth, and they are now increasingly specified for a growing number of more demanding applications.

While thermoplastic gears can be made by traditional gear machining methods, the majority of them are made by injection molding. With well-designed tooling, millions of gears at very tight tolerances can be turned out cost-effectively. Also attractive is the ability for part consolidation, including the molding of gear shaft and gear as a single unit, as well as one-piece compound gear units, where two or more spur or helical gears make up the design.

Regardless of the gear geometry or how it is manufactured, determining which of the many available materials to use is generally one of the first steps in the design process. Importantly, the material gives the gear its physical properties and greatly affects its usability for a given application. For example, in a high-temperature environment, a metal gear would traditionally be selected. In recent years, high-temperature, internally lubricated thermoplastic compounds have become available, providing designers with alternative material options. This can potentially offer savings in production by reducing the manufacturing steps involved. These compounds can also provide lubrication without the need for external oil or grease, avoiding problems from deterioration of lubricants over time and eliminating the need for maintenance and recurring application of oils or greases.

Finding Data on Thermoplastic Gear Materials

Historically the resins of choice for many thermoplastic gears were either neat polyamide (nylon) or neat polyoxymethylene (POM or acetal). As the available palette of materials has grown, and the weight, cost, corrosion resistance, low inertia, and noise advantages of thermoplastic gears have become more clear, interest has grown in thermoplastics for more demanding applications. In particular, the applicability of thermoplastics has been expanded by the development of specialized formulations that include reinforcement and internal lubrication.

Despite the availability of new thermoplastic compounds, however, designers can find themselves hampered by a scarcity of load-carrying and wear performance data, at least when compared to the large amount of easily accessible material performance information on metals. Granted, a certain amount of the design process used for metal gears can be carried over to thermoplastic gear design. However, simple interpolation of material data from metal to plastic does not work, largely because of the differences between the long-term mechanical and thermal behavior of thermoplastics versus metals.

Limitations of Single-Point Data

When choosing materials for a given application, single-point data can provide a place to begin. Such data are readily available across a range of materials and are typically displayed on a material supplier's technical datasheet. Attributes such as tensile strength, flexural modulus, and impact strength offer a snapshot of a material's performance—but single-point data do not provide the whole picture. The reason lies in the inherent characteristics of thermoplastics. Over a given temperature range, the physical and mechanical properties of a thermoplastic will change more significantly than do those of a metal. For example, tensile strength and stiffness (modulus) will decline with increasing temperature. Single-point data does not capture these types of changes.

Data-Development Initiatives

Because real-world gear designs depend on multivariate data, GE Plastics set out to establish performance and processing attributes for some of its specialty compounds in relation to gear design across appropriate ranges of environmental conditions found in gear applications. The dynamic variable differs by attribute, but most are time- or temperature-related (among these are stiffness, tensile strength and coefficient of thermal expansion). Whatever the attribute, in a performance application such as gear design, engineers need to know how a

Table I—Common resins used for thermoplastic gears. Almost all can be modified for flame retardancy and can be reinforced with glass, carbon fibers or lubricants. Several have been alloyed with other resins to create an application-specific set of characteristics.

Resin	Common Abbreviation	Key Resin Features
Polycarbonate	PC	High impact Good dimensional stability
Polyphenylene Oxide	PPO	Low specific gravity Good dimensional stability Low moisture absorption
Polyoxymethylene (Acetal)	POM	Low wear factor Superior friction resistance
Polyamide (Nylon) 6,6	PA66	Good chemical resistance Low specific gravity
Polyphenylene Sulfide	PPS	High strength High heat resistance Good chemical resistance Hydrolytic stability
Polyphthalamide	PPA	Good chemical resistance High heat resistance
Polyetherimide	PEI	High heat resistance Good dimensional stability High strength

Table II—Conventional single-point data for two grades of two different resins—a high modulus PPS and a lower modulus PA66. While this captures a number of resin attributes, it does not reflect some important dynamic data about, for example, tensile strength versus temperature (see Figures 1 & 2).

	ASTM Method	Unit	High Modulus PPS	Lower Modulus PA66
Specific Gravity	D792	g/cm^3	1.69	1.03
Mold Shrinkage	D955	%	1–3.5	18–23
Water Absorption (24 hours)	D570	%	---	0.20
Tensile Strength (Break)	D638	MPa	146	53
Tensile Modulus	D638	MPa	12,888	2,172
Tensile Elongation (Break)	D638	%	1.5	27
Flexural Strength	D790	MPa	200	76
Flexural Modulus	D790	MPa	11,000	2,320
Notched Izod Impact	D256	J/m	85	59
Heat Deflection Temperature (1.82 MPa)	D648	°C	269	78
Flammability	(UL94)	---	V-0 @ 1.5 mm	HB @ mm

thermoplastic compound's performance varies with time and temperature. Similar data is available for some of the more common engineering resins used in gearing, but our efforts concentrated on internally lubricated and glass fiber-reinforced compounds. In support of this effort, GE Plastics created a new laboratory specifically for developing performance data to support gear design in engineering thermoplastic materials.

In relation to gears, the new lab generates thermoplastic material performance data at multiple temperatures and loads, and it can also measure gear accuracy and gear performance characteristics, including wear, friction, noise generation, and allowable tooth stress. In addition, the laboratory develops injection molding production parameters for tooling design and processing. Resins tested to date include compounds based on polycarbonate (PC), polyphenylene oxide (PPO), polyoxymethylene (POM or acetal), polyamide (PA), polyphenylene sulfide (PPS), polyphthalamide (PPA), and polyetherimide (PEI) (see Table I).

Comparing Single-Point to Multivariate Data

While space precludes the inclusion of specific data for a broad range of resins suitable for gears, we can compare single-point data with dynamic data ranges for two contrasting resins as a means of illustrating how multivariate data contain more useful information than single-point data. The first resin is a relatively high-modulus, internally lubricated, 30 percent glass fiber-reinforced polyphenylene sulfide; the second is a relatively low-modulus, low-wear PA66. (*Important note*: *These data apply to two specific formulations. One advantage of thermoplastics is that they can be compounded, alloyed, or mixed using multiple resins, additives and processing or performance aids. Differing formulations result in differing performance and processing characteristics. Thus, it is important to know precisely the formulation to which a given data set applies. It is equally important to refrain from extrapolating data from known formulations to resins with similar descriptions, as generic descriptions such as "30 percent glass-filled" may not capture complete formulation details.)*

There are two key conclusions to be drawn from this comparison of single-point data (Table II) and dynamic or multipoint data (Figures 1 and 2). First—and this is the main point—is that each type of thermoplastic resin may exhibit very different material behaviors (in this case, as a function of temperature) across a given application's operating environment. Second, different thermoplastics can exhibit widely different performance for a given parameter. While these two material examples show very different performance characteristics, both have been successfully used in gearing, albeit in very different applications.

Key Parameters Studied

For a material to be successfully used in a gear application, it must meet several basic requirements. First, it must be strong enough to carry the transmitted load, both in a static position and as a repeated cyclic event. Second, it should not prematurely wear or cause wear on its mating gear. It must meet both of these requirements over the entire operating range of the application. Third, it should be dimensionally stable over the expected operating conditions of the application. A fourth requirement that is often missed is that the material should lend itself to a repeatable manufacturing process. Any test regimen selected should have these basic requirements in mind. Based on these general gear design requirements, as well as our experience with customer projects, we have gathered extensive data on the following performance properties:

- Load Carrying Capability
  - o Tensile strength
  - o Tensile creep
  - o Tensile fatigue
  - o DMA (Shear)
- Wear
  - o Gear wear testing
  - o Thrust washer wear testing
  - o Dimensional stability
- Dimensional Stability
  - o Coefficient of thermal expansion
- Processing
  - o Thermal conductivity
  - o Shear rate vs. viscosity
  - o Specific heat
  - o Mold shrinkage

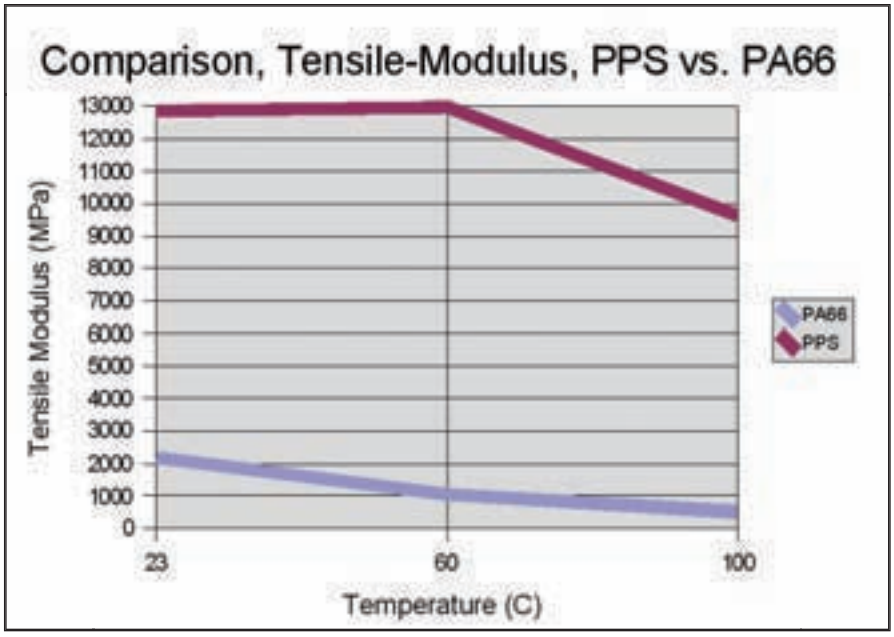


Figure 1—Comparison of tensile modulus for one grade of PA66 versus one grade of PPS resin. Note the changes in material behaviors as the temperature increases. This shift in performance with temperature is not captured by the single-point data in Table II. Resin grades were selected for maximum contrast and represent only one attribute. Do not use for general engineering purposes, as these data reflect only a range of values obtained in a specific series of testing at GE for specific grades (PPS = GE's LNP Lubricomp OFL-4036 specialty compound; PA66 = GE's LNP Lubriloy R specialty compound).

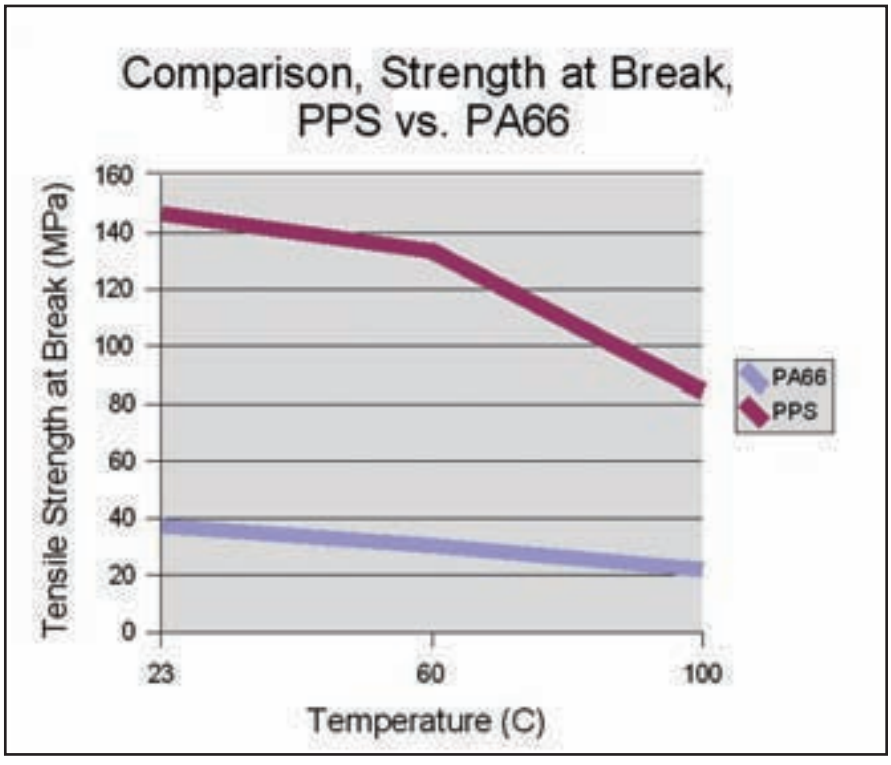


Figure 2—Comparison of tensile strength for the same grades of PA66 and PPS in Figure 1. Again, note the fact that these dynamic data capture differences in material properties for each resin grade versus temperature, similar to Figure 1. Single-point data at room temperature would not convey the shift in performance with temperature change. Resin grades were selected for maximum contrast and represent only one attribute. Do not use for general engineering purposes, as these data reflect only a range of values obtained in a specific series of testing at GE for specific grades.

Figure 3—Gear with broken teeth.

Figure 4—Gear with melted teeth.

Figure 5—Thinned gear teeth.

Load Carrying Capability (Bending Stress)

When evaluating the load carrying capability of a gear tooth, it is useful to know a material's strength characteristics. Even though the applied load is bending the tooth, the primary stress is on the side of the tooth in tension, and this is the location of most tooth failures due to overload (Fig. 3). For this reason we suggest looking at tensile strength and modulus as opposed to flexural strength. Tensile strength tests can be run at a variety of temperatures and can reveal information on a material's strength and ductility (toughness).

To assess the effect of the repeated nature of the load application in a gear set, some form of fatigue data is important. Flexural fatigue is a common test, but tensile fatigue testing can also be useful. Flexural fatigue testing requires a unique sample configuration, but the current ASTM standard (D671-93) has been withdrawn by ASTM and has not been replaced. Tensile fatigue tests can be run on the same type of sample used for other tensile tests, and tensile fatigue testing also better mimics the stress application seen in a one-directional gear-on-gear wear test currently being run by GE Plastics. Fatigue failures in gears can look like overload failures (tooth breakage at root), or can lead to thermal failures as the repeated flexing of the tooth leads to hysteresis heating and material flow (Fig. 4).

While it's typical to consider the cyclic nature of gear loading in most applications, many applications require the gear to hold a load in a fixed position for some period of time. In these situations it will be important to understand the material's creep performance—that is, its tendency toward permanent deformation. Under constant load, thermoplastic materials will exhibit varying degrees of permanent deformation, dependent on applied loading, resin type and reinforcement type. If, in a particular application, a gear is holding a load (that is, the teeth are under constant load), the teeth under load could deform permanently, potentially leading to increased noise, loss of conjugate action or outright tooth failure due to interference.

Figure 6—Tensile strength vs. temperature.

Rationale	**The physical properties of thermoplastics typically vary with temperature, so it is appropriate to test a target material across a range of temperatures that will be encountered in a given application.**
Test Method	**ASTM D638. Under controlled thermal conditions, the test specimen is pulled until it breaks. By measuring the force required to break the specimen, as well as the distance it stretches before breaking, this test produces a stress-strain diagram that is used to determine tensile strength, elongation and tensile modulus.**
Representative Data	**See Figures 1 and 2, above**

Wear Behavior

Tribological factors are highly important in all gear applications. A material's wear and friction characteristics are important to understand, because they can affect such critical factors as gear tooth life, tooth mesh and backlash, noise generation, and gear train efficiency. Self-lubricating properties and enhanced wear resistance are primary reasons that many designers switch to plastic gears. Consequently, the wear factor and coefficient of friction of a given resin are key properties to understand.

Even if the material data suggest that a particular material is strong enough to carry the applied load for the number of cycles expected in the application, another concern is wear of the gear set. The removal of material from the active flank of a gear tooth can dramatically limit the life of the gear, since a thinner tooth may not support the design load of the application (Fig. 5). Wear behavior is influenced by the materials/fillers used in the gear pair, environmental conditions and contaminants, and the load condition of the application.

Two different tests have been used to characterize the wear performance of gears. Traditional wear testing is done on a thrust washer wear configuration, which places the raised edge of a rotating disc (moving sample) in contact with another material (stationary counterface). The volume of material lost during the test is recorded, and a wear factor is calculated for both the moving and stationary sample. Measurements of coefficient of friction can also be made during the test.

Versions of this test have been widely used to determine if a particular material pair "wears well" or not. Failures can be characterized as a large loss of material (high wear) or a thermal failure (material flow, "PV" or pressure-velocity failure) due to frictional heat generation.

A new type of wear test using actual molded gears has also been developed. In this test two molded gears are run together at a predetermined speed and load. Any loss of material from the face of the gears is detected as a shift in the phase angle between the driving and driven gear shafts. This phase shift is expressed as a linear value and charted against the time the gear set is running. This wear value is a combination of the loss of material from the gear tooth and any additional deflection caused by the tooth thinning or increased flank temperatures. Some might describe the value as an increase in backlash, but backlash has a specific definition in gearing that doesn't fit this value. This same test can be used to generate fatigue curves (S-N) for a set of gears by simply running the gears at a series of loads/speeds and plotting the curves vs. cycles. Tooth wear as a factor in failure must be included. Similar tests are being adopted by the industry for application testing and validation.

Dimensional Stability

Even the best-designed gear set that uses an appropriate material for the strength and wear requirements of the application can fail if the gears cannot be held at the proper operational center distance. Two aspects of thermoplastics that can make this a challenge are changes in the size of the gear due to temperature change and moisture absorption. For most materials the thermal component will overshadow any growth due to moisture absorption. A gear designer needs to consider the gear mesh not only at a maximum and minimum material condition (as a result of runout in the finished gear), but also at those conditions as influenced by the maximum and minimum temperature in the application. Multi-point coefficient of thermal expansion data can be consulted to evaluate this effect.

Figures 6–12 discuss the testing of different gear-related parameters. In each figure, you will find (a) the rationale for considering a parameter as important to

Figure 7—Tensile fatigue.	
Rationale	Fatigue tests for thermoplastics simulate cyclic loading conditions that lead to fatigue failure. These tests can be important in characterizing a material's response in use. This test is useful because it can provide insight into a material's performance under load conditions similar to what gear teeth see in operation. Standardized tests exist for both flexural fatigue and tensile fatigue.
Test Method	Specimens are strained under a given load at a specific frequency, generally one that does not heat the specimen. The specimen may be loaded with a strain-controlled configuration that could result in reduced stress if elongation or yielding occurs. The applied load is the same on the first loading cycle as on the last cycle.
Representative Data	Tensile fatigue of a PPO-based compound at 23°C, 24 percent relative humidity (GE's LNP Lubriloy Z specialty compound). There was no break at the 15 MPa stress level over 1.000.E+06 cycles.

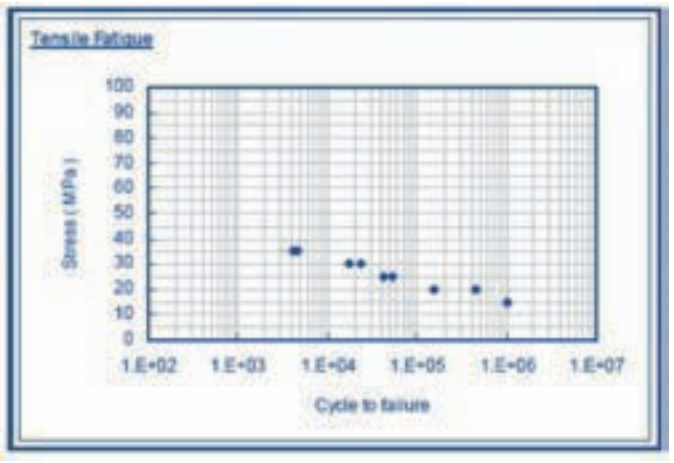


Figure 8—Tensile creep.	
Rationale	Under constant load, thermoplastic materials will exhibit varying degrees of permanent deformation. This is dependent on applied loading, resin type and reinforcement type. This can be important when gears are expected to support a load for a period of time in a static position and then resume rotational operation at a later time.
Test Method	ISO 899-1. This is a method for determining the tensile creep of plastics in the form of standard test specimens under specified pretreatment conditions of time, temperature, and humidity.
Representative Data	Tensile creep of a flame-retardant polycarbonate resin grade (GE's LNP Lubriloy D-FR non-chlorinated, non-brominated flame-retardant system specialty compound), at 23°C and 60°C.

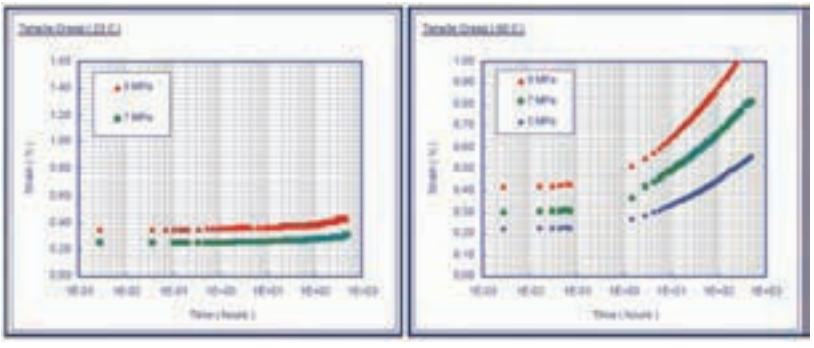


Figure 9—Wear factor.	
Test Method	Proprietary test developed by GE LNP Specialty Compounds. In this test, the plastic test sample rotates against a stationary counter face. Any pair of materials can be evaluated; however, the standard test is the thermoplastic compound of interest on 1141 cold rolled steel with a 12–16 µin finish. The weight loss of the plastic sample is converted to volume wear (W), and (W) is then used to calculate wear factor (K).
Representative Data	See Table III

Table III—Representative resin wear factor K and COF (coefficient of friction, static & dynamic) versus steel and unmodified POM. K factor is determined at 40 psi moving 50 ft./min; unit is 10^{-10} in^5-min/ft-lb-hr.

Specialty Compound Tested[1]	Wear factor (K_{moving}) at 40 psi, 50 fpm	Wear Factor ($K_{stationary}$) at 40 psi, 50 fpm	Static COF at 40 psi, 50 fpm	Dynamic COF at 40 psi, 5 0 fpm
PC[1] vs. Steel	60	0	0.09	0.16
Vs. POM	16	40	0.17	0.19
POM vs. Steel	10	0	0.24	0.38
Vs. POM	(failed)	(failed)	0.16	0.13
PPS vs. Steel	33	10	0.35	0.44
Vs. POM	3	73	0.36	0.46
PEI vs. Steel	124	3	0.11	0.17
Vs. POM	(failed)	(failed)	0.32	0.26

[1] This table reports data for the following LNP Specialty Compound resin grades: PC = GE's Lubriloy D specialty compound; POM = Lubriloy K specialty compound; PPS = Lubricomp OFL-4036 specialty compound; PEI = Ultem 4001 specialty compound.

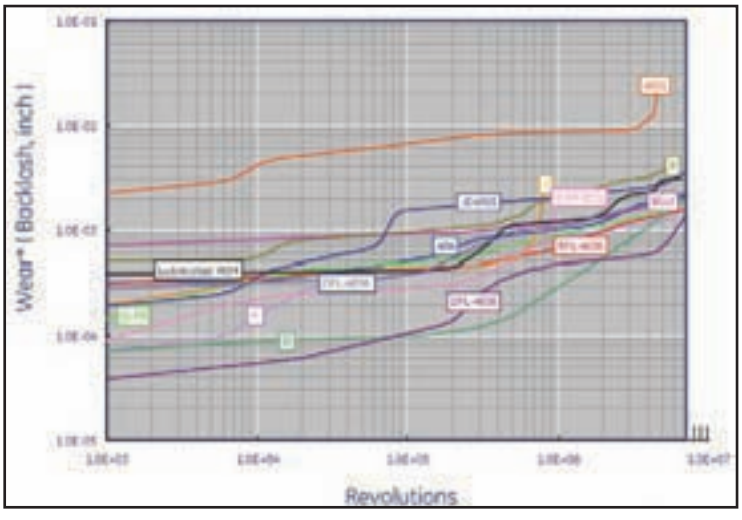
gears; (b) the test method; and (c) representative data. The data are necessarily representative because space limitations preclude inclusion of all data gathered to date for all compounds evaluated.

Dimensional Accuracy

Typically, the mold shrinkage values given for a material have been determined by measuring the shrinkage of a 5" x 1/2" x 1/8" rectangular bar measured in accordance with ASTM D-955 test methods, or a 60 mm x 60 mm x 2 mm plaque for ISO 294 test methods. These values are usually given corresponding to the dimensions that are parallel (flow) and perpendicular (transverse) to the direction of melt flow in the part. They are normally expressed as "inch/inch" or sometimes as a percentage. These mold shrinkage values can be useful in comparing the relative shrink rate of one material to another, but they should not be treated as absolutes. Mold shrinkage can and will vary with part thickness, mold layout, processing variations, and mold temperature.

Of greater value is mold shrinkage data collected on an actual part, whether it is a simple prototype mold or a similar application. It was this approach that was

Figure 10—Actual gear wear.	
Rationale	A material's wear and friction characteristics are important to understand, because they can affect critical factors such as gear tooth life, tooth mesh and backlash, noise generation, and train efficiency. Self-lubricating properties and enhanced wear resistance are primary reasons that many designers switch to plastic gears. Consequently, the wear factor and coefficient of friction of a given resin are key properties to understand.
Test Method	Proprietary test developed by GE LNP Specialty Compounds. In this test, two mated gears are rotated by a servo motor connected to the drive gear. The gears are run at 509 rpm at 22.2 inch-pounds torque until failure or 10^6 cycles.
Representative Data	Actual gear wear of selected resin grades. Seven grades show less wear than standard lubricated POM (dark gray line). Three exhibit greater wear. The wear value shown reflects a change in the tooth thickness of the tested pair.



used to study the effect internal lubricants and reinforcements have on the overall accuracy of a gear. A series of gear cavities based on a common spur gear geometry was created to mold a range of materials. The molded sample gears were then used to study how material composition affects dimensional parameters, including:

- Warpage
- Eccentricity
- Radial composite error
- Profile and helix deviation
- Pitch deviation

Specific data are not supplied here, because the range of conditions and results generated are both too extensive for presentation and are beyond the scope of this article.

Your Design Methodology

Key to specifying materials for gear applications is a full understanding of material properties in the conditions that the gear train will see in use. The availability of multipoint data is crucial for this engineering process. As a specifier, you will be best served by working with materials experts who can provide a rich dataset—one that captures performance across the full range of end-use environments—and, further, can work with both design and manufacturing to refine the selections from a universe of outstanding material candidates.

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Figure 11—High shear viscosity.	
Rationale	The screw in the barrel of an injection molding machine can create high shear as it turns, as can high pressure flow through runners and cavities in the molds themselves. This test is important for determining a variety of processing parameters.
Test Method	In this test, a capillary rheometer measures the viscosity of the resin under high shear rate conditions (>100 sec^{-1}). The material is kept at a constant temperature in the barrel as it is pushed by a piston through a capillary die at various rates of shear. The test is performed over a range of temperatures and shear rates that correspond to typical processing conditions.
Representative Data	Example of high shear viscosity data (fire retardant polycarbonate, GE's LNP Lubriloy D-FR non-chlorinated, non-brominated flame retardant system specialty compound) at three temperatures: 265, 280 and 295°C).

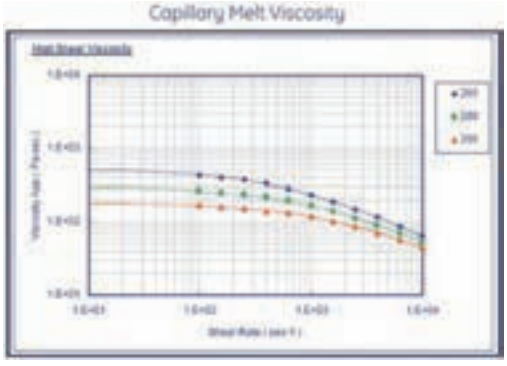
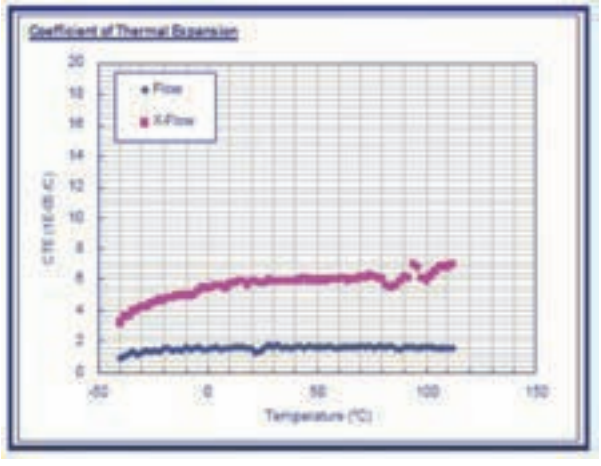
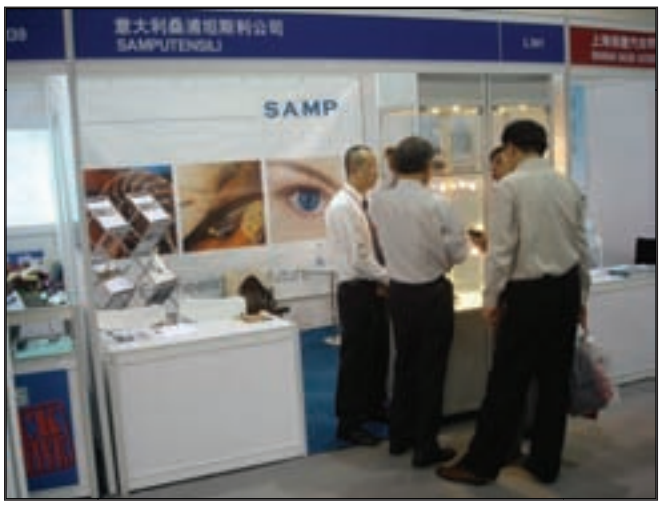


Figure 12—Coefficient of thermal expansion (CTE).	
Rationale	CTE helps predict dimensional changes as a result of changes in temperature. Dimensional changes are measured in two directions, one in the flow of the resin during molding and the second across or perpendicular to that flow. The reason is that many thermoplastics, especially thermoplastics filled, for example, with glass fiber reinforcement (in which the fibers tend to align themselves along the axis of flow), can exhibit differing dimensional changes in the flow and across-the-flow directions.
Test Method	ASTM E831. In a furnace or temperature bath, a test specimen is measured at room temperature and across a specified range of temperatures, with a soaking period at each temperature of interest. The results are then graphed.
Representative Data	Coefficient of thermal expansion for a grade of PEI-based compound, measured with the flow and cross-flow ("X-flow"). Compound grade is GE's Lubricomp BGU specialty compound.



Gear Manufacturers and End Users Congregate in Shanghai



Statistics compiled from the China Machinery Industry Federation say that the demand in China for gears has exceeded $6 billion in the construction portion of the industry alone. There are about 1,000 gear manufacturers in China, and industry experts predict that those figures will increase every year with more automotive and manufacturing projects.

Gear China was held concurrently with the Machine Components 2006 Show featuring fasteners, chain transmissions, gears, springs, powder metallurgy, hydraulics and pneumatics from September 25–28 in Shanghai.

In addition to the networking, visitors also had the option of attending any of four gear-related presentations. Speeches focused on gear rolling technology, gear lubrication development with Chinese-specific solutions, and autoshift gearbox technology, making Gear China an educational experience as well.

For George Boon, sales manager at Schnyder SA, a manufacturer of gear cutting tools, the decision to exhibit at Gear China just made sense because of logistics.

"We were very impressed with the quality and quantity of visitors. It was especially important when you take into consideration our business in China. It's a huge country and there is no way we could've met so many of our Chinese customers in just three and a half days without traveling all over. Shanghai is centrally located for most of our customer base and we got to see a lot more people because of this," he says.

Samputensili SpA attended Gear China in 2003 and noticed significant improvement in this fall's program. Patrizia Fiaccadori, marketing manager at Samputensili, says "Although we did get a good overall impression of the show three years ago, the number of exhibitors and visitors was still relatively low. This was probably due to the fact that there are so many local gear-related exhibitions in China that deciding which one to attend can often be confusing. This year, however, we saw many important local exhibitors and a significant increase in the number of visitors compared to last year and, of course, three years ago."

She continues that Samputensili SpA has emphasized local marketing in China for the past decade, mostly through the SU Beijing sales office. Earlier this year, the company opened its first cutting tool manufacturing facility in Shanghai and finds Gear China to be an important event.

"We chose to be at this event firstly because practically all major domestic gear manufacturers are there, but also because many interesting end-users visit the show. Even if these industries do not manufacture gears themselves, they use them. This event is a must if you operate in gear-related areas," she says.

Power Transmission and Gearing Conference Call for Papers

The 10th International Power Transmission and Gearing Conference will be held in conjunction with the ASME International Design Engineering Technical Conferences in Las Vegas, Nevada between September 4–7, 2007, along with eleven other ASME conferences.

ASME's Power Transmission and Gearing Committee is soliciting abstracts for the following topics:

- Gear Design and Analysis
- Gear Strength and Durability
- Gear Dynamics and Noise
- Gear Diagnostics
- Gear Manufacturing
- Gear Lubrication and Efficiency
- Engineered Surfaces and Tribology
- Transmissions
- Chains, Belts, and Traction Drives
- Couplings, Clutches, and Bearings

Please send your abstract as an e-mail attachment to *kahraman.1@osu.edu* before December 15, 2006.

November 1–3—2006 Motor and Motion Association Fall Technical Conference. Marriott St. Louis Airport Hotel, St. Louis, MO. Presentations, break-out sessions and tabletop exhibits focus on design, materials, performance and testing for suppliers to the motion control industry. Prices range from $250–$650. For more information, contact the Motion and Motor Association on the Internet at *www.smma.org* or by telephone at (508) 979-5935.

November 8–10—Advanced Gear Design and Theory. University of Wisconsin–Milwaukee, Milwaukee, WI. Users, beginning gear technologists and gear designers learn about proper selection, design application and use. Additional topics include manufacturing methods and considerations; inspection and quality control; materials and heat treatment; drawing data requirements, formats and specifications; basics of load capacity rating; and lubrication types and methods. $1,095. For more information, contact the University of Wisconsin School of Continuing Education on the Internet at *www.uwm.edu* or by telephone at (414) 227-3121.

EVENTS

November 14–16—Aerospace Design and Development Show. Anaheim Convention Center, Anaheim, CA. Design engineers, suppliers, development engineers and managers working in airframe, components, engine design and related subsystems can attend forums on design tools; rapid prototyping; simulation and modeling; materials; avionics design; managing strategies; aerodynamics; standardization, accreditation and regulations; outsourcing; next generation technologies; airframe, propulsion and sub-systems design and future aerospace design. The show is free to attend and includes 80 paper presentations. For more information, visit the conference website at *www.aerospacedesign-expo.com.*

November 14–16—UTS Metal Gear Design. UTS facility, Rockford, IL. The course covers gear fundamentals, gear tooth form, gear geometry, standard proportions, quality, gear modifications, gear design considerations and the gear design process. An hour of consultation with UTS gear design experts is included. Attendees receive free access to Fundamentals of Gearing, an e-learning course from UTS. $1,250. For more information, visit UTS online at *www.uts.com* or call (815) 963-2220.

November 16–17—Gears 2006. Holiday Inn at the Manchester Airport, Manchester U.K. The first day's seminar is broken down into the following categories: process industries; environment; design and manufacture; and total cost of ownership. Day two covers transportation; lubrication; and a plenary lecture. Price packages range from the all-inclusive option at 380 pounds (approximately $713) to 144 pounds (approximately $270) for a half-day seminar. For more information, contact The British Gear Association by e-mail at *admin@bga.org.uk* or visit the show's website at *www.gears2006.com.*

December 4–7—Gear School 2006. Gleason Cutting Tools facility, Loves Park, IL. Covers gear cutting, forming, generating, shaping, hobbing, tool tolerance vs. gear tolerance, tool design, use and maintenance, gear inspection and analysis. $895 includes a handbook, group dinner and all lunches. For more information, contact Gleason Cutting Tools by telephone at (815) 877-8900 or on the Internet at *www.gleason.com.*

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Chuck Bunch Appointed as NAM Chairman

The National Association of Manufacturers board of directors unanimously approved the nomination of Charles E. (Chuck) Bunch, chairman of the board and chief executive officer of Pittsburgh-based PPG Industries Inc., to become NAM Chairman for the 2007–2008 term.

PPG is a global supplier of coatings, chemicals, optical products, glass and fiberglass, with 110 manufacturing facilities and equity affiliates in more than 20 countries.

Bunch has served as vice chairman to NAM chairman John Luke, chairman and chief executive officer of MeadWestvaco Corp., since October 1, 2005.

Charles E. (Chuck) Bunch

Bunch joined PPG in 1979 and held a series of management positions before being named general manager of architectural coatings in 1992. He was made vice president of that unit in 1994 and vice president, fiberglass, in 1995. Bunch was elected senior vice president of strategic planning and corporate services in 1997, and executive vice president, coatings in 2000. In July 2002, Bunch was named president, chief operating officer and board member, becoming chief executive officer in March 2005, and taking his current post in July 2005.

As chairman of NAM, Bunch will focus on reducing the costs of manufacturing in the U.S., particularly with regard to reducing energy prices, taxes, and litigation, and working for a solution to the asbestos crisis.

"NAM is indeed fortunate to have a leader of Chuck Bunch's stature as chairman," said NAM president John Engler. "Chuck is well known throughout the business community as an inspired manager and visionary leader. We all look forward to his chairmanship."

The NAM board also confirmed Michael E. Campbell, chairman, president and chief executive officer of Arch Chemicals, Inc., of Norwalk, CT, to serve as NAM vice chairman.

Campbell will serve as vice chairman during Bunch's chairmanship, after which he will succeed Bunch for a two-year term as chairman.

AGMA Seeks New Vice President

Bill Bradley, AGMA's current vice president of the technical division, will retire at the end of 2006, and the association is currently accepting applications for his replacement.

The vice president, technical division is the senior technical employee and reports to the president. He/she is responsible for managing and operating technical activities, including those related to the development and maintenance of all U.S. and international standards; for operation and development of several technical programs, conferences and seminars; for relationships with outside vendors, contractors and educators; for operation of member committees necessary for the association's technical programs; for relationships with domestic and international members and prospects, associations, universities and other organizations as necessary.

The VP manages a staff of three and is also responsible for the relationship management of volunteers.

Suggested qualifications include an engineering degree with sufficient gear experience; a working knowledge of and experience with ANSI and ISO standards; proven management ability; strong public speaking and writing skills; and effective member relations.

To apply, e-mail a current resume to *vptech@agma.org*.

ISO Releases New Gear Standards

ISO's Technical Committee on Gears, comprised of a multi-national delegation, published several new standards, including:

ISO 6336-1:2006, Calculation of load capacity of spur and helical gears—Part 1: Basic principles, introduction and general influence factors.

ISO 6336-2:2006, Calculation of load capacity of spur and helical gears—Part 2: Calculation of surface durability (pitting).

ISO 6336-3:2006, Calculation of load capacity of spur and helical gears—Part 3: Calculation of tooth bending strength.

ISO 6336-6:2006, Calculation of load capacity of spur and helical gears—Part 6: Calculation of service life under variable load.

ISO 23509:2006, Bevel and hypoid gear geometry.

The AGMA Helical Gear Rating (ISO 6336) and Bevel Gearing (ISO 23509) committees served as the technical advisory groups, determining the U.S. position on technical issues, throughout the development of these standards. A more detailed explanation is available at *www.iso.org*.

Philadelphia Gear Offers 24/7 On-Site Technical Support

Philadelphia Gear announces its new On-site Technical Services (OTS) group, available twenty-four hours a day, seven days a week.

As an onsite solution to gearbox-related issues, OTS allows U.S. consumers to cut downtime caused by gear and transmission repairs. Removal, reinstallation, in-place machining, onsite overhauls, alignment, oil analysis and many other power transmission maintenance services are offered.

"It only takes one call for Philadelphia Gear to begin the evaluation process, dispatch a technician from one of five regional service centers, or schedule a 'job walk' in order to thoroughly understand the scope of the project and, most importantly, propose a solution," says Chuck Zirkle, manager for the OTS program.

Additionally, he says the company is in the position to supply OEM parts, then install them to bring decades-old gearboxes into "as-new" condition. Philadelphia Gear's service technicians will provide hands-on support throughout the process.

"OTS enables customers to stay focused on their business, while we seamlessly handle the repair with a 'one-stop-shop' philosophy," says Gerry Matteson, Philadelphia Gear's general manager. "By digitizing more than 3,000,000 pages of proprietary technical documents, we now have instant access to critical information from anywhere in the world with just a few keystrokes."

Ikona Exec Featured in Online Broadcast

Ikona Gear's CEO, Ray Polman, was featured live on Market News First on September 5.

According to the company's press release, he discussed the company's goals and current position in the stock market on the show.

Market News First is an online market news provider that brings investors current news on the market.

Ikona's gearing technology was invented in Russia between 1986–1991 for a lightweight, long-range, military assault helicopter. Laith Nosh acquired rights to the new gear invention and imported the technology to North America. From 1992–2001, Ikona's engineers worked under Dr. John R. Colbourne in the development and commercialization of powertrain products that incorporate the patented gear technology.

Northstar Aerospace and Rolls-Royce Sign Long-Term Agreement

Northstar Aerospace was awarded a seven-year contract by Rolls-Royce Corp. to provide machining for gearboxes and related parts used in commercial and military aircraft. The contract is estimated to provide $8 million in annual revenue to Northstar once in full production.

Northstar is establishing a facility in Anderson, IN to function as a specialized feeder plant for Rolls-Royce.

The Rolls-Royce facility in Indianapolis is the company's largest manufacturing operation in North America. They design, develop and manufacture engines and components for various fixed- and rotary-wing aircraft, including the Joint Strike Fighter, Embraer regional jets, Cessna Citation X corporate jet, V-22 tilt-rotor helicopter and other light single- and twin-engine helicopters.

"This contract is the latest in our growing relationship with Rolls-Royce. The proximity of a facility in Anderson provides the opportunity for Northstar to become a primary supply partner with Rolls-Royce, specializing in gearboxes and related components for Rolls-Royce engines used in defense and commercial applications," says Mark Emery, Northstar Aerospace's president and CEO.

According to Northstar's press release, the new facility will employ 40 people, mostly CNC machinists, by late 2007. The company estimates beginning to supply Rolls-Royce within the next 90 days and full production is estimated in 2008.

Mazda Hofu Plant Produces 25 Millionth Transmission

Mazda Motor Corp. announced that cumulative production of vehicle transmissions in the Nakanoseki district of its Hofu plant in Yamaguchi reached 25 million units. In addition, the company announced plans to increase annual production capacity of automatic transmissions for front-wheel-drive models from 655,000 to 764,000 units in response to the global demand for the Mazda 3 and Mazda 5.

According to the company's press release, the 25-million-unit milestone was achieved in 24 years and 9 months since the Hofu plant began production in December 1981. After production of the automotive parts began in 1981, the Hofu Plant No. 1 was built in the Nishinoura district in 1982 for vehicle production. Hofu plant No. 2 was added in the Nishinoura district in 1992 for vehicle production.

Lufkin Industries Announces Promotion of Larry Hoes to Executive VP and COO

Lufkin Industries promoted Larry M. Hoes to executive vice president and COO.

Hoes has been an executive officer since 1996. In his new position, he will manage the operations of the oil field division directly, including foundry operations. All vice presidents/general managers of the power transmission and trailer divisions will report to him.

"I am pleased to announce the promotion of Larry Hoes, a veteran Lufkin executive officer who has led the substantial growth of our oil field division into a position of worldwide industry leadership," says Douglas V. Smith, Lufkin's president and CEO.

Tool Maker Expands to Meet Automotive Demand

Engineered Tools Corp., a manufacturer of carbide cutting tools used in production of spiral bevel ring gears and pinions, announced the opening of its new Gear Cutting Systems Division facility. The expansion was driven by the Caro, MI-based company's recent positioning as a supplier to the automotive industry, which was seen primarily as an opportunity to grow new business.

According to John Ketterer, director of operations for Engineered Tools, the move—completed in October—was also made with an eye on the potential for meaningful growth within that market."We had been looking for an avenue to expand our business," he says, "and because this market has a significant percentage within the automotive industry, and given the state of that business, we took the risk of expanding within it."

The new 4,000-square-foot facility, located in Troy, MI, positions the toolmaker in close proximity to the Detroit axle manufacturing market. And, says Ketterer, given the company's growth beginning in 2004 and continuing through this year, he believes the timing of the expansion—despite the acknowledged risk—will dovetail with an eventual upturn for suppliers to the automotive market.

"After all, even though that market is very weak, currently it was new business growth to us," he says. "And entering it on the downside was gaining current market share with the potential for growth within the market."

But risk or not, Ketterer says that the expansion was needed in any case."We needed the room for expansion anyway, as our Caro manufacturing facility is full," he says. "So, we basically killed two birds with one stone. The facility was built to suit for our needs, and will accommodate our current

workload with enough room to accommodate significant growth in this business into the future."

For more information:
Engineered Tools Corp. Gear Cutting Systems Division
1307 East Maple Road, Ste. G
Troy, MI 48083
Phone: (248) 619-1616
Fax: (248) 619-1717

Engineered Tools Corp. Headquarters
2710 West Caro Road
Caro, MI 48723
Phone: (989) 673-8733
Fax: (989) 673-5886

Star Cutter Acquires Northern Tool Sale and Service

Star Cutter Company of Farmington Hills, MI, announced the acquisition by stock purchase of Northern Tool Sales & Service (NTSS) of Warren, MI, effective October 31.

Northern Tool Sales & Service is a design-and-build manufacturer of tooling concepts for special drills, reamers, step drills, form tools and solid carbide tooling, supplying approximately 170 customers in the ABS systems, cylinder head, and engine block manufacturing industries.

Star Cutter manufactures gear hobbing and shaping cutting tools, milling cutters, gundrills and reamers, carbide tools, PCD tools, and drills, selling through its partner, Star SU LLC. Star Cutter plans to integrate all NTSS customers with Star Cutter and Star SU.

Brad Lawton, president of Star Cutter, says, "This acquisition is synergistic, as well as complementary, to our market strategy for tool sales worldwide."

Chris Schulte, president of Northern Tool Sales & Service, says, "The sale to Star Cutter increases our ability to utilize the best technology of both corporations to increase our market penetration and service to our existing and potential customer base through Star SU."

AGMA Foundation's New Approach Yields Value for the Gear Industry

Starting last year, the AGMA Foundation Board redefined its mission.

Kyle Seymour, president and CEO of Xtek Inc., is board chairman. He outlines their new goals as two-pronged. The first part involves supporting work that enhances existing AGMA standards. Secondly, the foundation aims to fund the development of education and training so the industry can advance knowledge of the standards.

"We're changing our approach as well," Seymour says. "In the past, we've just let people know we're raising money. Now that we have identified two main areas—the development of science to support technical standards, and education and training—we can become more proactive based on need. We'll be able to identify where needs are and then search for a way to sponsor the project."

Numerous programs fall under the foundation's umbrella, and one of the most successful is the Detailed Gear Design Seminar. Seymour says the AGMA granted $6,000 to fund development of the course three years ago. Taught by Ray Drago, the class covers gear design; gear rating theory and analysis methods; differences in stress states among various surface durability failure modes; time-dependent and time-independent failure modes; examination of mesh action and tooth iteration with computer-generated graphics; and AGMA standards. The seminar has three classes that sell out very quickly and a waiting list of participants for the January 2007 class. Building on the success of the seminar, the foundation is providing $12,000 for a new Gearbox Failure Seminar that will be presented in early 2007.

One of the foundation's most frequent collaborators is the Ohio State University's GearLab. "OSU has historically had a great gear group and has always been a good partner for us," says Seymour. The AGMA Foundation funded a bi-annual research project on hypoid gear efficiency and has published year one's results on *www.agmafoundation.org* for interested parties to read free of charge. Year two results will be available in 2007.

The foundation's Workforce Education Program offers Internet-based interactive basic training courses in gears. Participants can take multi-level courses online and receive an AGMA certification for successful completion. Included in the nominal fee ($25 for Fundamentals of Gearing, $150 for Gear Inspection) is a study guide, sample exam, final exam and certificate.

Fundamentals of Gearing is a prerequisite to all other AGMA courses. Gear Inspection covers inspection methods and equipment.

Other foundation projects include "Where You Want to Be," a DVD presentation designed to recruit young people into the new gear industry. In addition the foundation funded a Gear Industry Technology Workshop. A full copy of the workshop is available on the foundation's website. Cindy Bennett, executive director of the foundation, says the foundation has already exceeded its 2006 fundraising goals and is only in the middle of the campaign season. In 2005, the foundation raised $183,276 between both the fall campaign and the auction that is concurrent with AGMA's annual meeting in the spring.

"We want the members to know that we're here and eager to match up your needs with the right providers and make good things happen for you," concludes Seymour.

Paulo Products Upgrades to ISO/TS 16949:2002

The St Louis, MO facility of Paulo Products Co. passed its upgrade audit and has been awarded accreditation to ISO/TS 16949:2002.

Created by the International Automotive Task Force (IATF), ISO/TS 16949:2002 represents the technical standard requirements of the major automotive manufacturers around the world. ISO/TS 16949:2002 is required to continually measure, monitor, and improve, with an emphasis on preventing defects and reducing waste throughout the supply chain. In addition to this recent quality system upgrade, Paulo–St Louis is approved to the Ford HTX standard and has received the Ford "Preferred Supplier Award."

According to the company's press release, Paulo–St Louis is the third Paulo facility to become accredited to ISO/TS 16949:2002. Paulo–Nashville and Paulo–Murfreesboro, TN received accreditation to ISO/TS 16949:2002 in 2005. Other Paulo facilities are currently working toward receiving the ISO/TS 16949:2002 upgrade.

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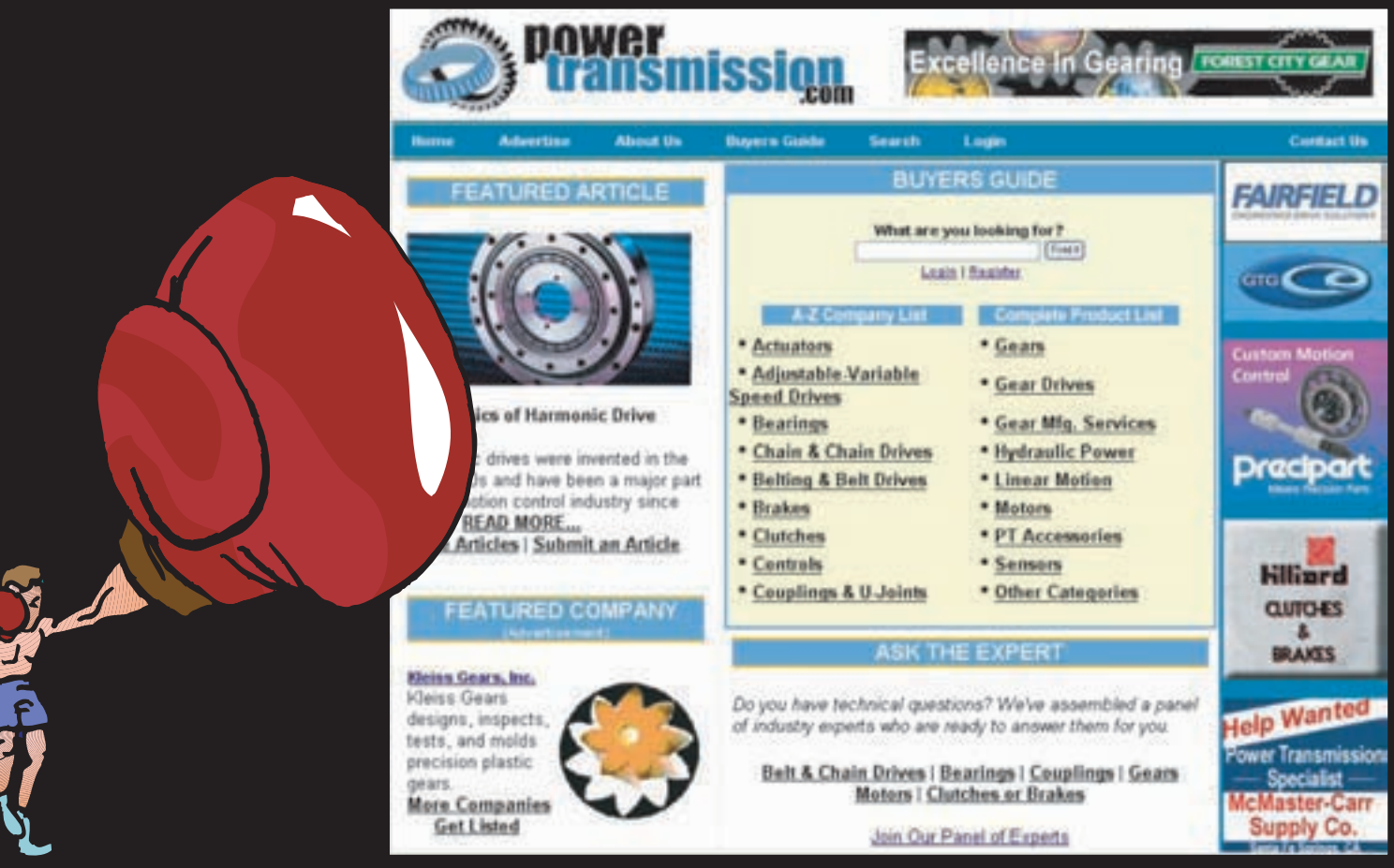

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Michael Goldstein, Publisher
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Publisher *(Name and complete mailing address)*
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Editor *(Name and complete mailing address)*
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Managing Editor *(Name and complete mailing address)*
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Full Name	Complete Mailing Address
Michael Goldstein	1425 Lunt Ave., Elk Grove Village, Cook County, IL 60007-1426
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11. Known Bondholders, Mortgagees, and Other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, or Other Securities. If none, check box → ☐ None

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The purpose, function, and nonprofit status of this organization and the exempt status for federal income tax purposes:
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PS Form **3526,** October 1999 *(See Instructions on Reverse)*

13. Publication Title: GEAR TECHNOLOGY The Journal of Gear Mfg			14. Issue Date for Circulation Data Below: Sept-Oct 2006	
15.	Extent and Nature of Circulation		Average No. Copies Each Issue During Preceding 12 Months	No. Copies of Single Issue Published Nearest to Filing Date
a.	Total Number of Copies *(Net press run)*		12,702	13,326
b. Paid and/or Requested Circulation	(1)	Paid/Requested Outside-County Mail Subscriptions Stated on Form 3541. *(Include advertiser's proof and exchange copies)*	9,491	10,368
	(2)	Paid In-County Subscriptions Stated on Form 3541 *(Include advertiser's proof and exchange copies)*	–	–
	(3)	Sales Through Dealers and Carriers, Street Vendors, Counter Sales, and Other Non-USPS Paid Distribution	422	543
	(4)	Other Classes Mailed Through the USPS	–	–
c.	Total Paid and/or Requested Circulation *[Sum of 15b. (1), (2),(3),and (4)]*		9,912	10,911
d. Free Distribution by Mail *(Samples, compliment ary, and other free)*	(1)	Outside-County as Stated on Form 3541	1,369	145
	(2)	In-County as Stated on Form 3541	–	–
	(3)	Other Classes Mailed Through the USPS	–	–
e.	Free Distribution Outside the Mail *(Carriers or other means)*		1,205	1,870
f.	Total Free Distribution *(Sum of 15d. and 15e.)*		2,574	2,015
g.	Total Distribution *(Sum of 15c. and 15f)*		12,487	12,926
h.	Copies not Distributed		215	400
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16. Publication of Statement of Ownership
☐ Publication required. Will be printed in the Nov-Dec 2006 issue of this publication. ☐ Publication not required.

17. Signature and Title of Editor, Publisher, Business Manager, or Owner: Michael Goldstein / Publisher — Date: 9/19/06

I certify that all information furnished on this form is true and complete. I understand that anyone who furnishes false or misleading information on this form or who omits material or information requested on the form may be subject to criminal sanctions (including fines and imprisonment) and/or civil sanctions (including civil penalties).

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3. Be sure to furnish all circulation information called for in item 15. Free circulation must be shown in items 15d, e, and f.
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5. If the publication had Periodicals authorization as a general or requester publication, this Statement of Ownership, Management, and Circulation must be published; it must be printed in any issue in October or, if the publication is not published during October, the first issue printed after October.
6. In item 16, indicate the date of the issue in which this Statement of Ownership will be published.
7. Item 17 must be signed.

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PS Form **3526,** October 1999 *(Reverse)*

Galleria Gears

For those of us in the gear industry, the concept of gear design is all about involutes, ratios and diameters.

Alexander Kirberg has a different vision of gear design, and his creativity brought him to the forefront of Sigma Pool's competition to show gears in a different light. With the contest, Sigma Pool hoped to acquire a visually unique piece to display artwork that would energize visitors at their EMO booth.

Kirberg was a photography student at Fachhochschule Dortmund and was the winner among the 14 participants from his class selected to create new and artistic ways of seeing gears.

The then 27-year-old student used mechanical processing to dramatize his black-and-white photography to the point where it resembled classical painting. Kirberg hoped viewers could optically experience the power of gearing.

"My pictures orientate themselves to the original colors of the company in order to later achieve presentation and correlation. Gear cutting—thematically seen—results from the combined or overlapped arrangement of photography, technical drawing and corporate design," he explains.

Unlike the design students vying for the top spot on "Project Runway," the winners of the Sigma Pool contest didn't get a chance to sell their line at Macy's. But he did find himself 2000 DM richer and his work exposed to EMO's audience of thousands of the most discerning gear designers anywhere.

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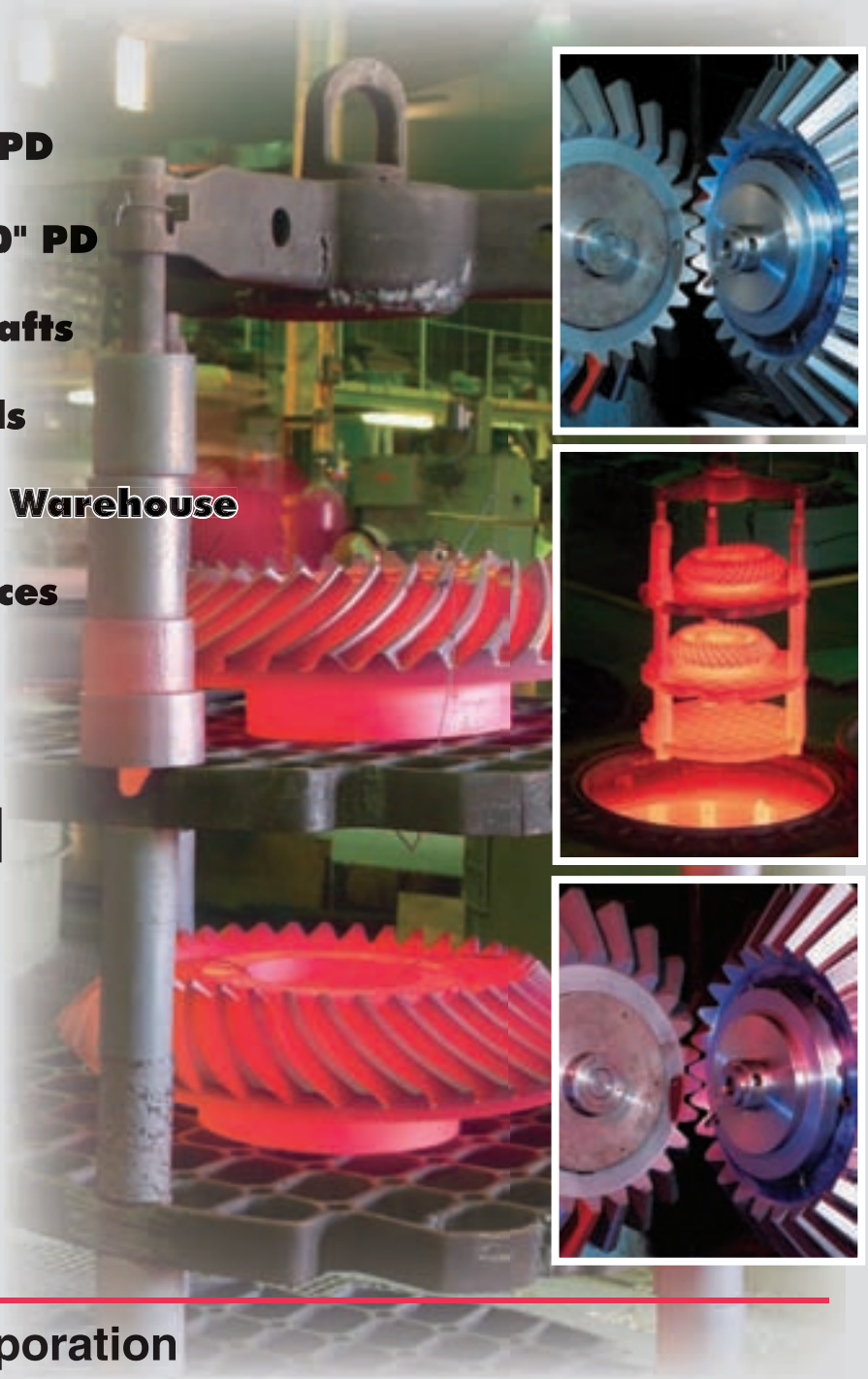

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